WG3 Summary
Higgs and BSM Physics

Chris Hays¹, Roman Kogler², Eleni Vryonidou³

¹ Oxford, ² Hamburg, ³ NIKHEF

DIS 2017
Birmingham, 3-7 April, 2017
Overview

- 42 excellent talks with many new results!

- 1. Higgs Physics
- 2. Higgs as a Probe of BSM
- 3. New Particles and Forces
- 4. Dark Matter
- 5. SUSY

Disclaimer:
Huge number of brand new results from experiments and theory - personal selection shown here!

The LHC at 13 TeV

Transition from Run 1 to Run 2

- Largest increase in $\sqrt{s}$ since the start of the LHC
- Luminosity doubling will need some time
News from the Higgs

1. Measurements (diboson couplings)
2. Searches (fermion couplings)
Higgs → ZZ* → 4l

Fiducial cross section

\[ \sigma_{\text{tot}} = 81^{+18}_{-16} \text{ pb} \]
\[ \sigma_{\text{tot,SM}} = 55.5^{+3.8}_{-4.4} \text{ pb} \]

Compatible with SM at 1.6\sigma

Higgs width

On-shell only: \( \Gamma_H < 3.9 \text{ GeV} \)
On- and off-shell: \( \Gamma_H < 41 \text{ MeV} \)

Assumes SM cross sections and no SM particles in loops
The signal shows the expected distribution, while the blue dashed curve represents a background-only fit to the data. The green curve illustrates the background distribution based on the predicted Standard Model signal for a Higgs boson mass of 125.09 GeV.

### Production Mode Cross-Sections

ATLAS has enriched different production modes. Reconstructed events are divided into 13 exclusive categories.

#### Signal

The black data points indicate the enriched leptonic production mode category. The black data points show the total uncertainty. The CMS has achieved a precision similar to that in Run-1, and the results agree with the Standard Model within 1-2 standard deviations.

#### Impact of Fixing the Higgs Mass

For the di-γ channel, the Higgs boson mass is compatible with the CMS results. The fitted Higgs boson mass is consistent with the SM predictions.

#### Total Production Process Cross Sections and Signal Strengths

The measurements are dominated by statistical uncertainties. The measurements presented above are consistent with the SM predictions. The slightly high measured VBF cross section is qualitatively consistent with the theoretical expectations.

#### Higher Multiplicities

The tendencies for the gluon fusion cross section to be higher than the theoretical predictions have been observed. The gluon fusion cross section is only based on hadronic decays of the vector bosons, particularly for higher multiplicities. The tendencies for the gluon fusion cross section to be higher than the theoretical predictions have been observed. The gluon fusion cross section is only based on hadronic decays of the vector bosons, particularly for higher multiplicities.

#### Run-2: Similar Precision Achieved as in Run-1!

The Run-2 results are similar to those achieved in Run-1, demonstrating the precision reached.

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**ATLAS** Simulation Preliminary

**CMS** Preliminary

35.9 fb⁻¹ (13 TeV)

**Higgs → γγ**

Reaching 400 GeV!
Precision for SM Higgs Production

Higgs production in association with jets

H+jets: Large impact of finite top quark mass effects at large $p_T$

Gionata Luisoni

Hadronic Higgs decays

Joshua Davies

Numerically small

QCD series is well converging
EFT for Higgs Physics

No light new particles:

\[ \mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}} \]

EFT@NLO in QCD

Higgs and BSM Summary

- VH and VBF
- \[ \mathcal{L}_{D6} = \frac{1}{\Lambda^2} \left[ \frac{g^2}{4} \mathcal{O}_{BB} \Phi^\dagger \Phi B^{\mu \nu} B_{\mu \nu} + \frac{ig}{2} \bar{c}_R [\Phi^\dagger T_{2k} \Phi^\dagger D^{\mu} \Phi^\dagger D^{\nu} \Phi^\dagger D^{\nu} \Phi^\dagger B_{\mu \nu} + \frac{ig}{2} \bar{c}_B [\Phi^\dagger T_{2k} \Phi^\dagger D^{\mu} \Phi^\dagger D^{\nu} \Phi^\dagger B_{\mu \nu} + \frac{g^2}{4} \bar{c}_{BB} [\Phi^\dagger B^{\mu \nu} B_{\mu \nu} + ig' \bar{c}_H [\Phi^\dagger T_{2k} \Phi^\dagger D^{\mu} \Phi^\dagger D^{\nu} \Phi^\dagger B_{\mu \nu} + \bar{c}_H [\Phi^\dagger T_{2k} \Phi^\dagger D^{\mu} \Phi^\dagger D^{\nu} \Phi^\dagger B_{\mu \nu}] \right] \]

