Highlights and Perspectives from ATLAS

Highlights (Recent and Selected)

HEP 2021 - 38th Conference on Recent Developments in High Energy Physics and cosmology
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Disclaimer: Only very few highlights are covered in this talk, ATLAS has many more Run 2 results.

All ATLAS results are available at this link.

- Latest ATLAS results from Run 2 presented at LHCP 2021 last week! See summary here.
- Latest ATLAS results from Run 2 presented at 2021 Moriond Conference! See summary here!
- Latest ATLAS results from Run 2 presented at 2021 ICHEP Conference! See summary here!
- Latest news from LS2 can be found here.
- European Strategy 2012-2013 Recommendations.
- European Strategy 2020 Recommendations.

- Check and bookmark our news page
- Subscribe to our ATLAS YouTube channel (and hit the like button)
Gearing up towards the LHC Run 3 and Beyond…

Mechanical structure of Muon
New Small Wheel A ready

Superb achievement of many groups, in particular from Greece!!
Where do we stand?

After 10 years of running with superb operation efficiency typically over the entire running period of 90%...

In 2019 opened the detector and started the Long Shutdown (LS) 2 operations!
The LHC Timeline

LHC Timeline

### Run 1
- **2011**
  - 7 TeV
  - ATLAS - CMS
  - HL upgrade
  - Installation

### Run 2
- **2012**
  - 8 TeV
  - ATLAS - CMS
  - HL upgrade
  - Installation

- **2013**
  - 13 TeV
  - ATLAS - CMS
  - HL upgrade
  - Installation

- **2014**
  - Diodes Consolidation
  - LIU Installation
  - Civil Eng. P1-P5

- **2015**
  - splice consolidation
  - button collimators
  - R2E project

- **2016**
  - experiment beam pipes

- **2017**
  - nominal Lumi
  - 2 x nominal Lumi

- **2018**
  - 190 fb⁻¹

### Run 3
- **2019**
  - ATLAS - CMS
  - Upgrade phase 1

- **2020**
  - ALICE - LHCb
  - Upgrade

### Run 4 - 5...
- **2021**
  - HL-LHC
  - 14 TeV
  - energy

### Run 4 - 5...
- **2022**
  - HL-LHC
  - 14 TeV
  - energy

### Run 4 - 5...
- **2023**
  - HL-LHC
  - 14 TeV
  - energy

### Run 4 - 5...
- **2024**
  - HL-LHC
  - 14 TeV
  - energy

### Run 4 - 5...
- **2025**
  - HL-LHC
  - 14 TeV
  - energy

### Run 4 - 5...
- **2026**
  - HL-LHC
  - 14 TeV
  - energy

### Run 4 - 5...
- **2027**
  - HL-LHC
  - 14 TeV
  - energy

### Run 4 - 5...
- **2040**
  - HL-LHC
  - 14 TeV
  - energy

### Initial 2018 calibration
- **2018**
  - More than 60 fb⁻¹ collected by experiments

### Record 2018
- 30 fb⁻¹

### Mean Number of Interactions per Crossing
- **2011**
  - Mean: 0
- **2012**
  - Mean: 10
- **2013**
  - Mean: 20
- **2014**
  - Mean: 30
- **2015**
  - Mean: 40
- **2016**
  - Mean: 50
- **2017**
  - Mean: 60
- **2018**
  - Mean: 70

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- **Run 1**: Centre-of-mass Energies of 7 and 8 TeV and luminosities of \(~20 \text{ fb}^{-1}\) and Pile-Up of \(~30-40\) (50 ns between bunch crossing).

- **Run 2**: Centre-of-mass Energy of 13 TeV and luminosities of \(~140 \text{ fb}^{-1}\) with Pile Up of \(~30-40\) (25 ns between bunch crossings).

