Recent results from the CMS Experiment

TeV Particle Astrophysics
CERN, 12-16 Sept. 2016

Francesco Costanza
on behalf of the CMS Collaboration
• LHC and CMS performance during 2016.
• Rediscovery of the Standard Model.
• Is H(125) still there?
• Search for Physics beyond the Standard Model:
  ‣ Search for heavy resonances.
  ‣ Dark matter searches.
  ‣ Search for supersymmetric particles.

• In this talk:
  ‣ Collection of highlights, not a comprehensive review.
  ‣ Focus on 13TeV recently published results.
Taking data at $\sqrt{s} = 13$ TeV

- LHC is breaking records after records with a maximum peak instantaneous luminosity of $1.2 \times 10^9 \text{ cm}^{-2} \text{s}^{-1}$ already exceeding its design value and both ATLAS and CMS have collected more than 30$\text{fb}^{-1}$ since the beginning of 2016 data taking.
- The CMS detector has been working spectacularly well, with no performance degradation over 3 years RunI and 2 years RunII operation.
- Temporary performance losses were always recovered!
The Stairway Plot

- The SM is extremely successful in predicting the x-sections for Z, W, dibosons, t\(\bar{t}\), single top, t\(\bar{t}\)V,…
- Experimental precision now approaching theory precision.
- Huge data samples allows to probe phase space corners never probed before.
- Background constraints for new Physics searches.

![Stairway Plot Diagram]

June 2016

Production Cross Section, \(\sigma [pb]\)

All results at: http://cern.ch/go/pNj7

CMS Preliminary

- 7 TeV CMS measurement (\(L \leq 5.0 \text{ fb}^{-1}\))
- 8 TeV CMS measurement (\(L \leq 19.6 \text{ fb}^{-1}\))
- 13 TeV CMS measurement (\(L \leq 2.7 \text{ fb}^{-1}\))
- Theory prediction
- CMS 95%CL limit
Recent results from CMS

LHC: a top quark factory

**tt x-section**

CMS PAS TOP-16-006

- Tevatron combined 1.96 TeV (L ≤ 8.8 fb⁻¹)
- CMS eq 5.02 TeV (L = 26 pb⁻¹)
- CMS eq 7 TeV (L = 5 fb⁻¹)
- CMS H+jets 7 TeV (L = 2.3 fb⁻¹)
- CMS all-jets 7 TeV (L = 3.54 fb⁻¹)
- CMS eq 8 TeV (L = 19.7 fb⁻¹)
- CMS H+jets 8 TeV (L = 19.6 fb⁻¹)
- CMS all-jets 8 TeV (L = 18.4 fb⁻¹)
- CMS eq 13 TeV (L = 43 pb⁻¹, 50 ns)
- CMS eq* 13 TeV (L = 2.2 fb⁻¹)
- CMS H+jets* 13 TeV (L = 42 pb⁻¹, 50 ns)
- CMS all-jets* 13 TeV (L = 2.3 fb⁻¹)
- CMS all-jets* 13 TeV (L = 2.53 fb⁻¹)

- Preliminary

Inclusive tt cross section [pb]

- CMS Preliminary
- Aug 2016

- Effect of the beam energy uncertainty: 12 pb (not included in the figure)

**Single top x-section**

CMS PAS TOP-16-003

- Tevatron 1.96 TeV (L = 9.7 fb⁻¹)
- CMS 7 TeV (L = 1.17/1.56 fb⁻¹)
- CMS 8 TeV (L = 19.7 fb⁻¹)
- CMS 13 TeV (L = 2.3 fb⁻¹)

- CMS-PAS-TOP-16-003, preliminary

**tt x-section measured at 4 √s.**

- Most precise measurement at 13 TeV from l+jets analysis.

| f_LV V_{tb} | = \sqrt{\frac{\hat{\sigma}_{t-ch}}{\sigma_{th}}} = 1.02 \pm 0.07(\text{exp}) \pm 0.02(\text{th})
Small BR predicted by the SM (~0.2%), huge background, but.. clean signature:
- Two isolated photons giving an invariant mass peak.
- Leptons, jets, and b-tagged jets are used for event categorization.
- Production modes addressed: ggH, VBF, ttH.

