Prospects for Higgs & precision SM physics at HL-LHC with the ATLAS detector

EPS-HEP2019, Ghent
11/7/2019

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on behalf of the ATLAS Collaboration
**High luminosity** → 200 soft $pp$ interactions per crossing

- Increased complexity
  - Rate of fake tracks, spurious energy in calorimeters, increased data volume
  - High radiation dose

- **Precision measurements & very rare processes** are major focus
  - Goal of the detector upgrades is to, at minimum, **maintain the current performance for all physics objects**.

- Requires developments in many places
  - Associate particles with primary hard scatter collision at high efficiency
  - Increased detector acceptance
  - Increased spatial granularity to resolve signals from individual particles
    - Timing measurements to provide additional dimension for discrimination

- Significant detector upgrades:
  - Requires **new tracker**, **muon system**, **calorimeter readout and electronics**, **high granularity timing detector** (HGDT), **TDAQ**
Significant detector upgrades:

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Relevant talks and posters:

- ATLAS Level-0 Endcap Muon Trigger for HL-LHC
- Development of the ATLAS Liquid Argon Calorimeter Readout Electronics for the HL-LHC
- Expected tracking performance with the HL-LHC ATLAS detector
- ATLAS Trigger and Data Acquisition Upgrades for the High Luminosity LHC
- The ATLAS Tile Calorimeter performance in the LHC Run-2 and its upgrade towards the High-Luminosity LHC
WG reports published in February contain ATLAS and CMS inputs:

- **Heavy Ions** - CERN-LPCC-2018-07
- **Higgs** - CERN-LPCC-2018-04
- **BSM** - CERN-LPCC-2018-05
- **SM & TOP** - CERN-LPCC-2018-03
- **Flavour** - CERN-LPCC-2018-06
I will focus on just SM precision and Higgs physics:

Overview of physics studies | WG Reports

- SM & TOP - CERN-LPCC-2018-03

Higgs - CERN-LPCC-2018-04

Standard Model Physics at the HL-LHC and HE-LHC

Higgs Physics at the HL-LHC and HE-LHC

Contributors:

For which the ATLAS inputs were:

**Higgs - CERN-LPCC-2018-04**
- Higgs boson couplings & properties (ATL-PHYS-PUB-2018-054)
- Differential Higgs cross sections (ATL-PHYS-PUB-2018-040)
- Measurement of the rare decay $H \rightarrow \mu \mu$ (ATL-PHYS-PUB-2018-006)
- Prospects for $H \rightarrow c\bar{c}$ using $c$-tagging (ATL-PHYS-PUB-2018-016)
- Prospects for HH measurements (ATL-PHYS-PUB-2018-053)
- Search for additional Higgs in $H \rightarrow \tau\tau$ (ATL-PHYS-PUB-2018-050)

**SM & TOP - CERN-LPCC-2018-03**
- Prospects for jet and photon physics (ATL-PHYS-PUB-2018-051)
- Measurement of $t\bar{t}t$ (ATL-PHYS-PUB-2018-049)
- Four-top cross section measurements (ATL-PHYS-PUB-2018-047)
- Flavour-changing neutral current decay $t \rightarrow qZ$ (ATL-PHYS-PUB-2019-001)
- Top quark mass using $t\bar{t}t$ events with $J/\psi \rightarrow \mu\mu$ (ATL-PHYS-PUB-2018-042)
- Measurement of the $W$ boson mass (ATL-PHYS-PUB-2018-026)
- Measurement of the weak mixing angle in $Z/\gamma^* \rightarrow e^+e^-$ (ATL-PHYS-PUB-2018-037)
- Electroweak $Z$ boson pair production with two jets (ATL-PHYS-PUB-2018-029)
- The $W^\pm W^\pm$ scattering cross section (ATL-PHYS-PUB-2018-052)
- Vector boson scattering in $WZ$ (fully leptonic) (ATL-PHYS-PUB-2018-023)
- Electroweak vector boson scattering in the $WW/WZ\rightarrow l\nu q\bar{q}$ final state (ATL-PHYS-PUB-2018-022)
- Production of three massive vector bosons (ATL-PHYS-PUB-2018-030)
Overview of physics studies | WG Reports

For which the ATLAS inputs were:

- Prospects for jet and photon physics (ATL-PHYS-PUB-2018-051)
- Measurement of tt̄ (ATL-PHYS-PUB-2018-049)
- Four-top cross section measurements (ATL-PHYS-PUB-2018-047)
- Flavour-changing neutral current decay t→qZ (ATL-PHYS-PUB-2019-001)
- Top quark mass using tt̄ events with J/ψ→μ+μ− (ATL-PHYS-PUB-2018-042)
- Measurement of the W boson mass (ATL-PHYS-PUB-2018-026)
- Measurement of the weak mixing angle in Z/γ*→e+e− (ATL-PHYS-PUB-2018-037)
- Electroweak Z boson pair production with two jets (ATL-PHYS-PUB-2018-029)
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SM & TOP - CERN-LPCC-2018-03