However impressive, to get to \(3000 \text{ fb}^{-1}\) would require **50 full years of running the LHC**!
### The LHC Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>LS1</th>
<th>EYETS</th>
<th>LS2</th>
<th>EYETS</th>
<th>LS3</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>7 TeV</td>
<td>splice consolidation button collimators R2E project</td>
<td>13 TeV</td>
<td>cryolimit interaction regions</td>
<td>13 - 14 TeV</td>
</tr>
<tr>
<td>2012</td>
<td>8 TeV</td>
<td>experiment beam pipes</td>
<td>Diodes Consolidation LIU Installation Civil Eng. P1-P5</td>
<td></td>
<td></td>
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<tr>
<td>2013</td>
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<tr>
<td>2018</td>
<td></td>
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<td></td>
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</tbody>
</table>

### RUNS
- **Run 1**: LS1 (7 TeV), EYETS
- **Run 2**: 13 TeV (expected PU: 140-200)
- **Run 3**: LS2 (13 - 14 TeV)

### HL-LHC Timeline
- 2020-2024: ATLAS - CMS HL upgrade
- 2025-2027: ALICE - LHCb HL upgrade
- 2030: ATLAS - CMS upgraded to HL-LHC

### Integrated Luminosity
- **Run 1**: 30 fb⁻¹
- **Run 2**: 190 fb⁻¹
- **Run 3**: 350 fb⁻¹
- **HL-LHC**:
  - 2020-2024: 5-7 x nominal Lumi
  - 2030: 5 to 7.5 x nominal Lumi

### Interaction Region at LHC IP
- ~5.6 cm

### Expected PU at HL-LHC
- HL-LHC 140-200
The LHC Timeline

- LINAC 4: Extremely important milestone on the road towards higher luminosities (90 meters machine).
- "Crabbing protons" also one additional major step towards the High Luminosity, successfully tested at SPS.
- Ni3Sn ~100 magnet elements (dipoles and quadrupoles) with fields above 10T.
- TDIS (dump/absorber to protect downstream equipment)
- Collimation upgrades.
- Civil engineering at P1 - P5.
**Phase 1** (Deployment ongoing during LS2)
- Muon chambers: **New Small Wheel** (innermost endocarp wheel replacement Micromegas and sTGC) and BIS78
- Trigger and Data Acquisition system (EM calorimeter increased granularity at L1, new trigger boards)
- Major software new release:
  
  **Entire software release from Multi-Process to Multi-Thread**
  
  Large improvement in MEM consumption and speed!

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**The LHC Timeline**

- **LS1**: splice consolidation button collimators R2E project
- **LS2**: Diodes Consolidation LIU Installation
  - **ATLAS - CMS** upgrade phase 1
  - **ALICE - LHCb** upgrade
- **LS3**: HL-LHC Installation
  - **ATLAS - CMS** HL upgrade

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From I. Ochoa LHCC June 2021
The LHC Timeline

Phase 2 (Major ATLAS upgrades with deployment during LS3)

- Full Silicon tracker
- Calorimeter electronics upgrade
- Timing detector with partial eta coverage (2.4 - 4) LGAD silicon: 30 ps resolution
- Muon coverage

2025-2027

 Longer term LS4 2031
Possible upgrades under discussion
Where do we stand?

Intense preparation, assembly, installation, and commissioning of all upgrade systems and performing maintenance of all sub-detectors systems!
Machine status towards Run 3

Powering tests and magnet trainings ongoing
- Magnet replacement in sector 78 (required warming up)
- Diode replacement in sector 23 (also requires warming up)

Closing by end of February!
Highlights and Perspectives
Latest result using the entire 5.02 TeV Run 2 PbPb sample

Measurements indicate a suppression increasing from peripheral to central collisions (charm being more suppressed than b).

First HI PbPb collisions in 2015

Measurement of the nuclear modification factors for inclusive heavy flavour muons (from B and D decays):

\[ R_{AA} = \frac{N_{AA}}{N_{ev}} \left( \frac{\langle T_{AA} \rangle \times \sigma_{PP}}{\sigma_{PP}} \right) \]

Measurements made as a function of centrality*

*Measured in the FCAL

Important inputs for our understanding of heavy quark transport and QGP properties!
The Higgs Boson

All the couplings of the Higgs boson to Standard Model particles (except to itself) known well before the discovery…

However, still many more questions!