- H → 4l implementation of H decays in the EFT
**H → bb, μμ**

*Full 13 TeV dataset!*

\[ \mu = 0.21^{+0.36}_{-0.35} \text{(stat.)} \pm 0.36 \text{(syst.)} \]

with significance of 0.42 \( \sigma \) (exp. 1.94 \( \sigma \)) and \( \mu < 1.2 \) (exp. 1.0) @95\%CL

**New for Run-2:** VBF selection

\[ \mu = -0.07 \pm 1.5 \text{ with } \mu < 3.0 \] (3.1)

**Simultaneous fit of all BDT outputs from all categories**

**Fit for signal strengths in each lepton category, for WH and ZH and all combined** with significance of 0.42 (exp. 1.94)

\[ \mu < 1.2 \] (exp. 1.0) @95\%CL
The Yukawa coupling $Y_t$ of the Higgs boson to the top quark is a key parameter of the SM. One of the most direct ways is by measuring the signal strength $\mu$ of the $6H$ production. Results on $\mu$ obtained by the ATLAS collaboration in Run I: $\sqrt{s} = 7-8$ TeV, $L_{\text{int}} = 4.5-20.3$ fb$^{-1}$ in part of Run II: $\sqrt{s} = 13$ TeV, $L_{\text{int}} = 13.3$ fb$^{-1}$. Details on several selected final states will also be given.

Any significant deviation of $\mu$ from 1 would be a signal for BSM physics. Here are the presented results.

Higgs to $WW\rightarrow$ leptons

Full 13 TeV dataset!

MVA methods for suppression of irreducible backgrounds
($tt+bb, tt+cc, ttV$)
Similar sensitivity between Run-1 and Run-2 (half the data)

Full 13 TeV dataset!

3.3σ (2.5σ expected) for ttH production
Precision ttH Modelling

Soft Gluon Resummation for ttH

- Dependence on scale choice reduced through resummation

NLO+PS matching for ttbb with massive b’s
(irreducible background to ttH)

- Shower corrections less significant

Threshold resummation for $t\bar{t}H$

Vincent Theeuwes

$\sqrt{S} = 13$ TeV

粉末

Preliminary
Higgs as a Probe of New Physics
In the absence of the Higgs boson, the amplitude for vector-boson scattering (VBS) grows with the partonic center-of-mass energy, until eventually unitarity is violated!

In the SM, the Higgs boson unitarizes the high-energy behaviour of VBS amplitudes.

On the other hand, VBF production has very little sensitivity to the Higgs self-coupling …
Rare Higgs Decays

\( H \rightarrow \Phi \gamma, \text{BR} \sim 10^{-6} \) access s quark coupling

**LFV Higgs decays**

\( H \rightarrow \mu\mu, e\tau, \mu\tau \)

\( \text{Br}(h \rightarrow \mu\tau) < 1.20\% \)

(1.62\% expected)

(2.4\% at 8 TeV from \( h \rightarrow \mu\tau \) not confirmed, comparable sensitivity)

**First measurement!**
Additional Scalars

High Mass Searches

Low Mass Searches

Upper cross section limits: fb region

Also: X→Zγ searches
**2HDM, MSSM**

**H/A → hh**

**Full 13 TeV dataset!**

\[ M_A \sim 300 \text{ GeV for small } \tan \beta \text{ excluded} \]

Starting to cover the \( \tan \beta / M_{H^+} \) plane with 13 TeV

**H^+ → τ_{had}V**

**H^+ → τ_{had}V**

\[ m_h^{\text{mod}^+} \]

**CMS Preliminary**

**Higgs and BSM Summary**
Doubly-Charged Higgs

Imma Riu

Direct production

Indirect constraints, $\tau \rightarrow 3\mu$

See-saw mechanism

Chris Hays

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 13.9 fb$^{-1}$

$\text{Br}(H^{\pm \pm} \rightarrow e^+e^{-}) = 1.0$

**Expected 95\% CL**

- Observed 95\% CL
- Expected limit $\pm 1\sigma$
- Expected limit $\pm 2\sigma$

$\sigma(pp \rightarrow H^{\pm \pm})$

$\sigma(pp \rightarrow H_R^{++})$

$\sigma(pp \rightarrow H_L^{++})$

$\Delta = \frac{\sigma(pp \rightarrow H^{++}) - \sigma(pp \rightarrow H_R^{++})}{\sigma(pp \rightarrow H_L^{++})}$