 Covered in this talk

Higgs - CERN-LPCC-2018-04

- Higgs boson couplings & properties (ATL-PHYS-PUB-2018-054)
- Differential Higgs cross sections (ATL-PHYS-PUB-2018-040)
- Measurement of the rare decay H→μμ (ATL-PHYS-PUB-2018-040)
- Prospects for H→cc using c-tagging (ATL-PHYS-PUB-2018-016)
- Prospects for HH measurements (ATL-PHYS-PUB-2018-053)
- Search for additional Higgs in H→ττ (ATL-PHYS-PUB-2018-050)
Uncertainties | Overview

- Large HL-LHC dataset enables unprecedented precision and reach
- In several analyses systematic uncertainties will become a limiting factor
- A common set of guidelines was developed to align ATLAS and CMS in the physics projections

Where possible report results as:

\[ \text{value} \pm \text{stat} \pm \text{syst(exp)} \pm \text{syst(theory)} [\pm \text{syst(lumi)}] \]

- Many results presented here with two scenarios:
  - **S1**: Assume same values as in published Run-2 analyses.
  - **S2**: Reduction of uncertainties according end of HL-LHC program follow the common recommendations.

- Focus on important **exp. systs** (can't be comprehensive!)
  - Jet Energy Scale/Resolution, MET, B-tagging, Tau-ID, & more...
- Statistics-driven sources: **data→√L**, **simulation→0**
- **Theory uncertainties** improve by factor 2
- PDF uncertainties may be dominant for several results presented here.
- Effort from PDF groups to quantify the precision of the PDF at the end of the HL-LHC running [1810.03639].
- Pseudo-data generated for various inputs: top Drell-Yan, iso photons, W+charm, W and Z in the forward region, inclusive jets...
- Scenario A(C) corresponds to factor 2(5) reduction of uncertainties on exp. inputs.
- LHeC could provide improvement of a factor 5 on PDF uncertainties.
Standard Model Precision
Huge increase in dataset size!
- ~60 billion \textit{W} bosons
- ~6 billion \textit{Z} bosons
- ~3 billion \textit{top quark pairs}

Many challenges
- Need to improve our understanding of systematic uncertainties and their interplay
- Improve techniques for uncertainty mitigation
- High precision differential measurements

Renewed recognition of importance of Standard model measurements for their contribution to electroweak precision observable (EWPO) fits
- Need engagement of theory community to match experimental precision
Key parameter of the SM but **direct** measurement currently less constraining than fits from **indirect** EWPO.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>6.8</td>
<td>6.6</td>
<td>6.4</td>
<td>2.9</td>
<td>4.5</td>
<td>8.3</td>
<td>5.5</td>
<td>9.2</td>
<td>18.5</td>
</tr>
</tbody>
</table>

Motivates low pile-up run: 200 pb\(^{-1}\) of \(\mu \sim 2\) data @ 14 TeV

Extended \(\eta\) coverage & HL-LHC PDFs \(\rightarrow\) large improvements

Exp syst assumed to be at same level of stat uncertainty

**Total uncertainty** \(\sim 10\) MeV, PDF unc \(\sim 3-4\) MeV

Larger (1fb\(^{-1}\)) dataset allows \(\sim 5\) MeV uncertainty

5-10 weeks of running \(\rightarrow\) \(\sim 3\) MeV (stat only)

Even lower with LHeC

[ATL-PHYS-PUB-2018-026]
Indirect constraints stronger than direct measurement.

Two most precise measurements (LEP/SLD) differ by over $3\sigma$

Forward-backward asymmetry is sensitive to $\sin^2\theta_W$

Enhanced by the $Z/\gamma^*$ interference

Dependence on the dilepton rapidity and invariant mass

Sensitivity at high $Z$ rapidity when $\geq 1$ lepton is forward

PDF uncertainties dominate

$\sin^2\theta_{\text{eff}}$ is extracted while constraining PDF uncertainties

Sensitivity improved by 10–25% depending on the prospective PDFs scenario considered.
A top mass measurement using $tt\rightarrow$lepton+jets events with $J/\psi \rightarrow \mu^+\mu^-$ in the final state

- Non-standard technique mitigates e.g. b-tagging/jet energy scale uncertainties.

**Selection**

- Loosened standard lepton+jets selection
  - No requirement on b-tagged jets.
- $J/\psi$ candidates are reconstructed using all pairs of opposite charge sign soft muons
  - $p_T > 4$ GeV and $|\eta| < 4.5$
- The top quark mass is obtained from a template method with unbinned likelihood maximisation approach.