Making the weak interaction short range

Fundamental non gauge couplings (never seen before)

Self interactions of a fundamental scalar (never seen before)

- Unsolved question of flavour Hierarchy
- Couplings to top critical for the stability of the vacuum
- $u$ and $d$ Yukawa decide the stability of nuclei

- No dynamical explanation in the SM for the shape of the potential
- The self coupling and shape of the potential critical to the EW transition

Measuring Higgs properties is a formidable potential window to physics beyond the Standard Model

Proof of condensate!
### Nano Overview of Main Higgs Analyses at (HL) LHC

Most channels already covered at the Run 2 with only 5% (~140 fb-1) of full HL-LHC dataset!

<table>
<thead>
<tr>
<th>Channel categories</th>
<th>Br</th>
<th>ggF</th>
<th>VBF</th>
<th>VH</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>~4 M vets produced</td>
<td>~300 k vets produced</td>
<td>~200 k vets produced</td>
<td>~40 k evts produced</td>
</tr>
<tr>
<td>Cross Section 13 TeV (8 TeV)</td>
<td>48.6 (21.4) pb*</td>
<td>3.8 (1.6) pb</td>
<td>2.3 (1.1) pb</td>
<td>0.5 (0.1) pb</td>
<td></td>
</tr>
<tr>
<td>γγ</td>
<td>0.2 %</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ZZ</td>
<td>3 %</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>WW</td>
<td>22 %</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>ττ</td>
<td>6.3 %</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>bb</td>
<td>55 %</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Zγ and γγ</td>
<td>0.2 %</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>μμ</td>
<td>0.02 %</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Invisible</td>
<td>0.1 %</td>
<td>✓ (monojet)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

*N3LO
Higgs Couplings
The intricate WW channel

One of the most intricate channels!

Channel where each of the W decays to leptons, the mass resolution is spoiled by the neutrinos!

Large event rate, but also large backgrounds from the WW and top production.

Requires good simulation of backgrounds and control regions in the data.

Analysis aiming at gluon fusion and VBF production modes!

Uses the V-A nature of the W coupling that transfers the W spin correlation to the electrons.

Measurements done in bins of number of jets and jet kinematics…
Higgs Couplings

The intricate WW channel

Measurement done in bins of Simplified Template Cross Sections STXS (hybrid fiducial cross sections)

Based on pTH, number of jets and di-jet mass

ATLAS Preliminary

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

$H \rightarrow WW^{*} \rightarrow e\nu\nu$ $p$-value = 52%

$\text{Total (Stat. Syst.)}$ | $\text{Systematic Unc.}$ | $\text{SM Predict.}$

| $ggH$+$H$, $p_T^H < 200$ GeV | $-0.16$ | $0.06$ |
| $ggH$+$H$, $p_T^H < 60$ GeV | $-0.16$ | $0.06$ |
| $ggH$+$H$, $60 < p_T^H < 120$ GeV | $-0.32$ | $0.16$ |
| $ggH$+$H$, $120 < p_T^H < 200$ GeV | $-0.41$ | $0.21$ |
| $ggH$+$H$, $p_T^H < 200$ GeV | $-0.41$ | $0.21$ |
| $ggH$, $p_T^H < 200$ GeV | $-0.50$ | $0.28$ |
| EW $ggH$+$2j$, $300 < m_{jj} < 700$ GeV, $p_T^H < 200$ GeV | $-0.40$ | $0.13$ |
| EW $ggH$+$2j$, $700 < m_{jj} < 1000$ GeV, $p_T^H < 200$ GeV | $-0.40$ | $0.13$ |
| EW $ggH$+$2j$, $1000 < m_{jj} < 1500$ GeV, $p_T^H < 200$ GeV | $-0.40$ | $0.13$ |
| EW $ggH$+$2j$, $m_{jj} \geq 1500$ GeV, $p_T^H < 200$ GeV | $-0.38$ | $0.09$ |

$\sigma / \sigma_{SM}$
Higgs Couplings

The intricate WW channel

Measurement done in bins of Simplified Template Cross Sections STXS (hybrid fiducial cross sections)

Based on pTH, number of jets and di-jet mass

More inclusive result, show good consistency with SM predictions.