$m_{\Delta^{++}} \approx 15$ TeV

$m_{\nu} \sim 0.1$ eV

Roman Kogler

Higgs and BSM Summary
New Particles and Forces
\[ \ell \ell / \ell \nu \text{ Resonances} \]

- Historic example: Discovery of W/Z bosons at UA1 & UA2

[UA1, PLB126, 398 (1983)]
[UA2, PLB129, 130 (1983)]
**\( \ell\ell/\ell\nu \) Resonances**

- **Historic example:**
  Discovery of W/Z bosons at UA1 & UA2

  [UA1, PLB126, 398 (1983)
   UA2, PLB129, 130 (1983)]

![Graph showing signal and background with \( M_z = 91.9 \pm 1.9 \text{ GeV} \)]
\( \ell\ell/\ell\nu \) Resonances

- Historic example: Discovery of W/Z bosons at UA1 & UA2
  - [UA1, PLB126, 398 (1983)]
  - [UA2, PLB129, 130 (1983)]

\[ Z' \rightarrow \ell\ell \]

- [Halil Saka]
  - higher backgrounds from multijet prod.

- Yanlin Liu
  - SSM Z': \( M_{Z'} > 4.5 \text{ TeV} \)
**$\ell\ell/\ell\nu$ Resonances**

- **Historic example:**
  Discovery of W/Z bosons at UA1 & UA2

  [UA1, PLB126, 398 (1983)  
  UA2, PLB129, 130 (1983)]

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**Yanlin Liu**

Photon induced contribution to the dilepton spectrum

- SSM $Z'$:
  $M_{Z'} > 4.5$ TeV

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**Juri Fiaschi**

- $Z'\rightarrow t\bar{t}$
- Halil Saka
- higher backgrounds from multijet prod.
qq/gg Resonances

[UA2, Z. Phys. C 49, 17 (1991)]
qq/gg Resonances

[UA2, Z. Phys. C 49, 17 (1991)]
$M_{jj} = 8.12 \text{ TeV}$
qq/gg Resonances

Full 13 TeV dataset!

Hanno Meyer zu Theenhausen
qq/gg Resonances

**High Mass Search for Resonant Phenomena**

5. April, 2017

H. Meyer zu Theenhausen, DIS 2017

Compare data to background estimation from sliding window fit:

Run BumpHunter algorithm to find most significant excess $y^* < 0$.

Search and limits for Quantum Black Holes

Full 13 TeV dataset!

**ATLAS**

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

- Data
- Background fit
- BumpHunter interval

- QBH, $m_B = 5.0$ TeV
- QBH, $m_B = 6.5$ TeV

$$f(z) = p_1 (1-z)^p_2 z^{p_3}$$

QBH $p$-value = 0.63
Fit Range: $1.1 - 8.2$ TeV
$|y^*| < 0.6$

**CMS Preliminary**

2.7 fb$^{-1}$ (13 TeV)

Jingyu Zhang

Single-jet mass!

Hanno Meyer zu Theenhausen
Run: 299584
Event: 563621388
2016-05-20 08:26:49 CEST
M(JJ) = 2.40 TeV

Diboson Ereignis
M_{JJ} = 2.4 \text{ TeV}
The data are shown as black markers. The filled red area corresponds to the 1 sigma statistical error of the fit. The solid curve represents a background-only fit to the 13 TeV data. On the left, the HP, and on the right, the LP categories are shown for the WW, WZ, ZZ categories from top to bottom. The HP, and on the right, the LP categories are shown for the WW, WZ, ZZ categories from top to bottom.

Figure 2: Full 13 TeV dataset!

Alberto Zucchetta

35.9 fb⁻¹ (13 TeV)

CMS Preliminary

- CMS data
- 2 par. background fit
- G(2 TeV)→WW (σ = 0.020 pb)

WW, high-purity
h_j ≤ 2.5, p_j > 200 GeV
M_j > 1050 GeV, |Δη_j| ≤ 1.3

Nicolò Vladi Biesuz

ATLAS Preliminary

Preliminary

2-tag WH

HVT Model A W’ (2 TeV) x 50

Roman Kogler

Higgs and BSM Summary
The data are shown as black markers. The data distribution where the filled red area corresponds to the 1 sigma statistical error of the fit. The solid curve represents a background-only fit to the 13 TeV data. On the left, the HP, and on the right, the LP categories are shown for the WW, WZ, and ZZ categories from top to bottom. The solid curve represents a background-only fit to the 13 TeV data.

