Highlights from the ATLAS and CMS experiments at the LHC

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on behalf of the ATLAS and CMS Collaborations

AWLC 2017
June 29th, 2017
• ATLAS and CMS overview
  - Challenges and recent highlights
• Physics results highlights
  - Standard Model and Higgs measurements
  - Search for physics beyond Standard Model
• Conclusions
Introduction

- Large scientific output of ATLAS and CMS Collaborations
  - > 600 papers submitted by each Collaboration
  - > 100 papers + preliminary results released only in 2017 (ATLAS+CMS)

- Will present an overview of the physics program highlighting a selection of the most recent results
  - Focus on high-$p_T$ proton-proton physics program
Recent hardware upgrades for 2017 (not yet used for current results)

- New CMS pixel detector: 3 layers / 2 disks → 4 layers / 3 disks
  - lighter and more robust tracker → improved track and vertex resolution
- ATLAS installed few new muon (sMDT) chambers
  - improve momentum reconstruction
• About 45 fb\(^{-1}\) of 13 TeV pp collisions data delivered by LHC

• Excellent performance by experiments, with > 90% data-taking efficiency (good for physics)

• Instantaneous peak luminosity above design, up to ~45 pp interactions per bunch crossing
Large effort to mitigate effects of pile-up

- PileUp Per Particle Identification
  - weight of particle $p_T$ based on surrounding activity

- Rejection of forward pile-up jets
Standard Model Production Cross Section Measurements

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

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Jet production

- Differential cross section for multi-jet production
- Strong coupling constant from energy-energy correlations, asymmetries and 3/2 jet $\sigma$ ratio:

![Graph showing $\alpha_s(Q)$ vs $Q$ with data points and fits from ATEC 2012, CMS, ATLAS, and W.A.]

<table>
<thead>
<tr>
<th>Ref.</th>
<th>$\alpha_s(M_Z)$ measurement</th>
</tr>
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<tbody>
<tr>
<td>CMS</td>
<td>$0.1150 \pm 0.023 (all except scale)_{-0.0}^{+0.0050} (scale)$</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$0.1196 \pm 0.0013 (exp.)_{-0.0045}^{+0.0075} (theory)$</td>
</tr>
<tr>
<td>W.A.</td>
<td>$0.1181 \pm 0.0011$</td>
</tr>
</tbody>
</table>
- Using low pile-up $\sqrt{s} = 7$ TeV data
  - Huge work in detector understanding
- Uncertainty compatible with previous best measurement from CDF
- Expect improvements from theory modeling and larger statistics sample to reduce experimental uncertainties

\[ m(W) = 80370 \pm 19 \text{ MeV} \]
\[ \pm 7 \text{ (stat.)} \]
\[ \pm 11 \text{ (exp. syst.)} \]
\[ \pm 14 \text{ (mod. syst.)} \]

![Graph](image-url)
**EWK Gauge couplings**

- Extensive studies of diboson and W/Zjj processes
- Vector-boson scattering measurements are a milestone in the study of the EWK sector
- $5\sigma$ observation of EWK $W^\pm W^\pm jj$ production
- First studies towards ZZjj EWK production

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**Figure**

- Histogram of $m_{jj}$ vs. events for $W^\pm W^\pm jj$ with 35.9 fb$^{-1}$ (13 TeV)
- CMS Preliminary
- Data
- EW WW
- WZ
- Non-prompt
- Bkg. unc.

- Graph showing ZZjj production with $m_{jj} > 100$ GeV
- CMS PAS-SMP-16-018
- CMS PAS-SMP-17-004
- Detailed studies of the heaviest fundamental particle known
- Differential cross section meas. to refine theory calculations in extreme phase-space

Recent results:
\[ m(\text{top}) = 172.62 \pm 0.80 \text{ GeV} \]
(\(\mu\)+jets. \(\sqrt{s}=13\text{ TeV}\))

172.84 \pm 0.70 \text{ GeV}

172.44 \pm 0.48 \text{ GeV}

\[ m(\text{top}) = 173.7 \pm 1.15 \text{ GeV} \]
( all-had. \(\sqrt{s}=8\text{ TeV}\))

ATLAS-PAS-TOP-16-022

CMS-PAS-TOP-16-023
Rare top processes

- Measurement of rare processes in association with top pair production
- Larger dataset will open the door to even rarer processes, as four top production
The only fundamental scalar in the Standard Model

Test (differential!) cross section prediction in various decay channels

Measure mass, spin/CP and constrain width

\[ m_H = 125.26 \pm 0.21 \text{GeV} \text{ (Run 1: } 125.09 \pm 0.24 \text{ GeV)} \]

\[ \Gamma_H < 1.1 \text{GeV} \text{ (95% C.L.)} \]
Difficult decay modes

$H \rightarrow \mu\mu$
- Expected BR $\sim 2 \cdot 10^{-4}$
- $\sigma/\sigma_{SM} < 2.8$ (2.0 exp.)