Taking a closer look at the ggF x H→WW measurement:

\[ \sigma_{ggF} \cdot B_{H→WW^*} = 12.4 \pm 1.5 \text{ pb} \]

\[ = 12.4 \pm 0.6 \text{ (stat.)} \pm 0.9 \text{ (exp syst.)} \pm 0.7 \text{ (sig theo.)} \pm 1.0 \text{ (bkg theo.)} \text{ pb} \]

Error largely due to modelling of WW production.
Measurements of inclusive and differential $pp \rightarrow WW \rightarrow e\nu\mu\nu + 1$ jet cross sections

Provide excellent ancillary measurements for other channels such as HWW, but also excellent probe of anomalous **Triple gauge couplings aTGCs** (in particular at higher energies using the jet in the initial state).
Measurements of inclusive and differential \( pp \to WW \to e\nu\mu\nu + 1 \text{ jet} \) cross sections

\( M_{e\mu} \) mass sensitive variable to constrain the \( c_W \) Wilson coefficient corresponding to the Dim. six \( Q_W \) (WWW) operator
Analysis similar to the VH(bb) but tagging charm quark jets instead and applying a b-tag veto!

$(H \rightarrow \ell \nu)$

$(W \rightarrow \ell \nu, Z \rightarrow \ell \ell, \nu \nu)$

Higgs Couplings
The challenging Yukawa coupling to charm
Higgs Couplings

The challenging Yukawa coupling to charm

\[ \text{H}^{(cc)} \text{ in the SM is only } 3\% \]

Charm tagging is key!

**ATLAS Preliminary**

**c-tagging efficiency**

(\text{with b-tag veto}) 25-30%

**b rejection**

(\text{with b-tag veto}) 10

**light rejection**

(\text{with b-tag veto}) 50

**ATLAS Preliminary**

\[ \text{VH}^{(cc)} < 26 \text{ (31) obs. (exa.) x SM} \]

\[ \text{VH}^{(cc)} < 8.5 \times \text{SM} \]
Di-Higgs boson production

Incredibly small cross section ~1000 times smaller than Higgs production!

**Huge challenge!** but still more than 100k event will be produced at HL-LHC!

**Multiple channels investigated:** depending on the both Higgs decays considering (bb, yy, tautau, WW) - All complex topologies!!

**Latest result** using the full Run 2 data set in the $b\bar{b}\gamma\gamma$ channel
Various regions defined from a BDT based on photon and jet kinematics, and separated in two regions in HH mass (high and low important to discriminate HH components and constrain the trilinear coupling).

Limits on HH production at 4.1 obs. (5.5 exp.) x SM at 95% CL
Yields constraints on the trilinear coupling at [-1.5,6.7] at 95% CL

Very interesting improvements w.r.t. results obtained through the combination with 36 fb$^{-1}$!

<table>
<thead>
<tr>
<th>Channel</th>
<th>WW $\gamma\gamma$</th>
<th>$bb \gamma\gamma$</th>
<th>$bb \tau\tau$</th>
<th>$bb$WW</th>
<th>$bbbb$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma \times B$</td>
<td>0.1 %</td>
<td>0.26 %</td>
<td>7 %</td>
<td>25 %</td>
<td>34 %</td>
</tr>
<tr>
<td>Limits</td>
<td>$&lt;747$ (386)</td>
<td>$&lt;22$ (28)</td>
<td>$&lt;13$ (15)</td>
<td>-</td>
<td>$&lt;13$ (21)</td>
</tr>
</tbody>
</table>

**Di-Higgs boson production**

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

**ATLAS Preliminary**

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

$HH \rightarrow b\bar{b}\gamma\gamma$

**ATLAS**

$\sqrt{s} = 13 \text{ TeV}$

27.5 - 36.1 fb$^{-1}$
SM Couplings Overview

Higgs boson coupling measurements

- To massive vector bosons (W and Z) scale as boson masses
- To massive fermions scale as fermion masses

Within the current precision all measurements are consistent with the Standard Model

- However current precision is still low:
  - vector bosons ~8% → 1-2% precision at HL-LHC
  - Fermions ~10-20% → 2-3% precision at HL-LHC
  - Self coupling ~ 6 x SM → ~50% precision at HL-LHC
Higgs Physics Broad Landscape

**Precision**
- Mass and width
- Coupling properties
- Quantum numbers (Spin, CP)
- Differential cross sections
- STXS
- Off Shell couplings and width
- Interferometry

**The Higgs particle**

In the following $h^0$ refers to the signal that has been discovered in the Higgs searches. Whereas the observed signal is labeled as a spin 0 particle and is called a Higgs Boson, the detailed properties of $h^0$ and its role in the context of electroweak symmetry breaking need to be further clarified. These issues are addressed by the measurements listed below.

