CMS Overview

Physics Highlights

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on behalf of the CMS Collaboration

National Centre for Nuclear Research
NCBJ – Warsaw, Poland

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Kolympari, Crete, Greece
LHC short intro

CMS Detector status
- Subdetector upgrades for data-taking in 2017
  - New: Pixel detector, L1 Trigger, HF calorimeter readout
  - 2017 Performance

CMS Physics highlights with full 2016 36/fb 13 TeV data
- 79 new results in 2017 realised at:
  - Moriond’17 – 39 publications
  - LHCP’17 – 22
  - EPS-HEP’17 – 20
- In this talk – only selected fresh proton-proton results
  - during this conference – other 22 presentations and 4 posters
Introduction

Large Hadron Collider at CERN
LHC schedule

LHC past, present, and future

- **LHC proton-proton data delivered** to CMS till yesterday
- **Run 2**: ~60/fb
  - **2016**: 41/fb
  - **2017**: 17/fb
CMS collaboration
- 199 institutes
- 46 countries
- x 3500 scientists, engineers, and students
CMS upgrades in 2016/17

- **New CMS Pixel detector:**
  - 3 layers (barrel) / 2 disks (endcaps) → 4 layers / 3 disks
    - Improved readout electronics
    - Innermost barrel layer closer to the interaction point
    - Lower material budget
  - Very good efficiency up to 99% for all pixel detector at L=1.5×10^{34} cm^{-2} s^{-1}

- Expected improvements in tracking, vertexing and b-tagging
CMS upgrades in 2016/17

- Full upgrade of **L1 trigger** system to manage with high inst. luminosity of $1 \times 10^{34}$ cm$^{-2}$s$^{-1}$ and high pile-up

- **L1 electron/photon trigger** re-optimization
  - better resolution → sharper turnON
  - 20% rate reduction
  - 15% gain in efficiency (keeping almost no PU dependence)

- **L1 muon** trigger
  - new track finders
  - Improved L1 muon track finding and $p_T$ resolution, and efficiency
  - Lowest unprescaled threshold 25 GeV in 2017
CMS Performance in 2017

- First illustration of di-muon spectrum taken with inclusive and dedicated muon trigger paths

![Di-muon spectrum](image-url)
CMS data-taking efficiency > 85 %

Some time was dedicated for testing the new Pixel detector

Successful restart of the LHC

Reaching inst. luminosity of $1.7 \times 10^{34}$ cm$^{-2}$s$^{-1}$
Data in 2016 → new results

- Excellent performance of the CMS detector
  - Efficiency of data-taking (41/fb) for:
    - 38/fb, recording > 92%
    - 35.9/fb, good for physics > 87%
Run 1&2 legacy – Nature is SM-like

- Theoretical description of high-$Q^2$ processes is with high agreement with LHC data

August 2017

CMS Preliminary

Production Cross Section, $\sigma$ [pb]

Electroweak physics

Top

Higgs

All results at: http://cern.ch/qo/pNj7
Run 2 continues – opened perspective

- **Higgs boson** and precise SM measurements
  - new possibilities for deciphering the properties opened up

New Physics
- no sign, but....
  - Large increase in signal xsecs for heavy particles from $8 \rightarrow 13$ TeV
  - Strong gluino pair production privileged
CMS Physics Highlights

CMS pp Physics (in this talk):

- **Standard Model**
  - Electroweak Physics

- **Higgs**

- **Top Physics**

- **Searches:**
  - **SUSY**
  - **Exotica**
    - Dark Matter

639 collider data papers submitted as of 2017-08-11
Electroweak precise measurements

- Challenging Standard Model predictions
**EWK Gauge Couplings**

- **Diboson and W/Zjj processes** extensively studied
- Vector-boson scattering is the ideal testbench to study of the EWK sector

First **5.5 σ observation** of **EWK same-sign WWjj** production

- Evts: two leptons of the same charge, moderate MET, 2 jets with large rapidity separation and large dijet mass
- Bkg: non-prompt leptons and the WZ → 3ℓν

First measurement of **VBS** in the **ZZjj** channel at the LHC

- Evts: fully leptonic (4ℓ) final state

**EWK ZZjj** is measured with sign. of **2.7 (1.6) σ** obs.(exp.)

**Statistical significance**

\[ \sigma = 0.29 \pm 0.02 \text{ (stat)} +0.13 \text{ (syst)} \text{ fb} \]

