LATEST SM STUDIES, HIGGS AND BEYOND
SM SEARCHES AT CMS

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on behalf of CMS collaboration

Colloquium on “Latest results from the LHC” - 12 July 2012 - CERN
Summary of results presented at

ICHU2012 Melbourne
Contents (and Disclaimer)

- CMS presented many new results at ICHEP
- Here presenting a selected list of results
  - Focussing mostly on new results on 8 TeV 2012 dataset

- **Standard Model Physics**
  - W/Z cross section @ 8 TeV and differential distributions @ 7 TeV
  - Di boson cross sections (WW/ZZ) @ 8 TeV & TGC
  - Top cross sections @ 8 TeV, combined top mass measurement, first observation of tt+V

- **Higgs search**
  - Observation of a new boson around 125 GeV

- **Beyond the SM**
  - New recent results from searches

- All physics results can be found @
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
CMS IN A NUTSHELL

3.8T Superconducting Solenoid

Lead tungstate E/M Calorimeter (ECAL)

Hermetic ($|\eta|<5.2$) Hadron Calorimeter (HCAL) [scintillators & brass]

All Silicon Tracker (Pixels and Microstrips)

Redundant Muon System (RPCs, Drift Tubes, Cathode Strip Chambers)
VERY GOOD UNDERSTANDING OF PHYSICS OBJECTS

electrons

muons

photons

taus

jets

MET
High lumi comes at a cost: in 2012 already exceeding detectors design capabilities for pile-up

- 2012 certified ‘Golden’: 5.19 fb⁻¹ (85%)
- Muon: 5.62 fb⁻¹ (92%)

2012: on average O(20) pile-up events
50 ns inter-bunch spacing

Expected size of 2012 dataset >15fb⁻¹
**ELECTROWEAK STUDIES**

- **W and Z production at LHC**
  - Precise test of the SM
  - Help to improve understanding of proton Parton Density Functions (PDF)
  - Candles used to calibrate our detector (trigger, energy scale, efficiencies...)
  - They are bkg for many searches

- **New studies presented @ ICHEP**
  - First inclusive W/Z and WW/ZZ xsec @ 8 TeV
  - Detailed differential distributions in Z+jets events
W AND Z INCLUSIVE @ 8 TeV

- In 2012 performed using special low pile-up runs
- Looking also at absolute inclusive xsec and ratio (W/Z, W^+/W^-) with reduced theoretical and experimental systematic errors
- Good agreement with predictions
Z+JETS DIFFERENTIAL DISTRIBUTIONS

- Critical test of pQCD at unprecedented level
  - Background to a plethora of searches

- Now studying differential cross-sections and event shapes in Z+jets events

- LO matrix element (many legs) + matched parton showering accurately describing data in all regions of analyzed phase space

\[
\frac{\sigma(Z + N_{jets} + 1)}{\sigma(Z + N_{jets})} \propto \alpha_s
\]

![Graph showing differential distributions](image)

![Graph showing differential distributions](image)
**Diboson Production**

- Critical test of the gauge structure of the SM
  - Allows to search for anomalous Triple Gauge Couplings (TGC)

- Mandatory preliminary study for Higgs searches: irreducible background for Higgs searches in WW and ZZ modes

- Probe for new physics
  - Resonances with diboson final states

- WW/WZ/ZZ cross section already measured @ 7 TeV and found in agreement with predictions
**WW** & **ZZ** @ 8 TeV

**CMS-SMP-12-014**

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**ZZ**

\[ \sigma = 8.4 \pm 1.0 \text{ (stat)} \pm 0.7 \text{ (sys)} \pm 0.4 \text{ (lum)} \text{ pb} \]

(NLO for qq→ZZ and LO for gg→ZZ, MSTW 2008 PDF)

**WW**: 2 opposite sign leptons (e,μ) + MET + jet veto

All backgrounds are estimated from data

\[ \sigma = 69.9 \pm 2.8 \text{ (stat)} \pm 5.6 \text{ (sys)} \pm 3.1 \text{ (lum)} \text{ pb} \]

NLO prediction:

\[ \sigma^{\text{NLO}}(gg \to W^+W^- + qq \to W^+W^-) = 57.25 \pm 2.35 \text{ pb} \]

Campbell, Ellis, Williams.