Concerning mass limits and cross section limits that have been obtained in the searches for neutral and charged Higgs bosons, see the sections “Searches for Neutral Higgs Bosons” and “Searches for Charged Higgs Bosons ($H^0$ and $H^{±1}$), respectively.

![PDG Listing entry for the Higgs boson](image)

**Rare production**
- $tH$ (single top and Higgs)
- FCNC top decays
- Di-Higgs production (and trilinear couplings)

**Rare decays**
- $Z\gamma$, $\gamma\gamma^*$, Muons $\mu^+\mu^-$
- LFV $\mu\tau$, $e\tau$
- $J/\psi\gamma$, $Z\gamma$, WD, $\phi\gamma$, $\rho\gamma$

**Non minimal Higgs sectors**
- 2 HDM searches
- MSSM, NMSSM searches
- Doubly charged Higgs bosons

**Tool for discovery**
- Portal to DM (invisible Higgs)
- Portal to hidden sectors
- Portal to BSM physics with $H^0$ in the final state ($ZH^0$, $WH^0$, $H^0H^0$)
Running of the Higgs self coupling:

- Knowing the Higgs boson mass has a radical effect on global analysis of precision data and on the fate of the Universe!
- Knowing the Higgs boson mass precisely has little impact on both aspects.

With the discovery of the Higgs for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.
\section*{Precision EW Measurements}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Precision EW Measurements}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Precision EW Measurements}
\end{figure}
Individual measurements can reach the level of the current World Average of $16 \times 10^{-5}$ CMS estimate alone with muons.

Future-ee 0.6
Top Physics
Four top quark production

Final state with four W bosons and four b jets!

**New intricate search channel:** 1 lepton (and 2 leptons opposite sign) with up 10 jets and 5 b-jets!!

57% of the four top events!

Much more intricate than the 2 Same sign leptons (larger systematics - from tt-HF modelling)!

\[ \sigma_{tttt}^{SM} = 12.0 \pm 2.4 \text{ fb} \]
Cross section measurement (dominated by systematics)

$$\sigma_{tttt} = 26 \pm 8 \text{(stat.)}^{+15}_{-13} \text{(syst.)}$$

Combined cross section measurement:

$$\sigma_{tttt} = 24 \pm 4 \text{(stat.)}^{+5}_{-4} \text{(syst.)} = 24^{+7}_{-6} \text{ fb}$$

Combined significance of observation: **4.7σ obs.** (2.6 exp.)
V-A coupling induces polarised production of single top quarks:

- Top (L) polarisation along spectator quark direction (anti-top (R) opposite)
- Use semi-leptonic top decays!

Definition of a 3D discriminant based on the octant in which the lepton is produced!

Fit to the polarisations $P_x$, $P_y$, $P_z$ done using a parametrisation of this octant variable.

- $P_y$ is sensitive to CP violating effects
- $P_x$ is sensitive to NLO QCD effects
Differential cross sections in $\cos \theta^x_\ell$ and $\cos \theta^y_\ell$, unfolded to particle level, are also measured. EFT Wilson coefficients for anomalous Dim. 6 tW coupling CP conserving and CP violating are fit simultaneously to the unfolded differential cross section measurements.
Flavor physics - Precision and Rare Decays

CP phase in Bs decays to $J/\Psi\phi$

Excellent sensitivity from ATLAS with the help of the Insertable B-layer of pixels at 3 cm from the beam.