**EWK production cross-section**

\[ \sigma_{WW} = 0.40 \pm 0.21 \text{ (stat)} +0.13 \text{ (syst)} \text{ fb} \]
Electroweak mixing angle at 8 TeV

- Precise measurement with the forward-backward asymmetry $A^\text{FB}$ of Drell-Yan (ee and $\mu\mu$) events at 8 TeV
  - Improved lepton momentum calibration, angular event weighting, and additional PDF constraints
- $\sin^2\theta$ extraction by fitting $A^\text{FB}$ inv. mass and rapidity bins
- Most precise measurement of $\sin^2\theta$ at the LHC
- Allows to constrain PDFs

$$\sin^2\theta_{\text{eff}}^\text{lept} = 0.23101 \pm 0.00036(\text{stat}) \pm 0.00018(\text{syst}) \pm 0.00016(\text{theory}) \pm 0.00030(\text{pdf})$$
EWK boson measurements

- Good agreement with SM to date
- Precision will be improved with increased luminosity

<table>
<thead>
<tr>
<th>Process</th>
<th>Experiment</th>
<th>Theory (NLO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma \gamma$</td>
<td>$1.06 \pm 0.01 \pm 0.12$</td>
<td>$5.0 \text{ fb}^{-1}$</td>
</tr>
<tr>
<td>$W\gamma$, (NLO th.)</td>
<td>$1.16 \pm 0.03 \pm 0.13$</td>
<td>$5.0 \text{ fb}^{-1}$</td>
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<td>$Z\gamma$, (NLO th.)</td>
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<tr>
<td>$WW+WZ$</td>
<td>$1.01 \pm 0.13 \pm 0.14$</td>
<td>$4.9 \text{ fb}^{-1}$</td>
</tr>
<tr>
<td>$WW$</td>
<td>$1.07 \pm 0.04 \pm 0.09$</td>
<td>$4.9 \text{ fb}^{-1}$</td>
</tr>
<tr>
<td>$WW$</td>
<td>$1.00 \pm 0.02 \pm 0.08$</td>
<td>$19.4 \text{ fb}^{-1}$</td>
</tr>
<tr>
<td>$WW$</td>
<td>$0.96 \pm 0.05 \pm 0.08$</td>
<td>$2.3 \text{ fb}^{-1}$</td>
</tr>
<tr>
<td>$WZ$</td>
<td>$1.05 \pm 0.07 \pm 0.06$</td>
<td>$4.9 \text{ fb}^{-1}$</td>
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<td>$WZ$</td>
<td>$1.02 \pm 0.04 \pm 0.07$</td>
<td>$19.6 \text{ fb}^{-1}$</td>
</tr>
<tr>
<td>$WZ$</td>
<td>$0.80 \pm 0.06 \pm 0.07$</td>
<td>$2.3 \text{ fb}^{-1}$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$0.97 \pm 0.13 \pm 0.07$</td>
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All results at: [http://cern.ch/go/pNj7](http://cern.ch/go/pNj7)
EWK boson measurements

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<tr>
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<th>$\sigma_{\text{exp}} / \sigma_{\text{theo}}$</th>
<th>$\sigma_{\text{exp}}$ (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>qqW</td>
<td>$0.84 \pm 0.08 \pm 0.18$</td>
<td>19.3</td>
</tr>
<tr>
<td>qqZ</td>
<td>$0.93 \pm 0.14 \pm 0.32$</td>
<td>5.0</td>
</tr>
<tr>
<td>qqZ</td>
<td>$0.84 \pm 0.07 \pm 0.19$</td>
<td>19.7</td>
</tr>
<tr>
<td>qqZ</td>
<td>$1.02 \pm 0.03 \pm 0.10$</td>
<td>35.9</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow WW$</td>
<td>$1.74 \pm 0.00 \pm 0.74$</td>
<td>19.7 fb$^{-1}$</td>
</tr>
<tr>
<td>qqW$\gamma$</td>
<td>$1.77 \pm 0.67 \pm 0.56$</td>
<td>19.7 fb$^{-1}$</td>
</tr>
<tr>
<td>ss WW</td>
<td>$0.69 \pm 0.38 \pm 0.18$</td>
<td>19.4 fb$^{-1}$</td>
</tr>
<tr>
<td>ss WW</td>
<td>$0.90 \pm 0.16 \pm 0.08$</td>
<td>35.9 fb$^{-1}$</td>
</tr>
<tr>
<td>qqZ$\gamma$</td>
<td>$1.48 \pm 0.65 \pm 0.48$</td>
<td>19.7 fb$^{-1}$</td>
</tr>
<tr>
<td>qqZZ</td>
<td>$1.38 \pm 0.64 \pm 0.38$</td>
<td>35.9 fb$^{-1}$</td>
</tr>
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</table>
QCD stress tests