JHEP 07 (2011), 018.

arXiv:1105.0020  MCFM

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EWK: Grand Summary

Production Cross Section, $\sigma_{tot}$ [pb]

- $W$: $10^5$ to $10^3$
- $Z$: $10^4$ to 10

- $E_T^{jet} > 30$ GeV
- $|\eta^{jet}| < 2.4$
- $N_{jet} \geq 4$

- $W_\gamma$: $E_T^{\gamma} > 10$ GeV
- $\Delta R(\gamma,l) > 0.7$
- $|\eta^\gamma| < 2.4$
- $N_{jet} \leq 4$

- $WW$: 4.9 fb$^{-1}$
- $WZ$: 11.1 fb$^{-1}$
- $ZZ$: 5.3 fb$^{-1}$

References:
- JHEP10(2011)132
- JHEP01(2012)010
- PLB701(2011)535
- CMS-PAS-SPM-12-011 (W/Z 8 TeV)
- CMS-PAS-SPM-12-005, 007, 013, 014 (WW ZZ)
Top Physics @ CMS

• Another pillar of the physics programme at the LHC
  – A very special particle ($Y_t \sim 1$), the only “free” quark
  – LHC a top factory. $t\bar{t}$bar cross-section @ 8TeV $\sim$230pb
  – Possibility to do precise measurements of important parameters of the SM ($m_t$, $V_{tb}$)
  – Critical from the experimental point of view: all sub-detectors are involved in top reconstruction

• Top sector also interesting to search for new physics
  – New particles decaying in top quarks or associated production with top quarks.
CMS-TOP-12-007
di-lepton channel
- very clean channel
- counting experiment with increasing number of b-tagged jets
- e-mu channel particularly clean: driving the xsec measurement

CMS-TOP-12-006
lepton + jets channel
- good compromise between purity and statistics
- Cross section extracted from a fit to the invariant mass of lepton and b-jet

Precision is challenging NNLO predictions
• Top mass measurement performed both in the di-lepton and in the l+jets channels

• **Dominant systematic from Jet Energy Scale**
  – Recently added the systematics error due to color reconnection and UE (increase the systematics error by about 20%).

• Systematic error at the moment ~50% worse than Tevatron
Top decays before hadronization: polarization or spin information is transferred to decay products
Studying in detail ttbar production can help revealing physics beyond SM

In SM top is produced unpolarized (polarization only coming through EWK corrections)
Measurement done looking at distribution of the angle between lepton and top direction in ttbar rest frame in di-lepton events

\[ \frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_{l,n}} = \frac{1}{2} (1 + 2\kappa_i P_n \cos \theta_{l,n}) \]

\[ P_n = -0.009 \pm 0.029 \pm 0.041 \]
Starting to observe associated production of top pairs with W or Z

\[ \frac{\sigma(t\bar{t})}{\sigma(t\bar{t} + V)} \approx 500 \]

Trilepton channel: \( \sigma(t\bar{t}Z \rightarrow l + \text{jets} + (Z \rightarrow ll)) \)

Same-sign dilepton channel: \( \sigma(t\bar{t}V \rightarrow l^+ + \text{jets} + (W \rightarrow l\nu) \text{ or } (Z \rightarrow ll)) \)

First measurement of \( ttV \):

Result combining all 7 channels:

\[ \sigma(t\bar{t}V) = 0.51^{+0.15}_{-0.13} \text{(stat.)}^{+0.04}_{-0.02} \text{(syst.)} \text{ pb} \]

Significance of \( 4.67 \sigma \)
Excluded SM higgs in 127.5-600 GeV range @ 95% CL
Close to 2.8σ excess at ~ 125 GeV (similar for ATLAS), 2.1σ after look else-where correction (110-145 GeV)

- After March analysis were blinded
  - Re-optimization performed only using simulation
  - Analysis validated in data using control regions
Higgs search strategy designed to cover the full mass range