Combined results on $B_{s,d} \rightarrow \mu^+\mu^-$

Combination of ATLAS, CMS and LHCb

Small tension with SM value of $2.1\sigma$
LFU Anomalies in B decays

Part of the “Footprints”* of rare B decays anomalies

Combining through SM-EFT Dim.-6 FCNC operators:

\[ O_{10}^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}_\nu \gamma_\mu \gamma_5 \ell) \]
\[ O_9^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}_\nu \gamma_\mu \ell) \]

These anomalies could be a sign of “non trivial flavour dynamics at the TeV scale”** further motivate direct searches of leptoquarks (both scalar and vector) and non universal heavy vector boson.

Combined with the RK* anomaly leads to a 4.6\(\sigma\) tension

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* C. Cornella et al. 2021

** Gino Isidori
High mass resonances decaying to taus

Search for $W' \rightarrow \tau \nu$

With high energetic taus reconstructed using a RNN technique.

Excellent agreement between data and MC predictions!

Results obtained to a fit of the transverse mass distribution.

Highest transverse mass candidate (see above event display is at $m_T \sim 2.8$ TeV)
Muons (g-2) anomaly motivates searches for smuons

Using the s-transverse mass (estimated varying hypotheses of individual MET components)

\[ m_{T2}(p_T,1, p_T,2, p_T^{\text{miss}}) = \min_{q_T,1 + q_T,2 = p_T^{\text{miss}}} \left\{ \max\left[ m_T(p_T,1, q_T,1), m_T(p_T,2, q_T,2) \right] \right\} \]

Search in scenarios with two leptons and MET

Searches for Natural and Strongly Produced SUSY

**Stop**
- Stop 2L
- Stop 1,2-L
- Stop 0L
- Stop 1L
- Stop 1,2-L
- Stop 0L

**Squarks and gluinos**
- 0L
- 0L-Njets
- 1L
- Multi top
- Multi b
- Multi top

**Not so natural SUSY:** Stops > 1 TeV ~tuning of factor 20, but these exclusions are under specific conditions, and there are unexcluded corridors.

Stop also a scalar requires light gluinos to be light enough: for gluinos > 2 TeV ~tuning of Factor of 30
Search for Electroweakinos

Search for electroweakinos at high mass in boosted fully hadronic final states (W/Z/H)

Topologies searched for qq,qq and qq,bb

Using boosted jets (above 200 GeV) with substructure (D2*)

Most stringent limit to date excluding EWKinos up to almost 1 TeV

(of course larger corridor in mass difference to LSP which in this case should be significantly lighter)

* Ratio of two-points to three points energy correlations between particles of a jet
Very Large Number of SUSY Searches
(in large variety of topologies and models)

ATLAS SUSY Searches - 95% CL Lower Limits

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>[1e-10 f]</th>
<th>[1e-4 f]</th>
<th>[1e-5 f]</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
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ATLAS Preliminary

<table>
<thead>
<tr>
<th>Model</th>
<th># jets</th>
<th>Mass limit</th>
</tr>
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<tbody>
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HL/HE-LHC SUSY Searches

<table>
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<tr>
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<th>Mass limit</th>
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<tbody>
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Simulation Preliminary

<table>
<thead>
<tr>
<th>Model</th>
<th># jets</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
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</tbody>
</table>

Example from ATLAS (same for CMS)

Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, cf. refs. for the assumptions made.
Very Large Number of SUSY Searches
(in large variety of topologies and models)

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

<table>
<thead>
<tr>
<th>Model</th>
<th>Signature</th>
<th>2j + 1 t</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.0 (2) TeV</td>
<td></td>
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</tbody>
</table>

**ATLAS Preliminary** ($\sqrt{s} = 13$ TeV)

**HL/HE-LHC SUSY Searches**

<table>
<thead>
<tr>
<th>Model</th>
<th>$R_i$</th>
<th>Jets</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td></td>
<td>1.0 (2) TeV</td>
</tr>
</tbody>
</table>

**Simulation Preliminary** ($\sqrt{s} = 14$, 27 TeV)

<table>
<thead>
<tr>
<th>Model</th>
<th>$R_i$</th>
<th>Jets</th>
<th>Mass limit</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.0 (2) TeV</td>
</tr>
</tbody>
</table>

At the HL-LHC:

- Discovery potential of gluinos up to O(2-3 TeV)
- Discovery potential of stops up to O(1.5 TeV)
- Discovery potential of EW SUSY up to O(1 TeV)

Example from ATLAS (same for CMS)
Tracklet topology: track disappearing in the ID

Jet needed to trigger event!