$\Delta m(t) \pm 0.14$ GeV (stat) $\pm 0.48$ GeV (syst)

- Big improvement on 100 fb$^{-1} = 0.7$ GeV (stat)
VBS provides a key opportunity to probe EWK symmetry breaking (EWSB) & BSM

Test preservation unitarity of the longitudinal VV scattering amplitude at different energies

Sensitive to BSM contributions

**VBS topology** composed of:
- **Electroweak** production *with* & *without* a scattering topology.
- **Strong** production.

Sensitive to anomalous EWK couplings and effects from new physics at higher scales
- Dim-8 EFT operators interpretation
- Distinct detector signature - benefits from upgrades
  - Also benefit from improved lepton and forward jet ID efficiencies.
- Large statistics allows detailed study in every channel

\[ qq \rightarrow WZjj \rightarrow 3\nu_{i} + jj, f_{\text{SM}}/A^4 = 3.8\text{TeV}^{-4} \]
Same-sign WW has largest cross-section ratio of electroweak to strong production

Selection
- Dijet mass > 520 GeV, Lepton centrality > -0.5

**Sensitivity > 5σ, uncertainty ~6%**

Dijet azimuthal separation $\Delta\phi(j, j)$ and leading lepton $p_T$ are particularly sensitive to the **longitudinal scattering** component

- Preferentially at large dijet separation and low lepton $p_T$

**Sensitivity ~1.8σ**

Potential for combined ~3σ with further optimisation.

[17] [ATL-PHYS-PUB-2018-052]
Sensitivity to **triple** and **quartic** gauge couplings

Addition test of SM

Multitude of potential decay channels categorised according to the number of leptons (e,μ) and jets in the final state.

HL-LHC offers a large improvement

Sensitivities larger than $3\sigma$ are expected in two channels and larger than $5\sigma$ in one channel.

More mature analysis techniques, such as MVA, would improve further.

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[ATL-PHYS-PUB-2018-030]
Higgs physics
At HL-LHC, we expect to produce ~170M single Higgs bosons, including ~120k of di-Higgs events. Over 1M events for even the lowest cross section production mechanisms, spread over many decay modes.

Enables a broad program:

- Precision $\mathcal{O}(\text{few\%})$ measurements of couplings across broad kinematics
- Exploration of Higgs potential (di-Higgs production)
  - Covered in previous talk
- Sensitivity to rare decays involving new physics
- Extend BSM Higgs searches (extra scalars, BSM Higgs resonances, exotic decays...)

Higgs
Higgs | Production & decay

- Production cross sections:
  - In S2 statistical, experimental & theory uncertainties are comparable for ggH & VBF.
  - For WH and ZH stat. & theory uncertainties are dominant.
  - Theory uncertainty on ttH ~2x larger than other components.

- Branching ratios
  - Precision from 2–4%, except $B_{\mu\mu}$ at 8% and $B_{Z\gamma}$ at 19%.
  - The S1 uncertainties are up to 1.5x larger than those in S2.
  - Systematic uncertainties generally dominate in S1 & S2.
  - In S2 the signal theory uncertainty is the largest, or joint-largest, for all parameters except stat-limited $B_{\mu\mu}$ & $B_{Z\gamma}$.
  - The correlations range up to 40%, and are largest between modes dominated by ggF production.
  - Reflects the impact of theory uncertainties on ggF production.

Increased sensitivity to deviations from SM

- Sensitive to $\kappa_b/\kappa_c$ at low $p_T$ and $\kappa_t$ and BSM at high $p_T$.

- Projections for combined $H\to ZZ$ and $\gamma\gamma$ results

- Expected precision of $\sim 10\%$ for $p_T(H) > 350$ GeV, statistically limited.
Higgs | Kappa/EFT frameworks

- Kappa framework
  - Uncertainty sources contribute similarly for $K_\gamma$, $K_W$, $K_Z$ & $K_\tau$.
  - The signal theory largest for $K_t$ and $K_g$.
  - $K_\mu$ and $K_{Z\gamma}$ are limited by statistics.

- Non-linear EFT
  - Correlation between coupling modifiers is larger compared to signal strength (up to +75%).
  - The largest correlations involve $K_b$, it gives largest contribution to total width.
  - Improving $H \rightarrow b\bar{b}$ precision will improve many other coupling modifiers at HL-LHC.

Mass:
- Most precise measurement using $H \rightarrow ZZ \rightarrow 4\mu, 2e2\mu$ events.
- Detailed muon, electron & photons calibration HL-LHC studies not yet available.
- ATLAS projection: $\Delta_{\text{tot}} = 33 \text{ MeV}$ ($\Delta_{\text{stat}} = 30 \text{ MeV}, \Delta_{\text{syst}} = 14 \text{ MeV}$)
  - $\mu$ resolution/scale improvement $30\% / 80\%$
- Reach of $10-20 \text{ MeV}$ precision plausible in combination
  - Assuming significant improvements on $\mu p_T$ scale from higher stats.

