Recent physics highlights from ATLAS

Valerio Dao (CERN)
on behalf of the ATLAS Collaboration

Symposium 25 Years of LHC Experimental Programme

CERN

15-12-2017
Another great and busy year for ATLAS

✦ Harvesting Run 1 measurements reaching unprecedented precision

✦ Exploiting the full potential of the 2015+2016 data:
  - constraining the Higgs sector
  - exploring new physics with high sensitivity

✦ Successful detector operation in 2017:
  - 93.3% data taking efficiency, 93.6% “good-for-Physics”
  - addressing challenges from higher pileup
Standard Model Total Production Cross Section Measurements

**ATLAS Preliminary**
Run 1,2 $\sqrt{s} = 7, 8, 13$ TeV

- **LHC pp $\sqrt{s} = 7$ TeV**
  - Data 4.5 – 4.9 fb$^{-1}$
- **LHC pp $\sqrt{s} = 8$ TeV**
  - Data 20.3 fb$^{-1}$
- **LHC pp $\sqrt{s} = 13$ TeV**
  - Data 0.08 – 36.1 fb$^{-1}$

- **Theory**

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Cross sections: from inclusive ...

**Standard Model Total Production Cross Section Measurement**

**Status:** July 2017

**Dao Valerio**
25 years LHC symposium - 15/12/2017

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4.2 σ evidence for tZ
Cross sections: … to differential

Lepton kinematics in tt events

Triple differential Drell-Yan cross section:

\[ d^3\sigma = \frac{d^3\sigma}{dm_{\ell\ell}d|y_{\ell\ell}|d\cos\theta^*} \]

PDF

Weak Coupling constant

Z/\gamma interference

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First measurement at the LHC

*Precision comparable with leading measurements from Tevatron*

\[
m_W = 80370 \pm 7 \text{ (stat.)} \pm 11 \text{ (exp. syst.)} \pm 14 \text{ (mod. syst.) MeV}
\]

Total error: 19 MeV (0.02%)
\( m_W, \ m_{\text{top}}, \ m_H \) are related to **fundamental parameters** of the Standard Model and provide key information to test its consistency.
**Precision: top quark mass**

- $m_{\text{top}}$ measured with different $t\bar{t}$ decay modes:

  - **$l+jets$:** $m_{\text{top}} = 172.08 \pm 0.39 \pm 0.82$ GeV
  - **di-lepton:** $m_{\text{top}} = 172.99 \pm 0.41 \pm 0.74$ GeV

- **Run1 combination:**

  $m_{\text{top}} = 172.51 \pm 0.27 \pm 0.42$ GeV

- **Combinations**

<table>
<thead>
<tr>
<th>Source</th>
<th>$m_{\text{top}}$</th>
<th>stat</th>
<th>syst</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF (Mar 2014)</td>
<td>173.16 ± 0.57 ± 0.74</td>
<td>0.019</td>
<td>0.70</td>
</tr>
<tr>
<td>D0 (Jul 2016)</td>
<td>174.95 ± 0.40 ± 0.64</td>
<td>0.019</td>
<td>0.70</td>
</tr>
<tr>
<td>CMS (Apr 2016)</td>
<td>172.44 ± 0.13 ± 0.47</td>
<td>0.019</td>
<td>0.70</td>
</tr>
<tr>
<td>ATLAS (Sep 2017)</td>
<td>172.51 ± 0.27 ± 0.42</td>
<td>0.019</td>
<td>0.70</td>
</tr>
</tbody>
</table>

**Note:**

- $l+jets$: measured with different $t\bar{t}$ decay modes:
  - Run1 combination: $m_{\text{top}} = 172.51 \pm 0.27 \pm 0.42$ GeV
  - $0.3\%$ uncertainty

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Precision: Higgs boson mass

H→ZZ*→4l

Higgs boson precision channels well established at 13 TeV

H→γγ

Preliminary Run-2 result approaching Run-1 legacy ATLAS+CMS measurement
The success of the Run 1 results relied on clean *bosonic decay modes* and *leading production mechanisms*.