In the case of puro Wino chargino: lower limit on chargino mass of ~650 GeV!

Long lived gluinos would hadronise with quarks and gluons and for R-hadrons!

R-hadrons can come a stop in the detector volume and decay after a period of time.

The search looks at “empty bunches” i.e. data taken at times when the no proton bunches collide.

Dominant backgrounds in absence of beams: cosmic muons and beam backgrounds (from collimators upstream).

Uses dedicated (jet) triggers in empty bunch crossings!

Limits between 400 GeV and 1.4 TeV over a very wide range of proper times!
Charginos

$\tilde{\chi}_1^\pm \rightarrow \pi^\pm \tilde{\chi}_1^0$ or $\tilde{W}^\pm \rightarrow e^\pm \nu e \tilde{\chi}_1^0$

- 136 fb$^{-1}$, $\sqrt{s}=13$ TeV
- Disappearing track
- Expected limits

Gluinos

- $\tilde{g}$ (R-hadron) $\rightarrow qq \tilde{\chi}_1^0$ ; $m(\tilde{\chi}_1^0) = 100$ GeV

- 36 fb$^{-1}$, $\sqrt{s}=13$ TeV
- Stable charged

- Observed limits
- 95% CL limits.
- $\sigma_{\text{SUSY}}$ not included

- Pixel dE/dx
- arXiv:1902.01636
- 20.3 fb$^{-1}$, $\sqrt{s}=8$ TeV

- Pixel dE/dx
- arXiv:1506.05332

March 2021

**ATLAS Preliminary**

**ATLAS Preliminary**
Many extensions of the Standard Model predict new particles that are long lived heavy (neutral and charged) and can decay after several cm or even meters.

Sample for ATLAS (same for CMS)

Difficult signatures requiring specific complex reconstruction and trigger!
Searches for High Mass Resonances

**ATLAS Dilepton search**

Highest mass di-electron event ~4 TeV

**ATLAS Dijet search**

Limits on excited quarks at 6.7 TeV

Exclusions up to ~5 TeV

Highest mass (central) dijet event ~8 TeV
Very Large Number of Searches
(in large variety of topologies and models)

Overview of CMS EXO results

Example from CMS (similar for ATLAS)
Very Large Number of Searches
(in large variety of topologies and models)

At HL-LHC:

Discovery potential of Z’ and W’ up to 6 TeV and 8 TeV

Discovery potential of Leptoquarks up to 1.5 - 2 TeV

Example from CMS (similar for ATLAS)
Generic Searches for Dark Matter

Primarily Searches for spectacular topologies: Mono-jet, mono-\(V\), mono-photon mono-Higgs, mono-top, etc…

Interpretations in simplified models, introducing generic mediator searched for as well.

Numerous strategies to also cover lower masses e.g.:
- boosting (ISR)
- Trigger level analyses
Dark Matter - Mono Higgs search

Higgs boson decaying to a pair of b-quarks

Using as benchmark Z' mediator simplified models and a CP-Odd A (2HDM) decaying to DM particles.

2HDM h is the observed Higgs boson decaying to b-quarks.

Analysis similar to the measurement of the H(bb) in the ZH production with Z decaying to neutrinos!

ATLAS Preliminary

Events: 769,715,031

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

Resolved: 0-lepton

2 b-tag Signal Region

$E_T^\tau \geq (200, 350)$ GeV

ATLAS Preliminary

Events / 5 GeV

Data

SM Vh

Z-$V$, VV

W+$V$, VV

W+$V$, VV

H

$Zb\bar{b}$

$Zl\bar{l}$

$Zl\bar{l}$

$Zl\bar{l}$

$Wl\bar{l}$

$WWl\bar{l}$

Background Uncertainty

Mono-H Z$^{'2}$-HDM ($\rightarrow Vb$)

$m_{m_{W},m_{Z}^{'}}$ (1400, 1000) GeV

Higgs boson and Z' masses

Exclusions set in the A and Z' masses plane (with DM mass of 100 GeV).