Width:
- Off-shell signal strength: $\mu_{\text{off-shell}}(\delta) = \frac{\sigma_{g \rightarrow H^* \rightarrow VV}^{\text{off-shell}}(\delta)}{\sigma_{g \rightarrow H^* \rightarrow VV}^{\text{off-shell, SM}}(\delta)} = \kappa_{g, \text{off-shell}}^2(\delta) \cdot \kappa_{V, \text{off-shell}}^2(\delta)$
- Probe new physics in the Higgs domain at large momenta.
- Direct measurement challenging even with HL-LHC statistics.
- Estimate that with CMS & ATLAS measurements combined, the precision on the width can reach $4.1 \pm 0.7 \text{ MeV}$.

Summary
Summary

- The (HL-)LHC has only delivered a very small percentage of the full dataset so far!
- Detectors will be able to handle high pile-up conditions
- A huge amount to learn from the precision SM and Higgs physics programme
  - Observation of new (SM) processes.
  - High sensitivity to BSM physics from precision measurements.
  - Will need improvements in theoretical tools to reach full potential.

- Results will shape the landscape of the field for decades
  - Perhaps even longer depending on future collider decisions...

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**Higgs@FC WG**

- FCC-ee+FCC-eeb+FCC-ttbar
- FCC-ee+LHCb+FCC-ett
- FCC-ett
- CEPC
- CLIC1000+CLIC1500+CLIC350
- CLIC1500+CLIC350

**Kappa-3, May 2019**

- CLIC150
- ILC350+ILC150+ILC250
- ILC250
- LHeC ($|\Delta| \leq 1$)
- HE-LHC ($|\Delta| \leq 1$)
- HL-LHC ($|\Delta| \leq 1$)

**Br_{inv} (< %, 95% C.L.)**

**Br_{unt} (< %, 95% C.L.)**

---

M. Cepeda
- The (HL-)LHC has only delivered a very small percentage of the full dataset so far!
- Detectors will be able to handle high pile-up conditions
- A huge amount to learn from the **precision SM** and **Higgs physics** programme
- Observation of new (SM) processes.
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- Will need improvements in **theoretical tools** to reach full potential.
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Back-ups
The (HL-)LHC has only delivered a very small percentage of the full dataset so far!

Detectors will be able to handle high pile-up conditions

A huge amount to learn from the precision SM and Higgs physics programme

- Observation of new (SM) processes.
- High sensitivity to BSM physics from precision measurements.
- Will need improvements in theoretical tools to reach full potential.

Results will shape the landscape of the field for decades

Perhaps even longer depending on future collider decisions...
Huge potential in the high statistics available from HL-LHC programme

The measurements that will come have the potential to:

- Discover new rare (SM) processes
- Measure the electroweak sector with unprecedented levels of precision.
- Improve constraints on BSM physics from direct measurements:

Theoretical advances in the contribution to the uncertainties have a major role in the ability to reach the ultimate precision.
Uncertainties | Reporting

- Statistics-driven sources: data→√L, simulation→0
  - account for larger data sample statistics available
  - to better understand full potential of HL-LHC
- Theory uncertainties typically halved
  - applies to both normalization (x-sec) and modeling
  - due to higher-order calculation and PDF improvements
- Uncertainties on methods kept as latest published results
  - Trigger thresholds same or better(lower) than current
- Assumption that pile-up effects are compensated by detector upgrades improvement and algorithmic developments
- Intrinsic detector limitations stay ~constant
- usage of full simulation tools for detailed analysis of expected performance, thanks to the large effort for TDRs preparation
- detector understanding and operational experience may compensate for e.g. detector aging
- harmonized definition of « floor » values for experimental systematics
- Luminosity uncertainty 1%
Baseline scenario defined as:

YR18(S2): based on synchronised estimates of ultimate performance for experimental and theory uncertainties, and applying guidelines as in previous slide

<table>
<thead>
<tr>
<th>Object</th>
<th>WP</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muons</td>
<td>reco+ID(+ISO)</td>
<td>0.1%(0.5%)</td>
</tr>
<tr>
<td>Electrons</td>
<td>reco+ID+ISO</td>
<td>0,5%</td>
</tr>
<tr>
<td>Taus</td>
<td>reco+ID+ISO</td>
<td>5%(as in Run2)</td>
</tr>
<tr>
<td>B-jet tag</td>
<td>30&lt;pt&lt;300GeV</td>
<td>~1%(2-6%)</td>
</tr>
<tr>
<td></td>
<td>(pt&gt;300GeV)</td>
<td></td>
</tr>
<tr>
<td>c-jet tag</td>
<td></td>
<td>~2%</td>
</tr>
<tr>
<td>Light jets</td>
<td>L/M/T WP</td>
<td>5/10/15%</td>
</tr>
<tr>
<td>JES</td>
<td>abs/rel scale</td>
<td>0.1-0.2%(0.1-0.5%)</td>
</tr>
<tr>
<td>JEC</td>
<td>Pile-Up</td>
<td>0-2%</td>
</tr>
<tr>
<td>JEC</td>
<td>Flavor</td>
<td>0.75%</td>
</tr>
<tr>
<td>Integrated Luminosity</td>
<td></td>
<td>1%</td>
</tr>
</tbody>
</table>
Z couplings differ for left- & right-handed fermions.