5.6σ observed
(6.2σ expected)
@ m_{\gamma\gamma}=125.09 GeV

Measurement compatible with SM.
Achieved similar precision to Run1.
Results still dominated by statistical uncertainties.
Higgs → ZZ* → 4l \ (l = e, \mu)

Spectacular \ H \rightarrow ZZ \rightarrow 2e2\mu \ candidate \ compatible \ with \ VBF!
Higgs → ZZ* → 4l (l = e, μ)

- Tiny signal but clean signature over a small background:
  - Two pairs of opposite-sign same-flavor electrons/muons.
- All production modes addressed: ggH, VBF, VH, ttH.

\[ m_H = 124.50^{+0.48}_{-0.46} \text{ GeV} \]
\[ = 124.50^{+0.47}_{-0.45}(\text{stat.})^{+0.13}_{-0.11}(\text{sys.}) \text{ GeV} \]

6.2σ observed (6.5σ expected) @125 GeV

\[ \Gamma_H < 4\Gamma \text{ MeV} \] (using off-shell events)

No anomalies wrt to 0⁺ hypothesis

Differential x-section

Heavy scalar search

\[ \Delta \sigma / \sigma \sim 30\% \]
ttH searches

✓ Probing the top-Higgs Yukawa coupling at LHC:
  ✓ Indirect: through ggH measurements, assuming no BSM particle in the loop.
  ✓ Direct: associate ttH production.

ttH(→bb) CMS PAS HIG-16-004
tt̄ decaying in 1 or 2 leptons.

ttH(multilepton) CMS PAS HIG-16-022
addressing H → ZZ, WW, ττ, additional leptons from top quark decays.

ttH(→γγ) CMS PAS HIG-16-020
part of overall analysis.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>BR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H→bb</td>
<td>58.1</td>
</tr>
<tr>
<td>H→WW</td>
<td>(&lt;) 21.5</td>
</tr>
<tr>
<td>H→ττ</td>
<td>(&lt;) 6.3</td>
</tr>
<tr>
<td>H→ZZ</td>
<td>(&lt;) 2.6</td>
</tr>
<tr>
<td>H→γγ</td>
<td>0.23</td>
</tr>
</tbody>
</table>

CMS Preliminary \( m_H = 125.7 \) GeV

Best fit \( \mu = \sigma/\sigma_{SM} \)

Combined \( \mu = 3.7^{+1.6}_{-1.4} \)
ttH multilepton

✓ Signature: two same-charge leptons or at least three charged leptons, b-tagged jets.
✓ Main Backgrounds:
  ✓ Irriducibile: ttV and diboson.
  ✓ reducible: non-prompt leptons in t\(\bar{t}\) events and charge mis-ID.
✓ Signal extraction: 2D fit on the BDT discriminators specifically optimized for t\(\bar{t}\) and t\(\bar{t}V\) rejection.

BDT classifiers used for signal extraction

 CMS PAS HIG-16-022

F. Costanza
Recent results from CMS
Search for diphoton resonances

**Phys. Rev. Lett. 117 (2016) 051802**

**CMS PAS EXO-16-027**

- **2015 dataset:**
  - Local/global significance for narrow resonance = 3.4/1.6 $\sigma$
  - Similar observation from ATLAS (for sure you saw in the previous talk!)

- **2016 strategy:** 2015 reloaded
  - Event deficiency observed around 750 GeV
Diphoton: combined results

✓ Combination of 2012, 2015, and 2016 results.

Spin-0 resonance

Narrow width (wrt detector resolution)

Spin-2 resonance

Wide width (wrt detector resolution)
Search for $Z\gamma$ resonances

- Two types of searches pursued:
  - Leptonic search $Z(\ell\ell)\gamma$ - best at low mass.
  - Boosted hadronic search $Z(qq)\gamma$, w/ categorization using b-tagging info and jet substructure - best at for $M > 1.5$ TeV.
Search for dilepton resonances

The \( m(ee) = 2.9 \text{ TeV} \) detected early last year is still the highest mass dilepton observed at 13 TeV!
Search for dijet resonances

✓ Invariant mass spectrum of dijet system. Two complementary strategies:
  ‣ low mass: hard jet recoiling against a jet with substructure.
  ‣ high mass: 2 “wide” jets (add jets to the closest of the two leading jets).
  ‣ Data scouting: lower trigger thresholds by storing reduced event info.