Many more aspects of the Higgs sector still to be explored: *direct coupling to quarks*.
Higgs boson coupling to quarks: $H \rightarrow bb$

**VH associated production:**

- Leptons from W/Z used for triggering/background reduction

$\mu_{VH}^{bb} \rightarrow \nu/\ell/\ell$ and $\nu/\nu/\ell$

**Run 1+Run 2:** \(3.6 (4.0) \sigma\) observed (expected)

\[
\frac{\sigma_{meas}}{\sigma_{SM}} = \mu_{VH}^{bb} = 0.90 ^{+0.18 \text{ (stat.)}} _{-0.18} ^{+0.21 \text{ (sys.)}}
\]

Evidence of $H \rightarrow bb$ through VH associated production

ATLAS
\(\sqrt{s} = 13\,\text{TeV},\ 36.1\,\text{fb}^{-1}\)
0+1+2 leptons
2+3 jets, 2 b-tags

Weighted by S/B

Dijet mass analysis
Higgs boson coupling to quarks: \( ttH \)

- \( ttH \) production:
  - direct access to top Yukawa coupling at tree level
  - expected cross section: 500 fb
  - rich phenomenology: need to combine many signatures

\( H \rightarrow WW, \tau\tau, ZZ \)

- very crowded final states
- large backgrounds constrained from data
- multivariate classification techniques

3l example

\( H \rightarrow bb \)
Higgs boson coupling to quarks: $ttH$

- **$ttH$ production:**
  - Direct access to *top Yukawa coupling at tree level*
  - Expected cross section: 500 fb
  - Rich phenomenology: need to combine many signatures

**$H \rightarrow WW$, $\tau \tau$, ZZ**

**$H \rightarrow bb$**

- Very crowded final states
- Large backgrounds constrained from data
- Multivariate classification techniques

**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- Post-Fit

Data - Bkgd.

**ATLAS-CONF-2017-076**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- Pre-Fit Bkgd.

**ATLAS-CONF-2017-077**

- Post-fit

$tH (b\bar{b})$ Combined Dilepton and Single Lepton

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**ttH: combination**

- Also including events targeting $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$:
  - very high S/B but still low number of expected events

![](image)

- evidence for $ttH$ production
- one of the rarest process measured at the LHC

\[
\sigma_{\text{meas}}(t\bar{t}H) = 590^{+160}_{-150} \text{ fb}
\]
Snapshot of the Higgs boson landscape: Run 1+Run 2

- Additional statistics is needed to:
  - improve the precision of the existing measurements
  - assess rare production/decay modes
  - expand differential cross section measurements

Observed decays: 31%
Evidence: 58%

(*) First direct limits on $H \rightarrow cc$
(ATLAS-CONF-2017-078)
$\sigma_{ZH} \times Br(H \rightarrow cc(\ell\ell)) < 2.7$ pb

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Higher $\sqrt{s}$ and luminosity have greatly increased our reach for new physics up to high masses.