- Leads to asymmetry in the angular distribution of +ve and -ve charged leptons produced in Z decays.
- Asymmetry depends on the weak mixing angle ($\sin^2\theta_W$) between the neutral states associated to the U(1) and SU(2) gauge groups.
  - I.e. the relative coupling strengths between the photon and the Z boson.
Expected precision of different techniques (from CMS):

<table>
<thead>
<tr>
<th>Method</th>
<th>Statistical</th>
<th>Systematic</th>
<th>Total (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$ lepton+jets</td>
<td>0.17</td>
<td>0.02</td>
<td>0.17</td>
</tr>
<tr>
<td>single-$t$ t-channel</td>
<td>0.45</td>
<td>0.06</td>
<td>0.45</td>
</tr>
<tr>
<td>$m_{sv\ell}$</td>
<td>0.62</td>
<td>0.02</td>
<td>0.62</td>
</tr>
<tr>
<td>$J/\psi$</td>
<td>0.24</td>
<td>0.53</td>
<td>0.58</td>
</tr>
<tr>
<td>$\sigma_{t\bar{t}}$</td>
<td>0.4% (exp)</td>
<td>0.4% (theory)</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Stat. dominated
Signal significance is limited by the theoretical uncertainty on the QCD-WZ/ZZ background

- Hard to predict theoretical uncertainty

WZjj

- QCD background can be controlled to a smaller value thanks to refined and diverse control regions

- Present as function of background uncertainty
  - Two scenarios in addition to the nominal one
    - better background rejection obtained from BDT
    - Application of q/g discriminant on the jets.

ZZ

- Present significances for 3 values of theory systematic: 5, 10, 30 %.

- 5σ sensitivity achievable in more optimistic scenarios!
## Vector boson scattering (VBS) - $W^\pm W^\pm jj$

<table>
<thead>
<tr>
<th>Selection requirement</th>
<th>Selection value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal lepton kinematics</strong></td>
<td>$p_T &gt; 28$ GeV (leading lepton)</td>
</tr>
<tr>
<td></td>
<td>$p_T &gt; 25$ GeV (subleading lepton)</td>
</tr>
<tr>
<td><strong>Tag jet kinematics</strong></td>
<td>$p_T &gt; 90$ GeV (leading jet)</td>
</tr>
<tr>
<td></td>
<td>$p_T &gt; 45$ GeV (subleading jet)</td>
</tr>
<tr>
<td><strong>Dilepton separation and charge</strong></td>
<td>Exactly two signal leptons with $\Delta R_{\ell\ell} \geq 0.3$, $q_{\ell_1} \times q_{\ell_2} &gt; 0$</td>
</tr>
<tr>
<td>Dilepton mass</td>
<td>$m_{\ell\ell} &gt; 28$ GeV</td>
</tr>
<tr>
<td>$Z_{ee}$ veto</td>
<td>$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>$E_T^{\text{miss}} &gt; 40$ GeV</td>
</tr>
<tr>
<td>Jet selection and separation</td>
<td>at least two jets with $\Delta R_{\ell,j} &gt; 0.3$</td>
</tr>
<tr>
<td>Number of b-tagged jets</td>
<td>0</td>
</tr>
<tr>
<td>Dijet rapidity separation</td>
<td>$\Delta \eta_{j,j} &gt; 2.5$</td>
</tr>
<tr>
<td>Number of additional preselected leptons</td>
<td>0</td>
</tr>
<tr>
<td>Dijet mass</td>
<td>$m_{jj} &gt; 520$ GeV</td>
</tr>
<tr>
<td>Lepton centrality</td>
<td>$\zeta &gt; -0.5$</td>
</tr>
<tr>
<td>SM</td>
<td>WZ fully leptonic</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>YR</th>
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<tbody>
<tr>
<td><strong>Leptons</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T^{lep}$</td>
<td>3 leptons</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\eta^{lep}</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td>$&lt; 4.0$</td>
<td></td>
</tr>
<tr>
<td>ZZ Veto</td>
<td>No extra leptons with $p_T^{lep} &gt; 25$ GeV</td>
<td></td>
</tr>
<tr>
<td>Z boson</td>
<td>SFOC lepton pair</td>
<td>$</td>
</tr>
<tr>
<td>W boson</td>
<td>$p_T^{W} &gt; 20$ GeV</td>
<td>$m_{W} &gt; 30$ GeV</td>
</tr>
<tr>
<td><strong>Jets</strong></td>
<td>2 jets</td>
<td></td>
</tr>
<tr>
<td>$p_T^{jet}$</td>
<td>$&gt; 30$ GeV</td>
<td>$&gt; 30$ GeV for $</td>
</tr>
<tr>
<td>$</td>
<td>\eta^{jet}</td>
<td>&lt; 3.8$ (see text)</td>
</tr>
<tr>
<td>opp. hemisphere</td>
<td>$M_{jj} &gt; 200$ GeV</td>
<td>$M_{jj} &gt; 200$ GeV</td>
</tr>
<tr>
<td><strong>Final selection</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benchmark</td>
<td>$M_{jj} &gt; 500$ GeV</td>
<td></td>
</tr>
<tr>
<td>Optimised</td>
<td>$M_{jj} &gt; 600$ GeV or BDT</td>
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</table>