**V V/V H Resonances**

**Full 13 TeV dataset!**

Alberto Zucchetta

35.9 fb\(^{-1}\) (13 TeV)

CMS

Preliminary

Events / 100 GeV

Data/Fit

\(\sigma_{\text{data}}\)

Dijet invariant mass (GeV)

ATLAS

Preliminary

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

2-tag WH

Events / 100 GeV

Events / 100 GeV

Data / Pred

\(m_{jj}\) [GeV]

Local: 3.3\(\sigma\), Global: 2.2\(\sigma\)

Nicolò Vladi Biesuz

35.9 fb\(^{-1}\) (13 TeV)

2 par. background fit

\(G(2\) TeV) \(\rightarrow WW (\sigma = 0.020\) pb\)

WW, high-purity

\(l_{|} < 2.5, p_{T} > 200\) GeV

\(M_{jj} > 1050\) GeV, \(\Delta \eta_{jj} \leq 1.3\)

HVT Model A W' (2 TeV) x 50

Multijet

Other Backgrounds

pre-fit

HVT Model A W' (2 TeV) x 50

HVT Model A W' (2 TeV) x 50

Local: 3.3\(\sigma\), Global: 2.2\(\sigma\)
VV/VH Resonances

Full 13 TeV dataset!

Alberto Zucchetta

35.9 fb⁻¹ (13 TeV)

Preliminary

CMS data

- 2 par. background fit
- G(2 TeV) → WW (σ = 0.020 pb)

WW, high-purity
- |η| ≤ 2.5, p_T > 200 GeV
- Mjj > 1050 GeV, |Δηjj| ≤ 1.3

Nicolò Vladi Biesuz

ATLAS Preliminary

|s = 13 TeV 36.1 fb⁻¹

2-tag WH

Events / 100 GeV

Data / Pred mjj [GeV]

Local: 3.3σ, Global: 2.2σ

Not confirmed by CMS
Vector Like Quarks

Pair production

Ht+X

Ht+X 1-lepton

Wb+X

Wb+X 1-lepton

Zt+X

Zt+X 1+Z_{miss} lepton

Mass limits above 1 TeV for each analysis at 100% BR!
Vector Like Quarks, Width Effects

Heavy quark decays to DM beyond the NWA

Width impact on total cross-section and mass exclusion
HERA and NA62

Limits on quark radius $R_q$ and $eq$ contact interactions

Full HERA-2 combined data $R_q < 0.43 \cdot 10^{-18}$ m

Heavy neutrinos in kaon-decay

First limit in this region!

Prospect with 2015 data

Measurement Strategy

• Many existing limits require the heavy neutrino to decay within the fiducial volume of the experiment
• This is not required at decay-in-flight Kaon experiments like NA62 where “missing mass” methods can be used
• NA62 makes a measurement of heavy neutrino production – NB limits on production scale linearly with the number of Kaons
• The missing mass is the mass of the heavy neutrino

Comparison with existing measurements

• NA62 (2007) sets the world’s most stringent limit on heavy neutrino production in the mass region $325 < m_h < 375$ MeV/$c^2$
• First limit in this region!

Prospect with 2015 data
Dark Matter
Mono-X Searches

- Recoil of SM particle against DM system

**High p_T**

**High P_T^{miss}**

**Angular separation**

**Full 13 TeV dataset!**

**H(bb) + P_T^{miss}**

**ATLAS Preliminary**

- Data
- Z+jets
- t\bar{t} + single top
- W+jets
- Diboson
- SM Vh
- Multijet

**Background Uncertainty**

**Pre-fit Background**

- mono-h Z'-2HDM
- m_{Z'} = 1400 GeV, m_A = 600 GeV
- c_{signal} = 4.74 fb

**Events / bin**

**Data/SM**

**Resolved**

**Boosted**

**E_T^{miss} [GeV]**

**200**  **300**  **400**  **500**  **600**  **700**  **800**
Interpretation in Simplified Models

Cora Fischer

DM Simplified Model Exclusions

ATLAS Preliminary March 2017

Dijet
\( \sqrt{s} = 13 \text{ TeV}, 37.0 \text{ fb}^{-1} \)

arXiv:1703.09127 [hep-ex]

Dijet 8 TeV
\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)


Dijet TLA
\( \sqrt{s} = 13 \text{ TeV}, 3.4 \text{ fb}^{-1} \)

ATLAS-CONF-2016-030

Dijet + ISR
\( \sqrt{s} = 13 \text{ TeV}, 15.5 \text{ fb}^{-1} \)

ATLAS-CONF-2016-070

Axial-vector mediator, Dirac DM
\( g_q = 0.25, g_i = 0, g_{DM} = 1 \)