### Exotics

**ATLAS Exotics Searches** - 95% CL Upper Limit Exclusions

**Status:** July 2017

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell^+\ell^-$</th>
<th>Jets</th>
<th>$E_{T}^{miss}$</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD $G_{H} \rightarrow g/q$</td>
<td>$0 \leq 1$</td>
<td>1-4</td>
<td>3.61</td>
<td>$1.76 , \text{TeV}$</td>
<td>ATLAS-CONF-2017-054</td>
</tr>
<tr>
<td>ADD non-resonant $\gamma\gamma$</td>
<td>$2 \leq 1$</td>
<td>3.67</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADD QED</td>
<td>$2 \leq 1$</td>
<td>3.70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADD $BH \rightarrow \sum_{\gamma\gamma}^2$</td>
<td>$1 \leq 1$</td>
<td>3.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADD BH multijet</td>
<td>$\geq 3$</td>
<td>3.6</td>
<td></td>
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<tr>
<td>RSI $G_{H} \rightarrow g/q$</td>
<td>$2 \leq 1$</td>
<td>3.67</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Bulk RS $G_{H} \rightarrow WW \rightarrow q\bar{q}X$</td>
<td>$1 \leq 1$</td>
<td>3.67</td>
<td>$1.76 , \text{TeV}$</td>
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<td></td>
</tr>
<tr>
<td>$Z$-plicity / RPP</td>
<td>$2 \leq 1$</td>
<td>3.12</td>
<td></td>
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</tr>
</tbody>
</table>

**Quark bosons**

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell^+\ell^-$</th>
<th>Jets</th>
<th>$E_{T}^{miss}$</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM $Z \rightarrow t\bar{t}$</td>
<td>$0 \leq 1$</td>
<td>3.61</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SM $Z \rightarrow t\bar{t}$</td>
<td>$2 \leq 1$</td>
<td>3.61</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leptophobic $Z' \rightarrow b\bar{b}$</td>
<td>$1 \leq 1$</td>
<td>3.61</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leptophobic $Z' \rightarrow W^+W^-$</td>
<td>$1 \leq 1$</td>
<td>3.61</td>
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</tr>
<tr>
<td>SM $W' \rightarrow c\bar{c}$</td>
<td>$1 \leq 1$</td>
<td>3.61</td>
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<tr>
<td>HVT $V' \rightarrow WW \rightarrow q\bar{q}pY$</td>
<td>$0 \leq 1$</td>
<td>3.67</td>
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<tr>
<td>HVT $V' \rightarrow WW, ZH$</td>
<td>$0 \leq 1$</td>
<td>3.67</td>
<td>$1.76 , \text{TeV}$</td>
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<tr>
<td>LRSM $W_0 \rightarrow b\bar{b}$</td>
<td>$1 \leq 1$</td>
<td>2.03</td>
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<tr>
<td>LRSM $W_0 \rightarrow t\bar{t}$</td>
<td>$1 \leq 1$</td>
<td>2.03</td>
<td>$1.76 , \text{TeV}$</td>
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**DM**

<table>
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<tr>
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<th>Jets</th>
<th>$E_{T}^{miss}$</th>
<th>Limit</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>Axial-vector mediator (Dirac DM)</td>
<td>$0 \leq 1$</td>
<td>3.61</td>
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<tr>
<td>Vector mediator (Dirac DM)</td>
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<td>3.61</td>
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<tr>
<td>VV $\gamma$ (Dirac DM)</td>
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<td>3.61</td>
<td>$1.3 , \text{TeV}$</td>
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<tr>
<td>LO</td>
<td>$2 \leq 1$</td>
<td>3.2</td>
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<tr>
<td>Scalar LO $1^{st}$ gen</td>
<td>$2 \leq 1$</td>
<td>3.2</td>
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<tr>
<td>Scalar LO $2^{nd}$ gen</td>
<td>$2 \leq 1$</td>
<td>3.2</td>
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<tr>
<td>Scalar LO $3^{rd}$ gen</td>
<td>$1 \leq 1$</td>
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<tr>
<td>VLO $TT \rightarrow H^{-}X$</td>
<td>$0 \leq 1$</td>
<td>3.61</td>
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<tr>
<td>VLO $TT \rightarrow Z^{-}X$</td>
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<td>3.61</td>
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<tr>
<td>VLO $TT \rightarrow W^{-}X$</td>
<td>$1 \leq 1$</td>
<td>3.61</td>
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<tr>
<td>VLO $BR \rightarrow B^{-}X$</td>
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<tr>
<td>VLO $BR \rightarrow W^{-}X$</td>
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<td>3.61</td>
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<tr>
<td>VLO $QO \rightarrow W_{Q}\bar{Q}$</td>
<td>$1 \leq 1$</td>
<td>3.61</td>
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</tbody>
</table>