$H \rightarrow bb$ (inclusive!)
- Dominant decay channel
- Huge QCD bb background
- Attempt to isolate signal looking at ISR-boosted regime
- $1.5\sigma$ (0.7$\sigma$ exp.) significance

Higgs boson search with $\not{E}_T$ and boosted jets

$Z$ as calibration

CMS-PAS-HIG-17-010

Higgs boson mass spectrum

arxiv:1705.04582
Higgs-top coupling

- Direct test of H-t coupling using ttH and tHq production
- Events with same-charge leptons (and >=3 leptons for ttH)
- ttW/Z irreducible background
- Evidence for ttH signal (3.3σ obs., 2.5σ exp.)
Higgs self-coupling

- Critical to test Higgs self-coupling in the SM
- Very low cross-section (interference)
- Current searches place limits on non-SM couplings and search for HH resonances
- Full HL-LHC dataset and combination of channels needed for SM sensitivity
Beyond SM searches

CMS Preliminary

Leptoquarks
- LQ1(±j) x2
- LQ1(±j)+LQ2(±j) β=0.5
- LQ2(±j) x2
- LQ3(±j) x2
- LQ3(±j)+LQ3(±j) β=0.5
- Single LQ1 (λ=1)
- Single LQ2 (λ=1)

RS Gravitons
- RS1(±j), k=0.1
- RS1(±j)+LQ2(±j) β=0.5
- RS1(±j)+LQ3(±j) β=0.5
- Single RS1 (λ=1)

Heavy Gauge Bosons
- SSM Z'(±j)
- SSM Z(±j)
- SSM Z(±j)+LQ2(±j) β=0.5
- SSM W(±j)
- SSM W(±j)+LQ2(±j) β=0.5
- SSM Z(±j)+LQ3(±j) β=0.5

Excited Fermions
- e^+ (M=±N)
- μ^+ (M=±N)
- q^+ (qg)
- q^+ (qg)+LQ3(±j) β=0.5
- b^+ (M=±N)

Multijet Resonances
- coloron(jj) x2
- coloron(4j) x2
- gluino(3j) x2
- gluino(3j)+LQ1(±j) β=0.5

Large Extra Dimensions
- ADD (γ+MET), nED=4, MD
- ADD (γγ), nED=4, MD
- ADD (γ), nED=4, MD
- ADD (γ), nED=4, MS
- ADD (γγ), nED=4, MS
- ADD (γ), nED=4, MS
- ADD (γ), nED=4, MS
- ADD (γ), nED=4, MS
- ADD (γγ), nED=4, MS

Compositeness
- dijets, Λ+ LL/RR
- dijets, Λ- LL/RR
- dimuons, Λ+ LL/LIM
- dimuons, Λ- LL/LIM
- dielectrons, Λ+ LL/LIM
- dielectrons, Λ- LL/LIM
- single e, Λ HnCM
- single μ, Λ HnCM
- inclusive jets, Λ+ LL/LIM
- inclusive jets, Λ- LL/LIM
• LHC in excellent position to test Dark Matter production at EWK scale

• Searches for DM giving Missing Transverse Energy when recoiling against identified object

• Comparison with direct detection only possible in specific models

**Dark Matter hunt**

- **LHC in excellent position to test Dark Matter production at EWK scale**
- **Searches for DM giving Missing Transverse Energy when recoiling against identified object**
- **Comparison with direct detection only possible in specific models**
Di-jet resonances

- Di-jet resonance search also sensitive to DM production
- Synergy between different strategies
  - trigger-level analysis (low-mass)
  - high-mass di-jet resonance and angular study
  - ISR + di-jet resonance
Heavy resonances

- Comprehensive searches for high-mass resonances
- Hadronic final states in boosted regimes for vector-boson final states
- Limits extend to several TeV in mass and 10fb – 0.1fb in cross section for benchmark models

$m(Z' \rightarrow ee, \mu\mu) > 4.1 \text{ TeV}$

$m(W' \rightarrow WH \rightarrow qq'bb) > 2.5 \text{ TeV}$
• SUSY represents an attractive solution to three main present questions

• Almost 20 null results per-experiment with full 2015+2016 dataset, and counting

• Very large improvements with respect to Run-1:
  - energy jump
  - increased luminosity
  - targeted search techniques

• In **simplified models** with light $\chi^0_1$
  - stop excluded up to $\sim 1$ TeV
  - gluino excluded up to $\sim 2$ TeV

• In particular scenarios even e.g. a light stop is still allowed!
Low expected cross section → need luminosity

2/3 leptons + $E_T$ (+jets)

- search for $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$, $\tilde{\chi}_1^{+}\tilde{\chi}_1^-$, $\ell\ell$

Higgsinos w/ HH+$E_T$

- $\tilde{\chi}_1^0$ NLSP in GMSB models
  - prompt decay
  - small but significant x-sec

- 2-4 b-jets signal region

**ATLAS Preliminary**

$\tilde{\chi}_1^0 + \tilde{\chi}_1^\pm \rightarrow 2\ell + n\nu \rightarrow 2\ell + n\nu \tilde{\chi}_1^0$

ATLAS-CONF-2017-039

**CMS Preliminary**

$pp \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_1^\mp \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 + X \rightarrow hhG + X_{soft}$