Table 1: Event selection for the $WZ - EW$ signal.
Vector boson scattering (VBS) - WWjj

Longitudinally polarised W scattering:

![Graphs showing distribution of angular and transverse momentum for ATLAS simulation preliminary.](image-url)
Theoretical uncertainties | Higgs

![Graph showing theoretical uncertainties vs. collider energy]
Results extrapolated from the most recent measurements by ATLAS with 80 fb$^{-1}$

Reduction of total uncertainty with respect to the 80 fb$^{-1}$ results:

- $yy$
  - $ggH + b\bar{b}H$, VBF, top: $x_2$ ($x_3$) for the S1 (S2) scenario
  - VH: $x_5$ ($x_6$) - remains dominated by the statistical uncertainty.

- $ZZ$
  - $ggH$: $\sim x_3$ for S1
  - VH and $t\bar{t}H$: remain dominated by the statistical uncertainty.

- $\sim 4\%$ uncertainties on $\sigma(ggH)$ are in reach

- Comparable to theory uncertainties

- Other results also using extrapolation (WW, taupTau, mumu, Zy,...), some with only 36 fb$^{-1}$
Higgs | WW, tautau, bb

ATLAS Preliminary VH, $H \rightarrow b\bar{b}$ | $\sqrt{s}=14$ TeV, 3000 fb$^{-1}$
Projection from Run 2 data

- Total
- Stat.

$WH$

$qq\rightarrow ZH$

$gg\rightarrow ZH$

Best fit $\alpha/\alpha_{SM}$

0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6

($\alpha \times B$) / ($\alpha_{SM} \times B$)

ATLAS Preliminary
Projection from Run 2 data
$\sqrt{s} = 14$ TeV, 3000 fb$^{-1}$

$H \rightarrow t\bar{t}$

ggF

VBF

Total Stat Syst SM

1.00 $\pm 0.12$ ($\pm 0.09$, $\pm 0.08$)

1.00 $\pm 0.08$ ($\pm 0.03$, $\pm 0.07$)

Total Stat Syst SM

1.00 $\pm 0.05$ ($\pm 0.01$, $\pm 0.04$)

1.00 $\pm 0.10$ ($\pm 0.03$, $\pm 0.08$)
Table 36: The expected ±1σ uncertainties, expressed as percentages, on the per-production-mode cross sections normalised to the SM values for ATLAS (left) and CMS (right). Values are given for both S1 (with Run 2 systematic uncertainties [182]) and S2 (with YR18 systematic uncertainties). The total uncertainty is decomposed into four components: statistical (Stat), signal theory (SigTh), background theory (BkgTh) and experimental (Exp).

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3000 fb⁻¹ uncertainty [%]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>Stat</td>
</tr>
<tr>
<td>σ_{ggH}</td>
<td>S1</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>2.4</td>
</tr>
<tr>
<td>σ_{VBF}</td>
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<td>5.5</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>4.2</td>
</tr>
<tr>
<td>σ_{WH}</td>
<td>S1</td>
<td>9.3</td>
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<tr>
<td></td>
<td>S2</td>
<td>7.7</td>
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<tr>
<td>σ_{ZH}</td>
<td>S1</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>4.8</td>
</tr>
<tr>
<td>σ_{ttH}</td>
<td>S1</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>5.3</td>
</tr>
</tbody>
</table>
Table 37: The expected ±1σ relative uncertainties, expressed as percentages, on the Higgs boson branching ratios normalised by the SM expectations for ATLAS (left) and CMS (right). Values are given for both S1 (with Run 2 systematic uncertainties [182]) and S2 (with YR18 systematic uncertainties). The total uncertainty is decomposed into four components: statistical (Stat), signal theory (SigTh), background theory (BkgTh) and experimental (Exp).