All limits at 95% CL

Mediator Mass [TeV]

DM Mass [TeV]

\( q \)

\( g \)

\( \chi \)

\( g_{\chi} \)

\( g_\text{med} \)

\( q \)

\( W/Z/\gamma \)

\( g_q \)

\( g_\text{med} \)

\( g_\chi \)

\( q \)

\( g \)

\( \chi \)

\( g_{\chi} \)

\( g_\text{med} \)

\( q \)

\( W/Z/\gamma \)

\( g_q \)

\( g_\text{med} \)

\( g_\chi \)
Interpretation in Simplified Models

Cora Fischer

<table>
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<th>DM Simplified Model Exclusions</th>
<th>ATLAS Preliminary March 2017</th>
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Vector mediator, Dirac DM

\[ g_q = 0.1, \ g_l = 0.01, \ g_{DM} = 1 \]

All limits at 95% CL

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**DM Mass [TeV]**

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**Mediator Mass [TeV]**

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DM+bb/tt

Fully-hadronic channel:
No $p_T^{miss}$ in SM tt
SUSY
Strong production

Full 13 TeV dataset!

- 0, 1, 2, multi-leptons
- Categorize in $N_{\text{jet}}, N_{b\text{-jet}}, H_T, P_T^{\text{miss}}$ ...

- 0/1 lepton, multiple b-jets, $P_T^{\text{miss}}$

0-lepton + b

1-lepton + b

Simplified Model:
$m_\tilde{g} > 1800$ GeV

$\tilde{g} \rightarrow b\tilde{b}\chi^0_1$, $m(\tilde{g}) \gg m(\chi_1^0)$
Chargino/Neutralino Production

- Electroweak production → smaller cross sections
- Multitude of final states

C1C1 & C1N2 production

T final states

C1C1 production

C1N2 production

light leptons

Nicky Santoyo Castillo
Chargino/Neutralino Production

- Electroweak production → smaller cross sections
- Multitude of final states

C1C1 & C1N2 production

**T final states**

C1C1 production

C1N2 production

**light leptons**

Nicky Santoyo Castillo

**CMS Preliminary**

pp → \( \tilde{\chi}_0^0 \tilde{\chi}_1^\pm \)

<table>
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<tr>
<th>Process</th>
<th>Expected</th>
<th>Observed</th>
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<td>SUS-16-039, 3l (( \tilde{\chi}<em>2^0 \rightarrow \tau \bar{\nu} )), ( x</em>\tau = 0.5 )</td>
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35.9 fb\(^{-1}\) (13 TeV)
Natural SUSY, $\tilde{t}\tilde{t}$ production

John Anders
Markéta Jansová

$\tilde{t} \rightarrow t \tilde{\chi}^0$
Jet-Substructure

$\tilde{t} \rightarrow W b \tilde{\chi}^0$
ISR Jet

$\tilde{t} \rightarrow b f f' \tilde{\chi}^0$
soft b-tagging, charm tagging

---

**Diagram:**

- **ATLAS Preliminary**
- $\sqrt{s} = 13$ TeV
- $t0L 36.1 \text{ fb}^{-1}$ [CONF-2017-020]
- $t1L 13.2 \text{ fb}^{-1}$ [CONF-2016-050]
- $t2L 13.3 \text{ fb}^{-1}$ [CONF-2016-076]
- MJ 3.2 fb$^{-1}$ [1604.07773]
- Run 1 [1506.08616]

**Status:** Moriond 2017

**Observed limits**

- All limits at 95% CL

---

**Figure:**

- $m_{\tilde{t}}$ production, $\tilde{t}_1 \rightarrow b f f' \tilde{\chi}^0 / \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$

---
RPV SUSY and Long-lived Particles

RPV:
no $P_T^{miss}$, but high jet multiplicity

$1\ell + 10$ jets!

Disappearing tracks from long-lived particles

Improved efficiency through IBL


SUSY Extensions

BLSSM: Extended Gauge group

\[ G_{B-L} = SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L} \]

- Solution to Hierarchy problem
- Similar fine-tuning as MSSM
- Right-handed neutrinos
- Dark Matter candidates

MSSM and U(1)\': UMSSM

\[ Z' \] decays to charginos, neutralinos and SM particles

Z' phenomenology in supersymmetry at the LHC

Simon King

Gennaro Corcella
On the verge of discovering direct Hbb and Htt couplings

Keep looking for the unexpected!

Thanks to all speakers and to the organisers for a very stimulating DIS2017!