Exclusions of Z' masses of 3.1 TeV for a mass of th A of 300 GeV.
Towards HL-LHC and Precision Physics at LHC

Towards HL-LHC still a **factor of 23** in luminosity:

- Still **room for discoveries!**

- Given that the **doubling time of the luminosity** is now counted in **several years**: discoveries will take time.

- Low hanging fruits typically have been (or are being) harvested! large effort in trying to expand search reach beyond the $\sqrt{L}$:
  - With new ideas and developments at all levels.
  - Improving precision!

**Precision in general will be key!**
Summary and Conclusions

- **Intense times for LHC** LS2 upgrades are being finalised and we are gearing up for Run 3!

- **After 10 years of running:** the LHC, ATLAS and all LHC experiments have been extremely successful!

  - **Landmark results:** the Higgs boson (Standard Model like) and so far nothing else!

  - Performance and precision reached in a number of major measurements (Higgs couplings, W mass, weak mixing angle, CPV in meson systems, top, EW, Heavy Ions, etc…) have exceeded our projections.

  - Pursuing a vast search program leaving no stones unturned!

- **Precision will be key to improve our measurements and searches for new phenomena!**

- The Run 3 will provide opportunities for new measurements (e.g. Yukawa coupling of the Higgs boson to second generation fermions (muons) and to consolidate important measurements and sharpen our tools towards the High Luminosity LHC.

- The HL-LHC will provide opportunities for percent level precision in Higgs couplings, first constraints on the Higgs boson self coupling, EW precision measurements, polarised vector boson scattering and unprecedented wide and strong probes of the SM through measurements and direct searches!
Backup
Stop Searches Summary

$\sqrt{s} = 8.13$ TeV, 20.3-139 fb$^{-1}$

**ATLAS Preliminary**

$\tilde{t}_1 \tilde{t}_1$ production

Limits at 95% CL

---

**Data 15-18, $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$**

- monojet, $\tilde{t}_1 \rightarrow bff \tilde{\chi}_1^0$ [2102.10874]
- $0L$, $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow bff \tilde{\chi}_1^0$ [2004.14060]
- $1L$, $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow bff \tilde{\chi}_1^0$ [2012.03799]
- $2L$, $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow bff \tilde{\chi}_1^0$ [2102.01444]

**Data 15-16, $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$**

- $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow bff \tilde{\chi}_1^0$ [1709.04183, 1711.11520, 1708.03247, 1711.03301]
- $f^\prime \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ [1903.07570]

**Data 12, $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$**

- $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0 / \tilde{t}_1 \rightarrow bff \tilde{\chi}_1^0$ [1506.08616]
Performance Achievements and Goals

- Run 1 and Run 2: So far excellent trigger and object reconstruction performance in **increasing levels of PU**. Trigger Thresholds kept relatively stable throughout.

- The gain in acceptance and in performance with new detectors (to improve PU mitigation), new algorithms and new computing capabilities is expected to at least match current experimental performance.
  - Keeping Trigger thresholds at similar levels
  - Object reconstruction performance (efficiency vs rejection and energy scale and resolution) at stable levels.
  - Challenge to come: improve calibrations not only with more data to come but also improved strategies.

**Objective Menus for HL-LHC**

<table>
<thead>
<tr>
<th>Signature</th>
<th>Run 1</th>
<th>Run 2</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single e (isolated)</td>
<td>25</td>
<td>27</td>
<td>22 / 27</td>
</tr>
<tr>
<td>Single photon</td>
<td>120</td>
<td>140</td>
<td>120*</td>
</tr>
<tr>
<td>HT</td>
<td>700</td>
<td>700</td>
<td>375 / 350</td>
</tr>
<tr>
<td>MET</td>
<td>150</td>
<td>200</td>
<td>200</td>
</tr>
</tbody>
</table>

- Increase readout rate 750-1000 kHz (currently 100 kHz).
- Increased latency and higher granularity.
- Enhanced data processing capabilities, storage rate up to 10 kHz (currently 1-2 kHz).