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>3000 fb⁻¹</td>
<td>relative uncertainty [%]</td>
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<tr>
<td></td>
<td>Total</td>
<td>Stat</td>
</tr>
<tr>
<td>B⁺⁺</td>
<td>S1</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
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<td>3.7</td>
</tr>
<tr>
<td>B⁺⁺⁺</td>
<td>S1</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>4.4</td>
</tr>
<tr>
<td>B⁺⁺</td>
<td>S1</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>3.8</td>
</tr>
<tr>
<td>B⁺⁺</td>
<td>S1</td>
<td>7.6</td>
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<tr>
<td></td>
<td>S2</td>
<td>5.0</td>
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<tr>
<td>B⁺⁺</td>
<td>S1</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>4.4</td>
</tr>
<tr>
<td>B⁺⁺</td>
<td>S1</td>
<td>14.9</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>13.7</td>
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</table>
Table 38: The expected $\pm 1\sigma$ uncertainties, expressed as percentages, on the coupling modifier parameters. Values are given for both S1 (with Run 2 systematic uncertainties [182]) and S2 (with YR18 systematic uncertainties). The total uncertainty is decomposed into four components: statistical (Stat), signal theory (SigTh), background theory (BkgTh) and experimental (Exp).

<table>
<thead>
<tr>
<th>ATLAS</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>3000 fb$^{-1}$ uncertainty [%]</td>
</tr>
<tr>
<td></td>
<td>Total Stat SigTh BkgTh Exp</td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>S1 3.7 0.9 2.2 1.4 2.5</td>
</tr>
<tr>
<td></td>
<td>S2 2.4 0.9 1.1 0.9 1.7</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>S1 3.1 0.8 1.9 1.9 1.3</td>
</tr>
<tr>
<td></td>
<td>S2 2.2 0.8 1.2 1.3 1.2</td>
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<td>$\kappa_Z$</td>
<td>S1 2.6 0.8 1.8 1.2 1.1</td>
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<tr>
<td></td>
<td>S2 1.8 0.8 1.0 0.8 0.9</td>
</tr>
<tr>
<td>$\kappa_g$</td>
<td>S1 4.2 1.0 3.2 2.2 1.4</td>
</tr>
<tr>
<td></td>
<td>S2 3.1 1.0 2.2 1.6 1.2</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>S1 6.3 1.1 4.9 3.4 1.6</td>
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<tr>
<td></td>
<td>S2 4.2 1.1 2.6 2.7 1.4</td>
</tr>
<tr>
<td>$\kappa_b$</td>
<td>S1 6.2 1.6 3.7 4.1 2.3</td>
</tr>
<tr>
<td></td>
<td>S2 4.4 1.6 2.1 2.8 2.0</td>
</tr>
<tr>
<td>$\kappa_\tau$</td>
<td>S1 3.7 1.1 2.6 1.8 1.7</td>
</tr>
<tr>
<td></td>
<td>S2 2.7 1.1 1.5 1.2 1.6</td>
</tr>
<tr>
<td>$\kappa_\mu$</td>
<td>S1 7.7 6.4 3.6 1.4 1.9</td>
</tr>
<tr>
<td></td>
<td>S2 7.0 6.4 2.0 0.9 1.8</td>
</tr>
<tr>
<td>$\kappa_{Z\gamma}$</td>
<td>S1 12.7 10.2 6.9 1.4 2.5</td>
</tr>
</tbody>
</table>
Kappa framework

- Uncertainty components contribute at a similar level for $\kappa_\gamma$, $\kappa_W$, $\kappa_Z$ and $\kappa_\tau$. The signal theory largest for $\kappa_t$ and $\kappa_\gamma$. $\kappa_\mu$ and $\kappa_{Z\gamma}$ are limited by statistics.

- The correlation between the coupling modifiers larger compared to signal strength (up to +75%).

- Rate of any signal process depends on total Higgs width which depends on other couplings.

- The largest correlations involve $\kappa_b$, as this gives the largest contribution to total width in SM.

- Improving measurement of $H \rightarrow bb$ will improve the sensitivity of many other coupling modifiers at HL-LHC.

- Even in S1 EFT params, $c$, & Higgs-couplings modifiers, $\kappa$, current limits improve by 2-3x

- Largest benefit in low stats channels: $H \rightarrow \mu\mu \sim 7x$ better, $H \rightarrow Z\gamma$ no strong bound in current data.

- The precision of the interactions associated with the main Higgs couplings will be controlled, to a large extent, by systematic and theory errors.
The upgraded tracker

- ITk layout:

- With appropriate trigger ITk allows to record single-electron events up to $|\eta| \sim 4$
- Muon trigger still stops at $|\eta| \sim 2.7$.
- The calculations in the following correspond to $e+\mu$ central and $e$ forward.
Pseudo-rapidity bins of the ATLAS measurement:

- **Tevatron**: extending the lepton pseudorapidity range from ~1 to ~2 is expected to divide the PDF uncertainty by ~2.

- **LHCb study** (arXiv:1508.06954): finds ~30% reduction of PDF uncertainty from combining the “GPD's” with LHCb.