**Heavy/quirky**

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell^+\ell^-$</th>
<th>Jets</th>
<th>$E_{T}^{miss}$</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excited quark $q'^{-} \rightarrow qg$</td>
<td>$2 \leq 1$</td>
<td>3.70</td>
<td>$8.0 , \text{TeV}$</td>
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<tr>
<td>Excited quark $q'^{-} \rightarrow q'Y$</td>
<td>$2 \leq 1$</td>
<td>3.70</td>
<td>$5.3 , \text{TeV}$</td>
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<tr>
<td>Excited quark $b'^{-} \rightarrow qg$</td>
<td>$1 \leq 1$</td>
<td>3.70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excited quark $W'^{-} \rightarrow b^{-}Y$</td>
<td>$1 \leq 1$</td>
<td>3.70</td>
<td></td>
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<tr>
<td>Excited lepton $l'^{-} \rightarrow qg$</td>
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<td>3.70</td>
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<tr>
<td>Excited lepton $l'^{-} \rightarrow q'Y$</td>
<td>$1 \leq 1$</td>
<td>3.70</td>
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<tr>
<td>Excited lepton $l'^{-} \rightarrow q^{-}Y$</td>
<td>$1 \leq 1$</td>
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<tr>
<td>LRSM Majorana $\nu$</td>
<td>$2 \leq 1$</td>
<td>20.3</td>
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<tr>
<td>Higgs triplet $H'^{+} \rightarrow t\bar{t}$</td>
<td>$3 \leq 1$</td>
<td>20.3</td>
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<tr>
<td>Higgs triplet $H'^{+} \rightarrow b\bar{b}$</td>
<td>$3 \leq 1$</td>
<td>20.3</td>
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<tr>
<td>Monojet (non-RH prod)</td>
<td>$1 \leq 1$</td>
<td>20.3</td>
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<tr>
<td>Multicharged particles</td>
<td>$2 \leq 1$</td>
<td>20.3</td>
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<tr>
<td>Magnetic monopoles</td>
<td>$1 \leq 1$</td>
<td>20.3</td>
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</tbody>
</table>

$E_{T}^{miss} = 8 \, \text{TeV}$ $E_{T}^{miss} = 13 \, \text{TeV}$

**Other**

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell^+\ell^-$</th>
<th>Jets</th>
<th>$E_{T}^{miss}$</th>
<th>Limit</th>
<th>Reference</th>
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<tbody>
<tr>
<td>$\nu_{L} \rightarrow \ell \nu_{L}$</td>
<td>$2 \leq 1$</td>
<td>20.3</td>
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<tr>
<td>$\nu_{R} \rightarrow \ell \nu_{R}$</td>
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<tr>
<td>$\nu_{L} \rightarrow \ell \nu_{L}$</td>
<td>$2 \leq 1$</td>
<td>20.3</td>
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</tr>
</tbody>
</table>

$\sqrt{s} = 8, 13 \, \text{TeV}$

**ATLAS Preliminary**

$\int L \, dt = (3.2 - 37.0) \, \text{fb}^{-1}$

**$\sqrt{s} = 8, 13 \, \text{TeV}$**

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Searches for physics beyond the SM

Higher $\sqrt{s}$ and luminosity have greatly increased our reach for new physics up to high masses