- Jet production at 13 TeV with full 2016
- Measurements of the normalized inclusive 2-jet, 3-jet, and 4-jet xSec. differential in $\Delta \phi_{1,2}$
  - Observations emphasize the need to improve predictions for multijet production
- $\alpha_s(M_Z)$ inferred from a fit of the ratio of the 3-jet over 2-jet event xSec

$\alpha_s(Q)$

$\alpha_s(M_Z)= 0.1150 \pm 0.0010$ (all except scale) $+0.0050-0.0000$ (scale)
Top quark

**LHC** is a top quark factory

- ~10 top pairs every second @ $10^{34}$ cm$^{-2}$s$^{-1}$ inst. luminosity
- Wide and detailed studies under top quark
- Testing SM and BMS physics
Top quark production

- **New xsec** \((69.5 \pm 8.4 \text{ pb})\)  
- **for tt pair prod. @ 5 TeV**  
  (special short run in 2016, \(L=27.4/\text{pb}\))  
  
  - Evts: 1 muon and at least 4jets, 2b-tag

<table>
<thead>
<tr>
<th>(\sqrt{s})</th>
<th>(\sigma(\text{tt}) \text{ [pb]})</th>
<th>(L[\text{fb}^{-1}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 TeV</td>
<td>(~70)</td>
<td>(0.03)</td>
</tr>
<tr>
<td>7 TeV</td>
<td>(~170)</td>
<td>(5)</td>
</tr>
<tr>
<td>8 TeV</td>
<td>(~250)</td>
<td>(19.7)</td>
</tr>
<tr>
<td>13 TeV</td>
<td>(~800)</td>
<td>(2.3)</td>
</tr>
</tbody>
</table>
Top quark mass

- Great accuracy (~0.3%) in the CMS top mass measurement from Run 1

- First top mass measurement from $\mu + \text{jets}$ with 13 TeV with only 2.2/ fb

$$M_{\text{top}} = 172.62 \pm 0.38 \pm 0.70 \text{ GeV}$$
Rare top processes

**Top pair prod. with W/Z**
Same-charge dilepton, 3- and 4-lepton final states where the jet and b-jet multiplicities are exploited to enhance the signal-to-bkg ratio

**Measured xSec. are in agreement with SM predictions**

\[
\begin{align*}
\sigma_{(ttZ)} &= 1.00^{+0.09}_{-0.08} \text{(stat.)}^{+0.12}_{-0.10} \text{(sys.)} \text{ pb} \\
\sigma_{(ttW)} &= 0.80^{+0.12}_{-0.11} \text{(stat.)}^{+0.13}_{-0.12} \text{(sys.)} \text{ pb}
\end{align*}
\]

**Four top production**
Single-lepton +jets and the opposite-sign +jets channels
Boosted decision trees to combine information on the global event and jet properties to distinguish between \( tt^-tt^- \) and \( tt^- \) production

**Upper limit on xSec.**
combined with same-sign dilepton search

\[
\sigma_{(tttt)} < 69 \text{ fb} @ 95\% \text{ C.L. (7.4xSM)}
\]

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**ttW/ttZ**

**Rare top processes**

**Four top production**
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\]
5th anniversary of the Higgs boson

4th July 2012
Higgs boson production

- New measurement at 13 TeV in $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$
- Discovery channels despite small BF of $\sim 0.013\% \,(4\ell)$, $\sim 0.23\% \,(\gamma\gamma)$
- Consistent with SM
Higgs mass and xSec

- Mass measurement in golden channel: $H \rightarrow ZZ^* \rightarrow 4\ell$
  via ggH, VH, VBF
  $m_H = 125.26 \pm 0.20\text{(stat.)} \pm 0.08\text{(sys.)}$ GeV

- As good as the world average of the ATLAS+CMS combination from Run 1
  $m_H = 125.09 \pm 0.21\text{(stat.)} \pm 0.11\text{(syst.)}$ GeV
Higgs couples to $\tau$ lepton