<table>
<thead>
<tr>
<th>mode</th>
<th>signature</th>
<th>S/B</th>
<th>Mass Resol.</th>
<th>N events in 10 fb(^{-1})</th>
<th>Good For</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H \rightarrow bb)</td>
<td>two b-jets, Z or W, bb inv. mass</td>
<td>low O(0.1)</td>
<td>10%</td>
<td>(\sim 10^5) (\sim 30) (sel)</td>
<td>couplings to fermions</td>
</tr>
<tr>
<td>(H \rightarrow \tau\tau)</td>
<td>had tau, leptons, MET</td>
<td>low O(0.1)</td>
<td>15%</td>
<td>(\sim 10^4) (\sim 20) (sel)</td>
<td>couplings to fermions</td>
</tr>
<tr>
<td>(H \rightarrow WW)</td>
<td>two leptons with opposite charge MET</td>
<td>medium O(1)</td>
<td>-</td>
<td>(\sim 10^3) (\sim 60) (sel)</td>
<td>cross section, BR, couplings to V</td>
</tr>
<tr>
<td>(H \rightarrow \gamma\gamma)</td>
<td>two photons peak in inv. mass</td>
<td>low O(0.1)</td>
<td>2%</td>
<td>400 (\sim 200) (sel)</td>
<td>H mass, couplings C, discovery</td>
</tr>
<tr>
<td>(H \rightarrow ZZ)</td>
<td>four leptons with right charge peaks in inv. mass (Z and Higgs)</td>
<td>high (&gt;1)</td>
<td>1-2%</td>
<td>20 (\sim 6) (sel)</td>
<td>H mass, discovery</td>
</tr>
</tbody>
</table>

@125 GeV all analysis shows very good sensitivity
- redundant measurement, possibility to compare different decay modes
- allows measurement of Higgs properties
H → bb

- **Two b-jets** with high pT
- Overwhelming background reduced **requiring associated Z,W**
- Analysis improvements wrt 2011 ~ 50% in sensitivity
- Results: **broad excess compatible with presence of 1xSM Higgs**

CMS-HIG-12-019
\[ H \rightarrow \tau\tau \]

- **No significant excess** wrt SM background
  - very broad excess expected
- **Sensitivity close to 1xSM Higgs** (improved by about 70% wrt 2011)

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**CMS-HIG-12-018**
Two leptons with opposite charge

Large missing ET

6 categories
- 0 jet, 1 jet and 2 jet (VBF)
- same and different flavor

Kinematic variables to reject background (most discriminant $\Delta \phi_{ll}$ and $m_{ll}$)

Main background is $t\bar{t}b$ and irreducible $WW$ (from control samples)
H $\rightarrow$ WW: RESULTS

- Broad excess compatible with presence of 1xSM Higgs

CMS-HIG-12-017
• Extremely clean analysis
  – four leptons with proper flavor, tiny contamination from jets
  – **Three modes** $\text{eeee, ee}\mu\mu, \mu\mu\mu$

$>20\%$ improvement for wrt 2011 analysis
Normalization and background shape ok

Excess at ~126 GeV
A bit less abundant than SM prediction (ok within errors)
**H → ZZ: Resulting Limit and P-Value**

- **Excess at ~125.6 GeV**
  - observed $3.2\sigma$, expected $3.8\sigma$

- **Resulting strength at 125.6 GeV**: $\mu = \sigma / \sigma_{SM} \approx 0.7$

- **ZZ alone excludes almost full mass region**

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CMS-HIG-12-016
Analysis very advanced: makes use of several multivariate techniques to enhance the small S/B signal

<table>
<thead>
<tr>
<th>STEP</th>
<th>CRITICAL ISSUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) two isolated photons with large transverse momentum</td>
<td>• isolation to reject γ+jet and QCD background</td>
</tr>
<tr>
<td>2) di-photon mass reconstruction&lt;br&gt;$m_H^2 = 2E_1 E_2 (1 - \cos \theta)$</td>
<td>• vertex determination in presence of multiple interactions pile-up (PU)&lt;br&gt;• energy scale and resolution</td>
</tr>
<tr>
<td>3) signal extraction</td>
<td>• event categories to maximize sensitivity: MVA categories + di-jet (VBF enriched)&lt;br&gt;• background shape</td>
</tr>
</tbody>
</table>
H $\rightarrow \gamma\gamma$: RESULTS

- **4.1 $\sigma$** excess at **125 GeV**
- Very consistent between 2011 and 2012
- Cross-checked with two alternative analyses (including fully cut based). Compatible results

**events weighted by expected S/B**

- CMS Preliminary
- $\sqrt{s} = 7$ TeV, $L = 5.1$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV, $L = 5.3$ fb$^{-1}$