$\tilde{\chi}_1^0$ mass $m_{\tilde{\chi}_1^0}$ = 1 GeV

CMS-PAS-SUS-16-044

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**RPV SUSY and Long-lived particles**

- Relax common assumptions
  - susy partners can easily acquire significant lifetime
  - R-parity violation can lead to unexpected signatures

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### Chart 1: $\tilde{g}$ and $\tilde{t}$ decaying in calorimeter

- CMS Preliminary 2015 + 2016
- $L dt = 2.7 + 36.8 \text{ fb}^{-1}$
- $\sqrt{s} = 13 \text{ TeV}$
- $E_{t} > 130 \text{ GeV}, E_{l} > 170 \text{ GeV}$
- $E_{W} > 70 \text{ GeV}$

<table>
<thead>
<tr>
<th>$m$ [GeV]</th>
<th>$\tau$ [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>2000</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>1800</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>1600</td>
<td>$10^{-7}$</td>
</tr>
</tbody>
</table>

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### Chart 2: R-parity violating $\tilde{t}$ decay

- **ATLAS Preliminary**
  - $\sqrt{s}=13 \text{ TeV}, 36.1 \text{ fb}^{-1}$
  - SR800
  - **dt**
  - **single-top**
  - **Z+jets**
  - **diboson**
  - **tt+jets**
  - **W+jets**

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**EXO-16-004**

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**ATLAS-CONF-2017-036**

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**ATLAS-CONF-2017-017**

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Conclusions

- LHC has been performing remarkably well
  - e.g. instantaneous luminosity beyond design value
- ATLAS and CMS are collecting and analyzing data efficiently
  - continuous improvements to detector and analysis technique to cope with increasingly challenging conditions
- Vast physics program to test the Standard Model
  - accurate measurement of known processes
  - direct search of beyond-SM physics in a variety of final states
- The Standard Model remarkably reproduces observations
- The current dataset is ~2% of what expected by end of HL-LHC
  - More luminosity will allow us to explore new ways to test theory
**ATLAS Simulation Preliminary**

\( \sqrt{s} = 14 \text{ TeV}: \int L dt = 300 \text{ fb}^{-1}; \int L dt = 3000 \text{ fb}^{-1} \)

- **H \rightarrow \gamma \gamma** (comb.)
  - (0j)
  - (1j)
  - (VBF-like)
  - (WH-like)
  - (ZH-like)
  - (ttH-like)
- **H \rightarrow ZZ** (comb.)
  - (VH-like)
  - (ttH-like)
  - (VBF-like)
  - (ggF-like)
- **H \rightarrow WW** (comb.)
  - (0j)
  - (1j)
  - (VBF-like)
- **H \rightarrow Z\gamma** (incl.)
- **H \rightarrow bb** (comb.)
  - (WH-like)
  - (ZH-like)
- **H \rightarrow \tau\tau** (VBF-like)
- **H \rightarrow \mu\mu** (comb.)
  - (incl.)
  - (ttH-like)

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**CMS Projection**

CMS-PAS-FTR-16-002

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ATL-PHYS-PUB-2014-016/
Links to ATLAS and CMS public results

- Complete list of CMS Published and Preliminary results
- Complete list of ATLAS Published and Preliminary results
Example of other Higgs rare decays

\[
H \rightarrow Z\gamma \\
\text{BR} / \text{BR}_{\text{SM}} < 11
\]

\[
H \rightarrow \phi\gamma \\
\text{BR} < 1.4 \cdot 10^{-3}
\]

\[
H \rightarrow J/\Psi\gamma, H \rightarrow Y(nS)\gamma
\]

\[
\text{ATLAS} \\
\text{L}_\text{dd} = 4.5 \text{ fb}^{-1}, s = 7 \text{ TeV} \\
\text{L}_\text{dd} = 20.3 \text{ fb}^{-1}, s = 8 \text{ TeV}
\]
\begin{itemize}
\item \(\tilde{t}, \tilde{b}\) production, \(\tilde{t}, \tilde{b} \rightarrow b \tilde{\chi}_1^+, \tilde{\chi}_1^0 \rightarrow W^+ \tilde{\chi}_1^0\)
\end{itemize}

**ATLAS**

\(\sqrt{s} = 8\) TeV, 20 fb\(^{-1}\)

- \(\Delta m(\tilde{\chi}_1^+, \tilde{\chi}_1^0) = 5\) GeV \(\rightarrow b0L, t1L\)
- \(\Delta m(\tilde{\chi}_1^+, \tilde{\chi}_1^0) = 20\) GeV \(\rightarrow b0L, t1L\)

**LEP**

- Observed limits
- Expected limits
- All limits at 95\% CL

**SUSY-2014-07**

\(m_{\tilde{t}}\) [GeV]
$\text{BR}(\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0) + \text{BR}(\tilde{t}_1 \rightarrow b f f' \tilde{\chi}_1^0) = 1$

$\tilde{t}_1$ pair prod. cross section

- $t_c$, $t_1$L, WW
- $\sqrt{s} = 8$ TeV, 20 fb$^{-1}$
- All limits at 95% CL

$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) = 80$ GeV