- **First observation** of $H \to \tau\tau$ at CMS with the full 2016 dataset using excellent CMS tau tagging
  - Tau semi-hadronic & leptonic decay channels
    - 4 final states ($\tau\tau, \mu\tau, e\tau, e\mu$)
    - 3 categories (0-jet, VBF, Boosted)

- CMS observed $H \to \tau\tau$ at $4.9 \sigma$ wrt $4.7 \sigma$ expected
- Run 1 + Run 2'16 result: $5.9 \sigma$

Best fit $\mu = \sigma/\sigma_{SM}$

$\mu = 1.09 \pm 0.27$
Higgs Physics: $H \rightarrow bb$

- Dominant $H$ decay channel (58.1%), but with huge QCD $bb$ background
- Presence of the vector boson (leptons, MET) **suppresses highly QCD**

- **Sig:** 2b-tag jets + 2 lep (+1 leptMET), (+MET) extracted via a simultaneous fit of all control regions and signal regions
- **Bkg:** fitted in simultaneous fit for V+jets and ttbar
- Analysis validated for $Z \rightarrow bb$
  - **5.0 $\sigma$** observation

- For $m_H = 125$ GeV,
  - Run 1&2 excess of events observed with local sig. of
  - **3.8 $\sigma$ (3.8 $\sigma$ SM exp.)**

- Signal strength
  $$\mu = \frac{\sigma}{\sigma_{SM}} = 1.06^{+0.31}_{-0.29}$$

**Strong evidence**

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**NEW**

CMS-HIG-16-044
**Higgs – top production**

- Direct test of **H-t coupling** using ttH and tHq channels
- H decaying to WW*, ZZ* or ττ
  - 2 same-sign leptons or at least 3 leptons, and b-tag jets
- Evidence for ttH signal
  - 3.3 σ obs. (2.5 σ exp.) comb. 2015 & 2016

**Upper limit on** $\sigma^{\text{th}+\text{ttH}} \times BR$
- 0.64 pb obs. (0.32 exp.)

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**CMS Higgs – top production**

**CMS Preliminary**

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

**Evidence for ttH signal**
- $3.3 \sigma$ obs. (2.5 $\sigma$ exp.) comb. 2015 & 2016

**Upper limit on** $\sigma^{\text{th}+\text{ttH}} \times BR$
- 0.64 pb obs. (0.32 exp.)

**Single top in the t-channel – unique opportunity to study the relative sign of the coupling**

- $\kappa_t < -1.25$, excluded
- $\kappa_t > 1.60$, excluded
**Searches**

LHC is a unique place to search for new particles

- **directly** and
- **indirectly**
  - precise SM measurements
Strong SUSY

- Gluino or squark \((gg, qq, gq)\) production
- **Sig.:** Jets+MET + \(N_{\text{jet}}\) + \(N_{\text{b-tag jet}}\)

- Experimental search based on signatures
- and kinematical variable sensitive to SUSY
- Multiple signal regions and searches in bins of different variables

- No SUSY particles detected

Run 2'16 at 13 TeV: Limits on gluino mass up to \(\sim 2\) TeV
Electroweak SUSY

- Electroweak SUSY production and decays of **chargino** and **neutralino**
- Statistical combination of several searches
  - Improvement of 40 GeV on the limit mass
- Optimized **analysis with 2- and 3-leptons**

\[ pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \]
SUSY R-parity violation

- R-parity can be not conserved!
- Minimal flavour violation, $\lambda_{tbs}, g \rightarrow t\bar{t} \rightarrow tbs$
- **Signature:** single lepton, large jet multiplicity, and large q-quark jet multiplicity, NO requirement on MET
- Signal extraction through shape fit to $N_b$ in bins of $N_{\text{jet}}$ and $M_J$

**Gluino mass > 1610 GeV (95% C.L.)**
Gauge Mediated SUSY

- Search for BSM with at least 1 photon, large MET, and large $H_T$
- **Sig**: strongly produced GMSB with $N1 \rightarrow \gamma \tilde{G}$
- **New limits** depending $m_{\text{neutralino}}$ & BR:
  - $m_{\text{gluino}}$ up to 1.5-2.0 TeV
  - $m_{\text{squark}}$ up to 1.3-1.65 TeV

- **Complementary searches:**
  - $\gamma V$, $\gamma\gamma$, $\gamma$+lepton, multi-lepton
  - Provide weaker limits