**CMS-HIG-12-015**

Interpretation Requires LEE

- $\sqrt{s} = 7$ TeV, $L = 5.1$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV, $L = 5.3$ fb$^{-1}$

Weighted Events / (1.67 GeV)

- Observed (Asymptotic)
- 1x SM Higgs Expected (Asimov)
- 7 TeV Observed (Asymptotic)
- 8 TeV Observed (Asymptotic)
QUESTIONS ON THE EXCESS

• Is it statistically significant?
• Is it a boson?
• Which is the mass?
• Is it “the” SM Higgs boson?
• Is it “a” Higgs boson?
γγ and ZZ combo only
- 5σ excess (exp. 4.7σ)
- Is it a boson?
  - Yes, for instance
    significance from di-photon channel

adding WW
- 5.1σ excess (exp. 5.2σ)

all channels together
- 4.9σ excess (exp. 5.9σ)
Starting to Measure Properties: Mass of the Boson

- Mass derived from **most sensitive channels** (best resolution)
  - $H \rightarrow \gamma \gamma$
  - $H \rightarrow \gamma \gamma$ dijet (VBF enriched)
  - $H \rightarrow ZZ$
- Likelihood scan (mass vs $\sigma$)
- Systematics mainly from **ECAL energy scale**

$m = 125.3 \pm 0.4 \text{ (stat)} \pm 0.5 \text{ (syst)} \text{ GeV}$
COMPATIBILITY WITH SM HIGGS

- **Best fit SM strength at 125GeV:** $\mu = \sigma / \sigma_{SM} = 0.80 \pm 0.22$
- **Good agreement among modes**
  - **exceptions:** $\tau\tau$ (small), $\gamma\gamma$ (large, about 1.6xSM)
Ratio sensitive to coupling to W and Z bosons \( (g_{HWW}/g_{HZZ}) \)
protected by gauge custodial symmetry

\[ R_{WZ} = \mu_{WW}/\mu_{ZZ} = 0.9^{+1.1}_{-0.6} \]

Another exercise: group couplings in fermionic and vectorial ones \( (C_F, C_V) \)

- Use LO prediction for loops in \( H \rightarrow \gamma\gamma \) and \( H \rightarrow gg \) couplings
- In agreement with SM within 95% CL
- Some tension to be studied with more exclusive channels and data
Beyond Standard Model Searches

- We believe SM is not the ultimate theory. LHC was built to understand if there is new physics at the TeV scale

- Does nature have any additional symmetry? SuperSymmetry (SUSY) is a very appealing theory
  - Light Higgs: Higgs mass is protected in SUSY
  - Dark Matter: SUSY has the possibility to generate DM candidates

- Is there any new force? Is there a new generation of particle? Are there extra-dimensions?

- Broad CMS program for searches
  - I will just show few results from analysis already updated with 8 TeV datasets
General purpose search for SUSY, use $\alpha_T$ and bins in $H_T$ to reduce QCD
Enhancing the sensitivity to third generation squarks introducing b-tag categories
Bkg is data driven from control regions ($\mu$+jets, $\mu\mu$ +jets,$\gamma$+jets)

Interpretation in simplified model where
$$\tilde{g} \rightarrow t \bar{t} \tilde{\chi}_1^0$$
**SUSY SEARCHES @ 8 TeV**

**2 Same sign leptons + b-jets + MET**

- Rare process in SM
- Sensitive to many SUSY models.
- Sensitivity to 3rd generation sparticles via b-tagging.

Also sensitive to anomalous $uu \rightarrow tt$ via $Z'$ (proposed to explain forward-backward $tt$ production asymmetry @ Tevatron)

13 events observed with $H_T > 80$ GeV
Consistent with SM expectation

Exclusion for various SUSY simplified models
Limits in the stop-gluino mass plane up to m(stop) > 700 GeV

- CMS-SUS-12-017
Gauge Mediated SUSY breaking: $\gamma+2$-jets+MET; $\gamma\gamma+$jet+MET

Gravitino is the LSP
Signatures with 1 or more photons

Exclusion is model dependent: in Wino-LSP scenario, chargino decays without photons suppress signal

$\tilde{\chi}^+ \rightarrow \tilde{\chi}^0 + X$  $\tilde{\chi}^0 \rightarrow \gamma \tilde{G}$  Photon