**Supersymmetry**

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

<table>
<thead>
<tr>
<th>Model</th>
<th>$\tilde{g}$, $\tilde{\tau}_1$, $\tilde{\chi}_1^0$, $\tilde{\chi}_1^0$</th>
<th>Mass limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0, 1$-jet + $\mu$, $\tau$</td>
<td>$0-2$ jets</td>
<td>Yes</td>
<td>$36.1$</td>
</tr>
<tr>
<td>$0, 1$-jet, $1-3$ jets</td>
<td>Yes</td>
<td>$36.1$</td>
<td></td>
</tr>
<tr>
<td>$0, 2-6$ jets</td>
<td>Yes</td>
<td>$36.1$</td>
<td></td>
</tr>
<tr>
<td>$0, 1$-jet</td>
<td>Yes</td>
<td>$14.7$</td>
<td></td>
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<tr>
<td>$0, 2-6$ jets</td>
<td>Yes</td>
<td>$14.7$</td>
<td></td>
</tr>
<tr>
<td>$0, 1$-jet</td>
<td>Yes</td>
<td>$3.2$</td>
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<tr>
<td>$0, 1$-jet</td>
<td>Yes</td>
<td>$3.2$</td>
<td></td>
</tr>
<tr>
<td>$0, 2-6$ jets</td>
<td>Yes</td>
<td>$3.2$</td>
<td></td>
</tr>
<tr>
<td>$0, 2$ jets</td>
<td>Yes</td>
<td>$3.2$</td>
<td></td>
</tr>
<tr>
<td>$0, 1$-jet</td>
<td>Yes</td>
<td>$3.2$</td>
<td></td>
</tr>
<tr>
<td>$0, 2-6$ jets</td>
<td>Yes</td>
<td>$3.2$</td>
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<tr>
<td>$0, 1$-jet</td>
<td>Yes</td>
<td>$3.2$</td>
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</tr>
</tbody>
</table>

**Gluino mass limit pushed up to 2 TeV**

**Stop mass limit reaching 1 TeV**

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25 years LHC symposium - 15/12/2017
Higher $\sqrt{s}$ and luminosity have greatly increased our reach for new physics up to high masses.

**Exotics**

**Supersymmetry**

Continuously developing new analysis techniques/exploiting more complete information:

- accessing difficult corners of phase space
- increasing coverage of new models

Dao Valerio  25 years LHC symposium - 15/12/2017
(compressed) **electroweak SUSY** is a very elusive sector

**First sensitivity to Higgsino beyond LEP**

- Few GeV-level splitting accessible through **soft leptons** (down to 4 GeV)
- O(100 MeV) splitting produces long-lived charginos: accessible through **disappearing tracks**

**ATLAS** Preliminary

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

- \( pp \rightarrow \tilde{\chi}_1^\pm, \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_2^\pm, \tilde{\chi}_1^\mp \) (Higgsino)
- All limits at 95% CL
  - Observed limits
  - Expected limits

> December 2017

Dao Valerio
Another great year for LHC

A big thank you to the CERN accelerator and support teams for the excellent performance

- Additional 50 fb\(^{-1}\) of pp collisions @ 13 TeV
- low pileup runs @ 5 and 13 TeV
Performance with 2017 pileup

**Efficiency**

- ATLAS Preliminary
- $\sqrt{s} = 13$ TeV, 32.8 fb$^{-1}$
- Medium muons $p_T > 10$ GeV
- ATLAS Preliminary $\sqrt{s} = 13$ TeV, 32 fb$^{-1}$
- Efficiency

**ETmiss**

- ATLAS Preliminary
- 33 fb$^{-1}$, $\sqrt{s} = 13$ TeV
- $Z \rightarrow \mu\mu$ topology, 2017 Data
- Track Soft Term (TST)
- Particle Flow jets
- Inclusive Jets
- Tight $E_{T}\text{miss}$

**Jets**

- ATLAS Preliminary
- $\sqrt{s} = 13$ TeV, 20.8 fb$^{-1}$
- Anti-$k_T$, $R=0.4$ EM+JES
- $p_T^{\text{jet}} > 20$ GeV, $|\eta| < 2.4$

**Z→μμ event with μ=50**

- ATLAS Preliminary
- $\sqrt{s} = 13$ TeV, 20.8 fb$^{-1}$
- Event with $\mu=50$
- $E_T\text{miss}$