**Figure:**
- CMS Supplementary plots for $pp \rightarrow \tilde{g}\tilde{g}, \tilde{g}\rightarrow q\tilde{\chi}_{1}^{0}$, $\tilde{\chi}_{1}^{0} \rightarrow \gamma \tilde{G}$
- Data and theoretical predictions for $m_{\tilde{g}}$ and $m_{\tilde{q}}$
Long-lived particles

LLPs are foreseen by many BSM models

- Small coupling, small mass splitting, hidden sector
- Signature depends on lifetime
LLP: stopped particles

- LLP (gluino or $|Q|=2e$) is stopped inside the detector and decay to muons from rest after unknown time (sensitivity to lifetimes between $0.1 \mu s$ and $10^6 s$)
- Events recorded out-of-time with collisions with the custom trigger

- No events observed
- 13 orders of magnitude of the lifetime tested
- Excluded gluinos with mass between 400 and 970 GeV, assuming 100% BF to muons
Heavy resonance searches

- Many BSM models predict narrow di-X resonances
- X – many object in the final state analysed
- Di-jets (from Axigluons, colorons, W'/Z' bosons, color octet scalars, string resonances, RS, etc)

![Graph showing di-jet resonance searches](image-url)
Dark Matter

Indirect searches
- **Vector** and **scalar** interactions → spin-independent (SI) DM-nucleon interactions
- **Axial-vector** interactions → spin-dependent (SD) DM-nucleon interactions

Direct searches
Dijet searches

- Used for the DM interpretation
- New 36/fb upper limit on mass of mediator 2.6 TeV extends previously reported limits in the dijet channel (2.0 TeV @13/fb)

**Vector**

- $g_q = 0.25$, $g_{DM} = 1$

**Axial-vector**

- $g_q = 0.25$, $g_{DM} = 1$
Mono-object searches for DM

- Searching for **excess on MET** with mono-jet or mono-V

Bkg. evaluated with combined fit to the data in control samples

No significant excess of events is observed with respect to the SM backgrounds
Mono-object search results

- **Limits**\(^\star\) for simplified models in which DM production is mediated by spin-1 (vector or vec-axial) or spin-0 (scalar, pseudo-scalar) particles

\[ \text{Boson as a mediator} \]
Obs. (exp.) 95% C.L. upper limit of 0.53 (0.40) on the invisible BR of SM-like 125 GeV Higgs

\[ g_q = 0.25, \quad g_{\text{DM}} = 1 \]

\[ \text{Vector-axial} \]

\[ \text{Vector} \]

\[ g_q = 0.25, \quad g_{\text{DM}} = 1 \]
Dark Matter searches

- Dijet angular correlation search probes \textit{interactions} between quarks and DM particles
- Also constrains models of
  - quark contact inter. (scale limit $\Lambda_{\text{CL}} = 13.1 - 17.4$ TeV)
  - ExDim (mass limit graviton = 10.6 TeV)
  - quantum black holes (mass limit BH = 6.3 – 8.0 TeV)

Vector
$g_q = 1, \, g_{\text{DM}} = 1$

DM mediator excluded
2.5 – 5 TeV
CMS Highlights summary

- **Excellent performance** of LHC and the CMS detector resulting in publications with the 13 TeV data of Run 2’16

- Precise measurement of Higgs and Standard Model starting with the increase of luminosity
  - Higgs is very SM-like
    - the observation of decays to taus and an evidence for decays to b-quarks

- New Physics can be discovered if it exists at the TeV scale
  - ~3 times more data (150/fb) till end of 2018 than now (>50/fb)
  - and ~3 orders of magnitude (3000/fb) more for HL-LHC

References:

- **Next CMS presentations during the conference**
  Details and much more about the CMS physics, its performance, and the future

- All CMS public results: [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults)
Thank you!

Supported in part by the NCN grant: 2014/039982014/15/B/ST2/03998
BACKUP
Higgs

CMS

\[ \lambda_f \text{ or } (g_V/2\sqrt{\sigma})^{1/2} \]

19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)

\[ \text{Particle mass (GeV)} \]

\[ \text{(M, } \epsilon) \text{ fit} \]

- 68% CL
- 95% CL

SM Higgs

- \( t \)
- \( W^+Z \)
- \( b \)
- \( \tau \)
- \( \mu \)
High Pt event in 2017

2017 highest di-muon mass candidate with mass = 2.4 TeV