Prospects for Higgs and di-Higgs measurements at the ATLAS experiment

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on behalf of the ATLAS Collaboration

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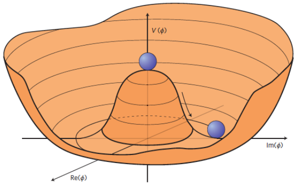
Higgs physics

In the Standard Model all properties of the Higgs boson are defined once its mass is known
but this model leaves many open questions
and many alternative theories make different predictions
for the properties of one or more Higgs bosons

→ After the Higgs boson discovery a vast programme of measurements of its properties was launched and it is currently ongoing using the LHC Run 2 data

Precise measurements in the Higgs sector are a high priority in the future programme of particle physics to probe the compatibility of the measured values of the Higgs boson properties to the SM predictions



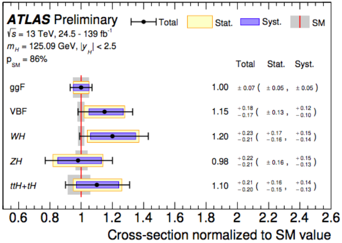
→ with increased precision might be able to observe deviations from the SM expectations that would be a hint of new physics beyond the SM

Where we are now: Higgs LHC Run 2 ATLAS results - ATLAS-CONF-2020-027

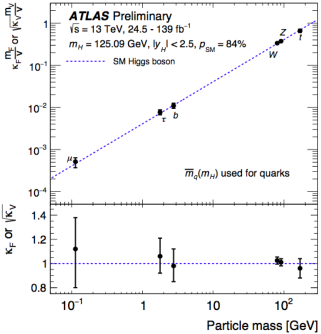
Finalising ATLAS Higgs analyses with LHC Run 2 data collected between 2015 and 2018 and preparing for new Run 3 analyses

From current published Higgs combinations, using up to the full Run 2 dataset:

- Observed ggF, VBF, VH and ttH production modes
- Observed decays in bb, WW, $\tau\tau$, ZZ, $\gamma\gamma$
- Measurements in agreement with SM predictions



Higgs global signal strength: $\mu = 1.06 \pm 0.07$, 10%-20% precision on Higgs production modes cross sections

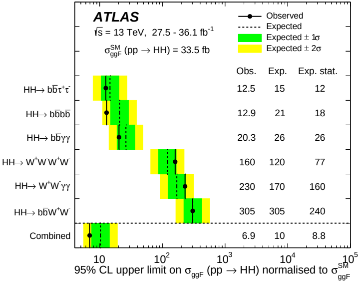


5% uncertainty on Higgs to vector boson couplings and
10%-15% uncertainty on Higgs to the 3rd generation fermion couplings

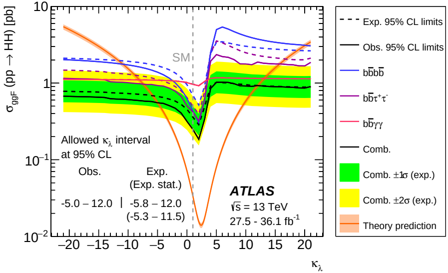
Where we are now: double-Higgs LHC Run 2 ATLAS results - Phys. Lett. B 800 (2020) 135103

Finalising ATLAS double-Higgs analyses with LHC Run 2 data collected between 2015 and 2018 and preparing for new Run 3 analyses

From current published double-Higgs combinations, using a partial Run 2 dataset:



95% C.L. upper limit on the HH signal strength: $\mu < 6.9$

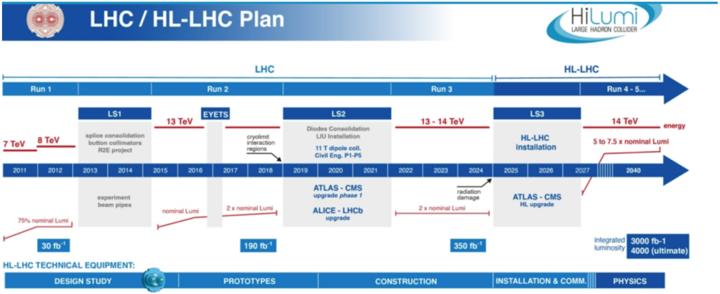


Higgs self-coupling modifier κ_λ constrained to $-5.0 < \kappa_\lambda < 12.0$ at 95% C.L.