![CMS PAS EXO-16-030 diagram](image)

<table>
<thead>
<tr>
<th>Resonance Mass [TeV]</th>
<th>σ A [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>gluon-gluon</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>quark-gluon</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>quark-quark</td>
<td>$10^{-1}$</td>
</tr>
</tbody>
</table>

95% CL limits

- CMS PAS EXO-16-032
- CMS Preliminary
- 12.9 fb$^{-1}$ (13 TeV)
Three main complementary approaches to detect DM (crossing symmetry of the same Feynman diagram):

- Direct detection (i.e. DM-nucleon scattering).
- Indirect detection (i.e. annihilation).
- Pair production at colliders.

Run I modeling: interpretation within EFTs assuming contact interactions between DM and SM particles.

This approach works well only for heavy mediators.

Run II modeling: interpretation within Simplified models

Easier to compare LHC results with I/DD.

4D problem: \( m_{\chi}, M, g_{\chi}, g_q \).

LHC DM Working group (arXiv:1603.04156) recommends to set \( g_\chi = 1, g_q = 0.25 \) (V/A case) or \( g_\chi = g_q = 1 \) (S/P case).

The choice of couplings is motivated by requiring the mediator width to be below \( \sim 10\% \) of its mass. In the case of V/A mediators, \( g_q = 0.25 \) is required to avoid previous dijet constraints.
How can we trigger on DM particles at colliders?
ISR (g, γ, W/Z, h, ...) to rescue!

Example: Mono-jet and Mono-V search **CMS PAS EXO-16-037**
Main backgrounds: Z(νν)+jets (irreducible), W(lν)+jets (lost lepton).
Background estimation: control region with ll+jets, γ+jets, l+jets
(leptons are ignored in the calculation of MET).

- **Spin 0**
- **Spin 1**
Mono-jet and Mono-V interpretations

More on Mono-X searches: “DM searches using missing ET at LHC” by C.-S. Moon, DM &colliders session this afternoon

Limit comparisons:

- Vector mediator: CDMSLite, LUX, PandaX-II and CRESST-II.

Also available:

- scalar and pseudo-scalar mediators
LHC does not need to produce DM to look for the mediator.

Since the mediator it is coupled with the initial state, we can recycle dijet resonance searches!

More on DM searches through dijet resonances:
“Searches for light dark matter through dijets and long-lived particles at the LHC” by R.C. Rosten, DM &colliders session this afternoon
SUSY searches: strong production

- Typical signatures:
  - (b-tagged) Jets + MET
  - 0l powerful, but depending on the addressed decay leptonic channels and boson tags add sensitivity

An example: **CMS PAS SUS-16-019**

Search variables:
- \( H_T, \Delta \phi(\text{MET} + \ell, \bar{\ell}) \)
- \( L_T = \text{MET} + p_T^\ell \)
- \( N_{\text{jets}} \geq 5 \)

Main backgrounds:
- \( W \) and \( t\bar{t} \) production (data-driven estimation)
Recent results from CMS

SUSY: Strong production summary

**Top**

- \( pp \rightarrow \tilde{t}, \tilde{t} \rightarrow t \tilde{\chi}_1^0 \)
- CMS Preliminary
- 13 TeV
- Expected and Observed

**Bottom**

- \( pp \rightarrow \tilde{b}, \tilde{b} \rightarrow b \tilde{\chi}_1^0 \)
- CMS Preliminary
- Expected and Observed

**Light Quarks**

- \( pp \rightarrow \tilde{q}, \tilde{q} \rightarrow q \tilde{\chi}_1^0 \)
- CMS Preliminary
- Expected and Observed

GLUINO PRODUCTION

SQUARK PRODUCTION

COMBINATION 0-lep and 1-lep stop, 12.9 fb

SS:

\( \tilde{t} \rightarrow t \tilde{\chi}_1^0 \)