- **What do we gain from the extended pseudorapidity range in ATLAS?**

PDF uncertainty:
- in each bin: 20-30 MeV
- combined: ~8-9 MeV

De/correlation of PDF uncertainties

![Graph showing correlation and PDF uncertainty](image)
mW | Potential of low pile-up datasets

Recoil resolution is vital for $m_T$ measurement:

- In 2017(+2018) ATLAS recorded $\sim 270 \text{ pb}^{-1}$ at 5 TeV and $\sim 155(+195) \text{ pb}^{-1}$ at 13 TeV, $\mu=\sim 2$
- Several million W events in clean environment
- Statistical sensitivity $\sim 13 \text{ MeV}$ from each sample and each distribution ($p_T, m_T$)
- At 14 TeV $\sim 2M$ W boson events can be collected per week
A truth-level smearing framework is used to investigate correlations.

Methodology:
- Get **truth-level** input distributions
- **Smear** by lepton pT/E and recoil resolution functions
- Good closure wrt **full simulation**
- Construct mW fit
- Vary PDFs and check impact on mW
- Assess correlations between different measurement categories
Moderate or negative correlations are observed between categories with different W charges and forward vs central pseudorapidity for a given $\sqrt{s}$.
Correlations are large and positive between $\sqrt{s} = 14$ and 27 TeV, for a given boson charge and lepton pseudorapidity range.
Combining the central and forward pseudorapidity ranges brings significant reduction in the PDF uncertainty.

Combining the 14 and 27 TeV samples mostly improves the statistical uncertainty.

With 200 pb\(^{-1}\) of data collected at each energy, a total uncertainty of about 11 MeV is obtained.
The statistical uncertainty decreases as expected as the size of the collected sample increases (combination of measurements at 14 TeV in all categories).

- Integrated luminosities range from $200 \text{ pb}^{-1}$ to $1 \text{ fb}^{-1}$
  - $1 \text{ fb}^{-1}$ approximately corresponding to one to five weeks of machine time.

- The statistical sensitivity of the forward categories improves with increasing luminosity.
  - This enhances their impact in the combination with the central categories and explains the slight decrease in the PDF uncertainty.

mW | Impact of more data
The CT10 and CT14 sets display similar uncertainty correlations while the combined MMHT2014 uncertainties are about 30% lower.

The three projected HL-LHC PDF sets give very similar uncertainties.

Scenario 2, the most conservative, is shown.

About a factor of two reduction is obtained compared to existing sets.

If the LHeC is built and runs synchronously with the HL-LHC, the additional constraints on the proton structure from the new DIS data combined with the anti-correlation between central and forward categories could reduce the uncertainty below 2 MeV.
\[ \sigma_e (E_\ell) = a(|\eta|) \sqrt{E_\ell} \oplus b(|\eta|) \oplus c(|\eta|) \cdot E_\ell, \]
\[ \sigma_\mu (p_T^\ell) = r_0(|\eta|) \oplus r_1(|\eta|) \cdot p_T^\ell, \]
\[ \sigma_{u_T} (p_T^W, s) = q_0 \cdot (s/s_0)^\alpha + q_1 \sqrt{p_T^W}; \]

- a, b, c = calorimeter resolution
- r_0,1 = muon resolution
- q_0,1 = recoil resolution
- s_0 = 5 TeV
- \( \alpha \) = CoME dependence of contribution from UE activity
mW | templates & PDF uncertainties

- mW reweighting for template

\[ w(m,m_W,m_W^{\text{ref}}) = \frac{(m^2 - m_W^{\text{ref}})^2 + m^4 \Gamma_W^{\text{ref}} / m_W^{\text{ref}}}{(m^2 - m_W^2)^2 + m^4 \Gamma_W^2 / m_W^2} \]

- mW uncertainty from to PDF Hessian variations:

\[ \delta m_W^+ = \left( \sum_i \delta m_W^i \right)^{1/2} \quad \text{if } \delta m_W^i > 0, \quad \delta m_W^- = \left( \sum_i \delta m_W^i \right)^{1/2} \quad \text{if } \delta m_W^i < 0 \]

- Correlations between measurement categories:

\[ \rho_{\alpha\beta} = \frac{\sum_i \delta m_W^i \delta m_W^j}{\delta m_W^\alpha \delta m_W^\beta} \]
PDF uncertainties for different categories

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [TeV]</th>
<th>Lepton acceptance</th>
<th>Uncertainty in $m_W$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$p_T^\ell$ fits</td>
</tr>
<tr>
<td>14</td>
<td>$</td>
<td>\eta</td>
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<tr>
<td>14</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>27</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>27</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>14+27</td>
<td>$</td>
<td>\eta</td>
</tr>
</tbody>
</table>

Table 2: Measurement uncertainty for different lepton acceptance regions and center-of-mass energies, using the $p_T^\ell$ and $m_T$ distributions and their combination in the fit, using the CT10 PDF set and for 200 pb$^{-1}$ collected at each energy. The numbers quoted for $0 < |\eta| < 2.4$ correspond to the combination of the four pseudorapidity bins in this range. In each case, the first number corresponds to the sum of statistical and PDF uncertainties, and the numbers between parentheses are the statistical and PDF components, respectively.