LHC upgrade

Start of HL-LHC planned for 2027

- Run at nominal energy of 14 TeV
- Plan to run at 5-7.5 times nominal luminosity
- Expected 3000 fb^{-1} integrated luminosity $\rightarrow$ a factor of 20 more than what we have now



$\rightarrow$ A Higgs factory that will produce close to 200M Higgs bosons!

The large dataset that will be collected at HL-LHC will be used to measure the Higgs boson properties in detail using the single-Higgs and double-Higgs processes

ATLAS detector upgrade

HL-LHC Run will be a challenging collision environment,
with new operation conditions for detectors:

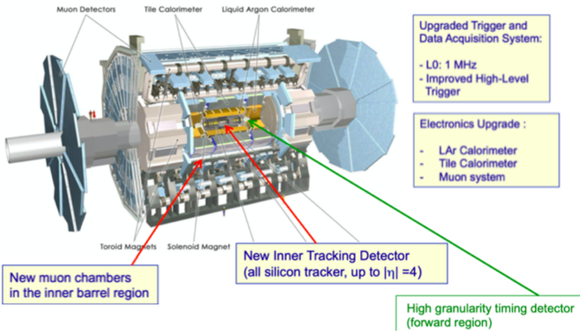
- Increased instantaneous luminosity by factor 2-4 compared to Run 3
- Reaching mean value of 200 interactions per bunch-crossing

To maximise physics outocome need of:

- Maintain or improve object reconstruction efficiency and resolution
- Reduce fake rates even with more pile-up jets

ATLAS phase-2 upgrade:
(Documented in Technical Design Reports)

- Upgrade of readout electronics
- Replace detectors with most recent technologies
- Extend angular coverage to forward region
- Upgrade of trigger and data acquisition systems to sustain higher rate



Projection strategy

Studies based on the current Higgs and double-Higgs analyses using LHC Run 2 data have been carried out to understand the expected precision and limitations these measurements at the HL-LHC

(Published in the CERN Yellow Report, CERN-LPCC-2018-04)

The projections are made by extrapolating the latest published LHC analyses results were performed between 2018 and 2019 using available partial Run 2 results, general strategy is:

- Use early Run 2 data analyses corresponding to 36 fb^{-1} or corresponding to 80 fb^{-1}
- Scale to 3000 fb^{-1} expected at HL-LHC
- Scale signal and background cross section to $\sqrt{s} = 14$ TeV
- Assumption that upgraded detector performance will compensate pile-up degradation
- Assumption on theoretical systematics reduced by factor 2
- Uncertainties due to available statistics of Monte Carlo simulation neglected
- Systematics driven by intrinsic detector limitations left unchanged, or revised according to detailed simulation studies of the upgraded detector

ATL-PHYS-PUB-2019-005

Extrapolation from the ATLAS Run 2 Higgs couplings analyses using:

- data collected in 2015 and 2016, corresponding to 36 fb^{-1} for the WW, $Z\gamma$, ttH and $\tau\tau$ analyses
- data collected in 2015, 2016 and 2017, corresponding to 80 fb^{-1} for the $\gamma\gamma$, ZZ, VH with $H \to bb$ and $\mu\mu$

Two uncertainty scenarios were considered for the Higgs analyses projections:

- S1: Conservative, based on the current Run 2 systematic uncertainties (including theory)
- S2: Ultimate, based on estimates of ultimate performance for experimental uncertainties, and applying a factor of 1/2 for theoretical uncertainties

Expected results presented on: global signal strenght, production modes cross sections, branching ratios and Higgs coupling parameters in the κ framework

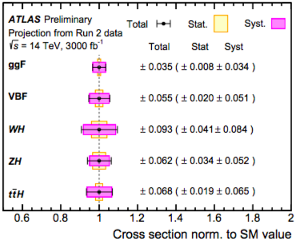
Global signal strength μ:

The expected precision of the measurement of the global signal strength for the S1 (S2) systematic scenario is:

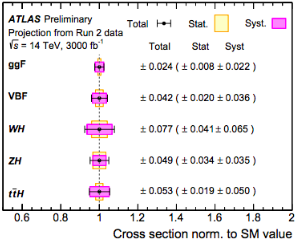
$$\mu = 1.000^{+0.038}_{-0.037} \left(^{+0.025}_{-0.024}\right)$$
$$= 1.000 \pm 0.006 \text{ (stat)} \pm 0.016 \text{ (0.013) (exp)} \; ^{+0.030}_{-0.028} \left(^{+0.017}_{-0.017}\right) \text{ (sig)} \; ^{+0.016}_{-0.015} \left(^{+0.010}_{-0.010}\right) \text{ (bkg)}$$