$\tilde{\chi}^+ \rightarrow W + X$  $M(\tilde{\chi}^+) \sim M(\tilde{\chi}^0)$  No photon
NEW RESONANCES @ 8 TeV

8 TeV data extends the reach in the current searches for a possible new resonance

- x10 qq parton luminosity @ 4 TeV mass

No excess seen... Setting limits

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z' (SSM)</td>
<td>2.5</td>
</tr>
<tr>
<td>W' (SSM)</td>
<td>2.8</td>
</tr>
<tr>
<td>E6 (qq)</td>
<td>4.2</td>
</tr>
<tr>
<td>S8 (gg)</td>
<td>2.5</td>
</tr>
<tr>
<td>String resonance (qg)</td>
<td>4.7</td>
</tr>
<tr>
<td>Λ (contact interactions)</td>
<td>9-12</td>
</tr>
</tbody>
</table>

**di-lepton**

**di-jet (qq, qg, gg)**

- CMS-EXO-12-010
- CMS-EXO-12-015
- CMS-EXO-12-016
**Microscopic Black Holes @ 8 TeV**

- Updated also the search for microscopic black holes @ 8 TeV
- Microscopic black holes production possible if Planck scale moved @ O(TeV) (need extra dimensions!)

BH decays very quickly (~$10^{-27}$ s)
Searching for events with high multiplicity of $e, \gamma, \mu, j$ets characterized by large scalar sum $p_T(S_T)$

Limits between 4 and 6 TeV on the black-hole mass
SUMMARY

• CMS is producing new results at very high rate. Looking forward to full 2012 dataset >20fb$^{-1}$

• SM is behaving as better then ever ;-) 
  – Impressive agreement in all corners of phase space which have been studied
  – We have finally observed a new boson at around 125 GeV compatible with the SM Higgs
  – Is it really “the” SM Higgs? We need more data to start assessing its properties.

• No sign of new physics at the horizon, yet :-(
  – Tremendous effort to search in many different directions
  – Most obvious SUSY models are becoming unnatural
  – Many BSM models are being challenged
EXOTICS 95% CL LIMITS

Resonances

4th Generation

Long Lived

LeptoQuarks

Compositeness

Contact Interaction

Black Holes
**ANOMALOUS TRIPLE GAUGE COUPLINGS (ZZZ AND ZZγ)**

Possible vertices using an effective Lagrangian

\[ \mathcal{L}_{ZZZ} = -\frac{e}{M_Z^2} \left[ f_4^V (\partial_\mu V^{\mu\beta}) Z_\alpha (\partial^\alpha Z_\beta) + f_5^V (\partial^\sigma V_{\sigma\mu}) \tilde{Z}^{\mu\beta} Z_\beta \right] \]

ZZZ, ZZγ

\[ (f_4^Z, f_4^\gamma, f_5^Z, f_5^\gamma) = (0,0,0,0)_{\text{SM}} \]

Use no form factors, i.e., \( \Lambda = \infty \)

-0.012 < \( f_4^Z < 0.013 \)
-0.012 < \( f_4^\gamma < 0.013 \)
-0.014 < \( f_4^Z < 0.013 \)
-0.015 < \( f_5^\gamma < 0.015 \)

at 95% CL, the strongest limit to-date

Using \( m_{4l} \) as discriminating variable
Drell Yan Double Differential

- Going double differential
  - Measured DY cross-sections vs mass of the dimuon system and also vs rapidity in 6 mass bins
- Some discrepancies observed for low mass bins
  - Interesting input for PDF fits

Paolo Meridiani
TTBar Spin Correlation

Spin correlation in SM: low $m_{tt\bar{t}}$ prefers aligned orientation, high $m_{tt\bar{t}}$ prefers opposite

$$A = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\downarrow\uparrow) - N(\uparrow\downarrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\downarrow\uparrow) + N(\uparrow\downarrow)}$$

Measurement performed from a fit to the $\Delta\phi_{l^+l^-}$ distribution

$$A = 0.24 \pm 0.02 \text{ (stat)} \pm 0.08 \text{ (syst)}$$

Nice agreement with SM expectation 0.31
Selecting events with MELA>0.5 makes excess more evident

Final discrimination using 2D likelihood approach

Data w.r.t 126 GeV Higgs Expectation