Combination 0-lep and 1-lep stop, 12.9 fb

One light \( \tilde{q} \)
SUSY searches: EW production

- Typical signatures:
  - Few jets
  - Many leptons
  - W/Z/h bosons

An example: **CMS PAS SUS-16-025**

- Compressed spectra: small $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$
- Signature: MET and soft leptons [5,30] GeV
- Two trigger strategy:
  - MET > 200GeV
  - MET > 125GeV and soft muon pair
- Main background: DY+ jets, $t\bar{t}$ and $VV$
- Signal extraction: fit on $M(ll)$ and $p_T(l_1)$
- First analysis covering $5 < \Delta m < 30$ GeV
Summary

✓ Very successful operation of LHC and CMS during 2016.
✓ SM processes and its particles properties are being studied with great precision. H(125) is back!
✓ A first broad scan of beyond the SM scenarios have been performed.
✓ No significant deviation from the SM expectations yet..
✓ but only few percent of the expected LHC dataset has been analyzed! New channels are opening and new searches become possible!
✓ Run II has just started, exciting times are in front of us!

✓ You can find all CMS results at: http://cms-results.web.cern.ch/cms-results/public-results/publications/
Backup
Dark Matter bar plot summary

**CMS Preliminary**

**Dark Matter Summary - ICHEP 2016**

- **DM + jets/V(φ)**
  - $g_{DM}=1$, $g_q=0.25$

- **DM + γ**
  - $g_{DM}=1$, $g_q=0.25$

- **DM + Z(t¯t)**
  - $g_{DM}=1$, $g_q=0.25$

- **DM + t**
  - $g_{DM}=1$, $a_{FC}=b_{FC}=0.25$

- **DM + H(bb/γγ)**
  - $m_A=300\text{GeV}$; $m_{DM}=100\text{GeV}$
  - $g_z=0.8$

- **DM + jets/V(φ)**
  - $g_{DM}=g_q=1$

- **DM + t¯t**
  - $g_{DM}=g_q=1$
  - $\sigma/\sigma_0 = 2$

- **DM + bb/t¯t**
  - $g_{DM}=g_q=1$
  - $\sigma/\sigma_0 = 30$

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**Observed limits at 95%CL**

for considered simplified models
Theory uncertainties not included

V = vector; AV = axial-vector
S = scalar; PS = pseudoscalar

**Maximal excluded mass [GeV]**

- **EXO-16-037**
  - 13TeV, 12.9fb⁻¹

- **EXO-16-039**
  - 13TeV, 12.9fb⁻¹

- **EXO-16-038**
  - 13TeV, 12.9fb⁻¹

- **EXO-16-040**
  - 13TeV, 12.9fb⁻¹

- **EXO-16-012**
  - 13TeV, 2.3fb⁻¹

- **EXO-16-011**
  - 13TeV, 2.3fb⁻¹

- **EXO-16-037**
  - 13TeV, 12.9fb⁻¹

- **EXO-16-005**
  - 13TeV, 2.2fb⁻¹

- **B2G-15-007**
  - 13TeV, 2.2fb⁻¹
Recent results from CMS

Exotica Grand Summary

CMS Preliminary

Leptoquarks

RS1(jj), k=0.1
RS1(γγ), k=0.1
Single LQ1 (λ=1)
Single LQ2 (λ=1)

RS Gravitons

SSM Z'((ττ))
SSM Z'(jj)
SSM Z'((ee)+Z'(μμ))
SSM W'(jj)
SSM W'(lv)
SSM Z'(bb)

Heavy Gauge Bosons

dijets, A+ LL/RR
dijets, A- LL/RR
dimuons, A+ LLIM
dimuons, A- LLIM
dielectrons, A+ LLIM
dielectrons, A- LLIM

Excited Fermions

e^+ (M=Λ)
μ^+ (M=Λ)
q^+ (qg)
q^+ (qγ) f=1
b^+


Compositeness

ADD (v+MET), nED=4, MD
ADD (jj), nED=4, MS
QBH, nED=6, MD=4 TeV
NR BH, nED=6, MD=4 TeV

Large Extra Dimensions

ADD (γγ), nED=4, MS
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MD

Jet Extinction Scale

dimuons, Λ+ LLIM
dimuons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+ HnCM
inclusive jets, Λ-