Precision of a few %, dominated by systematic uncertainties, important impact of theoretical uncertainties on signal

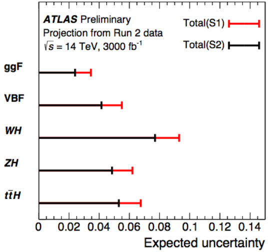
Systematics scenario 1



Systematics scenario 2

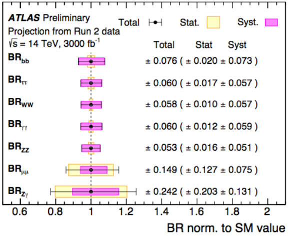


Comparison between systematics scenarios

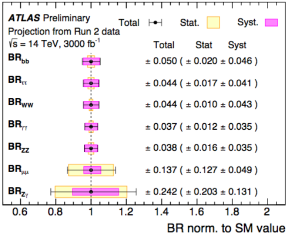


Reaching few % precision on all production modes cross sections, all dominated by systematic uncertainties

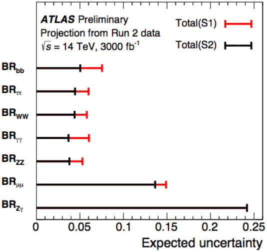
Systematics scenario 1



Systematics scenario 2

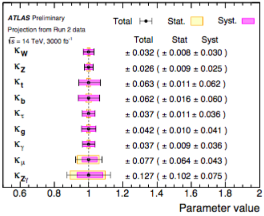


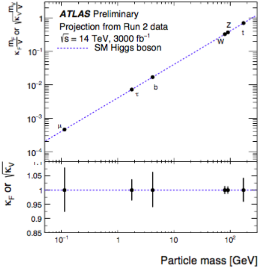
Comparison between systematics scenarios



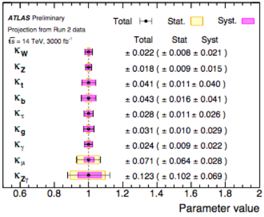
Reaching few % precision on the branching ratios, dominated by systematic uncertainties
Exceptions : $\mu\mu$ and $Z\gamma$ decay channels
reaching 15-25% precision dominated by statistical uncertainties

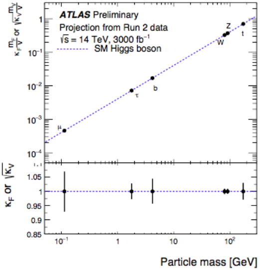
Systematics scenario 1



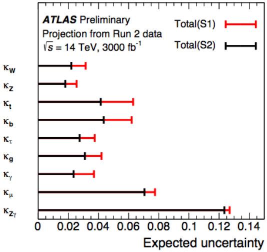


Systematics scenario 2





Comparison between systematics scenarios



Reaching few % precision on the coupling parameters, dominated by systematic uncertainties

Exceptions : μ and $Z\gamma$ reaching 10% precision

dominated by statistical uncertainties

Extrapolation from the ATLAS Run 2 Higgs differential cross sections analyses using:

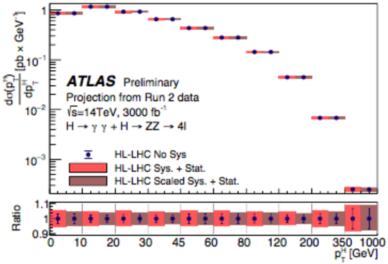
- $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ decay channels
- expected results presented on four observables: p_T^H, $|y^H|$, N_{jets}, p_T^{j1}
- data collected in 2015 and 2016, corresponding to 36 fb^{-1}, with the exception of the p_T^H observable in $H \to ZZ^* \to 4\ell$ where the measurement based on 80 fb^{-1} is used
- Two uncertainty scenarios considered for the Higgs differential cross sections projections: current systematics and reduced ultimate systematics

Sensitivity to new physics:

- Low p_T^H: couplings to c and b quarks
- High p_T^H: new physics at large scale

Expected results:

- Low-medium p_T^H regime: precision of about 5%, 3% (stat), 5% (stat+syst), 4% (stat + reduced syst.)
- Large p_T^H regime [350-1000 GeV]: 8% precision dominated by statistical uncertainties



Projections for the ATLAS Run 2 double-Higgs analyses:

- using *bbbb*, $bb\tau\tau$ and $bb\gamma\gamma$ decay channels
- *bbbb* and $bb\tau\tau$ projections from extrapolation of the analyses using data collected in 2015 and 2016, corresponding to 36 fb^{-1}
- $bb\gamma\gamma$ dedicated new analysis using simulations at 14 TeV

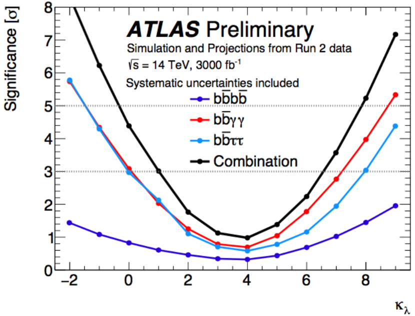
Results presented on: expected significance for HH signal and exclusion limit on Higgs-self coupling modifier κ_λ

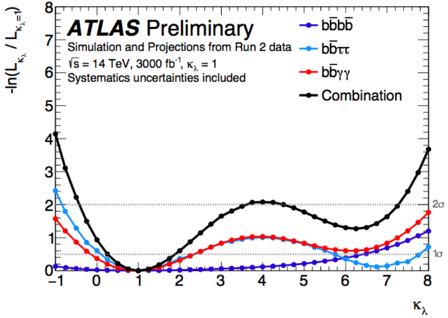
Expected significance for SM HH signal: 3σ, evidence!

Channel	Statistical-only	Statistical + Systematic
$HH \to b\bar{b}b\bar{b}$	1.4	0.61
$HH \to b\bar{b}\tau^+\tau^-$	2.5	2.1
$HH \to b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.5	3.0

Expected 40% precision on μ for SM HH signal dominated by statistical uncertainties

Channel	Measured μ (Statistical-only)	Measured μ (Statistical + Systematic)
$HH \to bbbb$	1.0 ± 0.6	1.0 ± 1.6
$HH \to b\bar{b}\tau^+\tau^-$	1.0 ± 0.4	1.0 ± 0.5
$HH \to b\bar{b}\gamma\gamma$	1.0 ± 0.6	1.0 ± 0.6
Combined	1.00 ± 0.31	1.0 ± 0.4





Constraints on Higgs self-coupling modifier κ_λ:
Expected $-0.4 < \kappa_\lambda < 7.3$ at 95% C.L. for $\kappa_\lambda = 1$

Scenario	1σ CI	2σ CI
Statistical uncertainties only	$0.4 \le \kappa_\lambda \le 1.7$	$-0.10 \le \kappa_\lambda \le 2.7 \cup 5.5 \le \kappa_\lambda \le 6.9$
Systematic uncertainties	$0.25 \le \kappa_\lambda \le 1.9$	$-0.4 \le \kappa_\lambda \le 7.3$

Summary and outlook

From the current projections, based on analyses still using a partial Run 2 dataset, we learn that the HL-LHC will provide a great opportunity for Higgs precision measurements:

- Few % of precision expected for the Higgs couplings
- New rare processes will become accessible, with the observation of $H \to \mu\mu$ and $H \to Z\gamma$
- The rare HH production will also be accessible at the HL-LHC

But this is not the end of the story,
already seen with the full Run 2 analyses that improvements
are going beyond the increase of luminosity

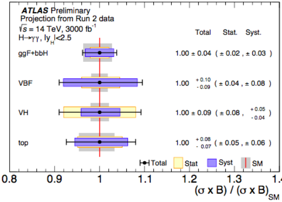
Major progress is expected in the future on:

- Improving performance
- Reducing systematic uncertainties (experimental and theoretical)
- Improving analysis techniques