**b-tagging**

- ATLAS Preliminary
- $\sqrt{s} = 13$ TeV, 32 fb$^{-1}$
- Mean b-tagged jet multiplicity
  - Jet $p_T > 25$ GeV
  - Jet $p_T > 60$ GeV
  - Jet $p_T > 100$ GeV

**Muons**

- ATLAS Preliminary
- $\sqrt{s} = 13$ TeV, 32.8 fb$^{-1}$
- Medium muons $p_T > 10$ GeV

**Electrons**

- ATLAS Preliminary
- $\sqrt{s} = 13$ TeV, 32.8 fb$^{-1}$
- OS $e\mu$ events
- Mean b-tagged jet multiplicity
  - Jet $p_T > 25$ GeV
  - Jet $p_T > 60$ GeV
  - Jet $p_T > 100$ GeV
Looking ahead

- This was only a small selection of the full set of ATLAS results:
  - 46 results released on 2015/16 data
  - ~700 from pp and heavy ions since 2010

- New 2017 data on tape is larger than what we have analysed so far at 13 TeV
- Even more data to come in 2018 for both pp and heavy ion collisions

Thank you for your attention
**Exotics: resonances**

- **Comprehensive searches for \( Y \rightarrow XZ \):**
  - leptons, photons, jets
  - vector boson
  - SM-like Higgs boson to \( bb \)
  - generic state decaying into \( qq \)

- **Boosted hadronic final states**
  - \( (V, H, X) \) bridge into the multi TeV regime

---

**VV→qqqq→JJ**

**EXOT-2016-19**

- **Data / Pred.**
  - Events / 0.1 TeV
  - \( 1 \rightarrow 10 \)
  - \( 1 \rightarrow 10 \)
  - \( 1 \rightarrow 10 \)
  - \( 1 \rightarrow 10 \)

**Vh→qqbb→JJb**

**EXOT-2016-12/**

- **Data**
  - Fits + HVT model B \( m=1.5 \) TeV
  - Fits + HVT model B \( m=2.4 \) TeV

---

**NN Events**

**Sensitive Variable**

**N Events**
... from 2015 PbPb run: measuring “quenching” in Heavy Ions medium for different probes
Looking at Di-Higgs production as a window for Higgs self coupling

$HH \rightarrow bb\gamma\gamma$ is the golden channel:
- $Br: 0.1\%$ but very striking signal
- better tracker: improved b-tagging / $\gamma$ reconstruction
- better calorimeter: improved $\gamma\gamma$ mass resolution

$\sim 40$ fb
@14 TeV

**best Run2 result:**
$HH \rightarrow bbbb$ ($13$ fb$^{-1}$)
$\sigma/\sigma_{SM} < 29$ @95%CL

$-0.9 < \lambda/\lambda_{SM} < 7.7$

1 sigma expected for SM HH

$\lambda_{HHH}/\lambda_{H} < 29$ @95%CL
✦ **Gluino** mass limit pushed well into the TeV regime

<table>
<thead>
<tr>
<th>May 2017</th>
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<tbody>
<tr>
<td>ATLAS Preliminary</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow t\tilde{t}_1^0$, $\sqrt{s} = 13$ TeV</td>
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<tr>
<td>$36.1 \text{ fb}^{-1}$</td>
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</tbody>
</table>

**Stop** mass limit approaching 1 TeV: challenging naturalness

- Observed limits
- Expected limits
- All limits at 95% CL
The top sector: very rare process

- **tZ associated production:**
  - 3 lepton final state
  - 1 Z pair, 2 jets, 1 b-tag jet
  - multivariate discriminant

\[ \sigma_{tqZ} = 600 \pm 170 \text{(stat.)} \pm 140 \text{(syst.)} \text{ fb} \]

\[ \sigma_{tqZ} \text{ (SM)} = 800 \pm 60 \text{ fb} \]

4.2 s.d. evidence !!!