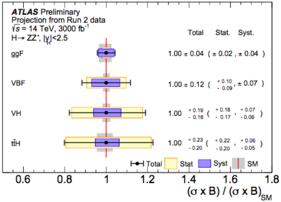
Back-up slides

Higgs single channel analyses projections - ATL-PHYS-PUB-2018-054

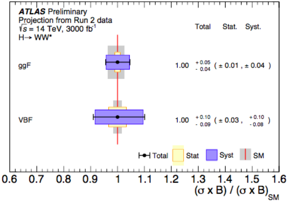
$H \to \gamma\gamma$



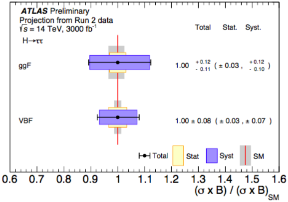
$H \to ZZ^*$



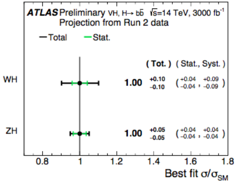
$H \to WW^*$



$H \to \tau\tau$



$VH, H \to bb$



$H \to \mu\mu$

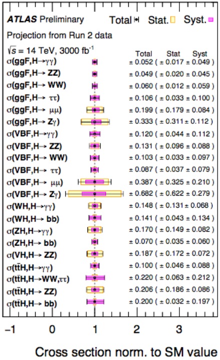
Scenario	$\Delta_{\text{tot}}/\sigma_{\text{SM}}$	$\Delta_{\text{stat}}/\sigma_{\text{SM}}$	$\Delta_{\text{exp}}/\sigma_{\text{SM}}$	$\Delta_{\mu_{\text{sig}}}/\sigma_{\text{SM}}$
Run 2, 79.8 fb^{-1}	$^{+1.04}_{-1.06}$	$^{+0.99}_{-1.03}$	$^{+0.03}_{-0.03}$	$^{+0.32}_{-0.27}$
HL-LHC S1	$^{+0.15}_{-0.14}$	$^{+0.12}_{-0.13}$	$^{+0.03}_{-0.03}$	$^{+0.08}_{-0.05}$
HL-LHC S2	$^{+0.13}_{-0.13}$	$^{+0.12}_{-0.13}$	$^{+0.02}_{-0.02}$	$^{+0.05}_{-0.04}$

$H \to Z\gamma$

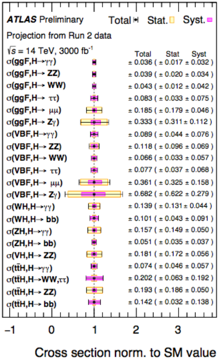
Scenario	$\Delta_{\text{tot}}/\sigma_{\text{SM}}$	$\Delta_{\text{stat}}/\sigma_{\text{SM}}$	$\Delta_{\text{syst}}/\sigma_{\text{SM}}$
HL-LHC S1	0.23	0.20	0.11

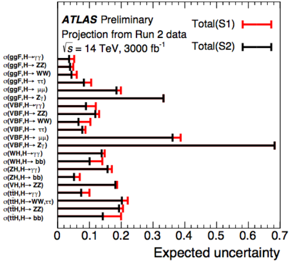
Higgs cross sections times branching fraction - ATL-PHYS-PUB-2018-054

Systematics scenario 1



Systematics scenario 2





Higgs mass projections - ATL-PHYS-PUB-2018-054

Projection from $H \rightarrow ZZ^* \rightarrow$ and $H \rightarrow \gamma\gamma$ mass measurement with data collected in 2015 and 2016 (36 fb^{-1}).
The result is $m_H = 124.79 \pm 0.36(stat.) \pm 0.05(syst.)$ GeV.
The analysis has been extrapolated to 3000 fb^{-1} considering four systematic scenarios

	Δ_{tot} (MeV)	Δ_{stat} (MeV)	Δ_{syst} (MeV)
Current Detector	52	39	35
μ momentum resolution improvement by 30% or similar	47	30	37
μ momentum resolution/scale improvement of 30% / 50%	38	30	24
μ momentum resolution/scale improvement 30% / 80%	33	30	14

Uncertainties in bins of the p_T^H observable

Bin [GeV]	Relative uncertainty [%] Without Sys.	Relative uncertainty [%] With Unscaled Syst.	Relative uncertainty [%] With Scaled Syst.
0, 10	3.2	5.5	4.5
10, 20	3.0	4.8	3.8
20, 30	2.8	5.0	3.9
30, 45	2.7	4.7	3.6
45, 60	3.2	5.0	4.1
60, 80	3.3	5.1	4.2
80, 120	2.9	4.6	3.7
120, 200	2.7	4.4	3.5
200, 350	3.4	5.4	4.5
350, 1000	6.8	8.7	8.2