Hints from Run 1 and Prospects from Run 2 at CMS

Qiang Li
Peking University, Beijing, China
2015.07.02
CMS DETECTOR

- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

STEEL RETURN YOKE
- 12,500 tonnes

SILICON TRACKERS
- Pixel (100x150 μm) ~16 m$^2$ ~66M channels
- Microstrips (80x180 μm) ~200 m$^2$ ~9.6M channels

SUPERCONDUCTING SOLENOID
- Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
- Silicon strips ~16 m$^2$ ~137,000 channels

FORWARD CALORIMETER
- Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76,000 scintillating PbWO$_4$ crystals

HADRON CALORIMETER (HCAL)
- Brass + Plastic scintillator ~7,000 channels
2010-2012: Successful Run1

CMS Integrated Luminosity, pp

Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC

- 2010, 7 TeV, 44.2 fb⁻¹
- 2011, 7 TeV, 6.1 fb⁻¹
- 2012, 8 TeV, 23.3 fb⁻¹

The Nobel Prize in Physics 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider."
Observation of the rare $B_s^0 \rightarrow \mu^+ \mu^-$ decay from the combined analysis of CMS and LHCb data

The CMS and LHCb collaborations

2010-2012: Successful Run1 and Standard Model

Rare B decay, Top mass, SM test over vast magnitudes
2010-2012: Successful Standard Model up to ?

CMS/ATLAS Measured Higgs mass works well in SM global fit

\[ V = m_H^2|H|^2 + \lambda|H|^4 \]

Higgs self coupling \( \lambda \) goes to zero or negative at around \( 10^{11} \) GeV
TeV Scale New Physics: Many hints and candidates

- Fine Tuning
- Dark matter
- Gauge Unification
- Flavor structure
- Baryon Asymmetry

\[ \delta M_i^2 = \left( \frac{1}{4} (9g^2 + 3g'^2) - 6y_i^2 + 6\lambda \right) \frac{\Lambda^2}{32\pi^2}. \]

- SUSY
- Extra Dimensions
- Extra Gauge Symmetry: \( W', Z' \)
- Exotic heavy Quarks, Leptons, Leptoquarks …
- Compositeness: contact interaction …
BSM Searches

Resonance
- Excited quarks/gluons
- Extra-dimensions (RS graviton)
- Extended gauge symmetry
- Technicolour
- Composite Higgs

Shape
- \( \ell \ell \)
- HH
- VH
- \( VY \)
- \( VV \)
- \( gg \)
- \( qq \)

Rate
- \( lq, l\gamma, q\gamma, l+MET \) as well

Katharine Leney
Impossible to cover all

Will focus on CMS recent progress from

Higgs
SU(2)Y
Exotics
B2G

especially those related to BSM

DM will be discussed in detail by T. Kamon
Significance ($m_H = 125.0$ GeV)

<table>
<thead>
<tr>
<th>Combination</th>
<th>Expected (post-fit) fit</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ$ tagged</td>
<td>6.3 $\sigma$</td>
<td>6.5 $\sigma$</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$ tagged</td>
<td>5.3 $\sigma$</td>
<td>5.6 $\sigma$</td>
</tr>
<tr>
<td>$H \rightarrow WW$ tagged</td>
<td>5.4 $\sigma$</td>
<td>4.7 $\sigma$</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$ tagged</td>
<td>3.9 $\sigma$</td>
<td>3.8 $\sigma$</td>
</tr>
<tr>
<td>$H \rightarrow bb$ tagged</td>
<td>2.6 $\sigma$</td>
<td>2.0 $\sigma$</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$ tagged</td>
<td>&lt;0.1 $\sigma$</td>
<td>0.4 $\sigma$</td>
</tr>
</tbody>
</table>
Higgs Properties: Width, Spin, CP


arXiv:1411.3441
Heavy SM-like/BSM Higgs

H \rightarrow WW/ZZ, interpreted also in EWK Singlet

H \rightarrow \gamma\gamma, interpreted also in 2HDM
Light Higgs in NMSSM

CMS PAS-HIG-14-030 produced in SUSY cascades and decaying into bbar

arXiv:1506.00424

h → aa + X → 4μ + X

In NMSSM or dark SUSY
Higgs LFV decay: first direct search

2.4σ excess at MH=125GeV
B(H→μτ)<1.51% at 95%C.L.

Limit also given for LFV Yukawa Couplings

arXiv:1502.07400
Charged Higgs

$H^+ \rightarrow \tau \nu + t \rightarrow Jets$

Or

$H \rightarrow \tau \nu + t \rightarrow \mu + J$

Or

$H \rightarrow tb$ with both $t \rightarrow l$
$X \rightarrow \text{HH or Zh/H/A}$

$X =$ spin 0 Radion or spin 2 KK Graviton
arXiv:1503.04114

$A \rightarrow \text{Zh in llbb}$

arXiv:1504.04710

$H/A \rightarrow ZA/H$ in llbb or llττ

CMS PAS HIG-15-001
Multi - jets, b-jets, leptons, MET HT, edges, alphaT, Razor, MT2…

Inclusive searches, 3rd-generation, EWK searches, VBF, RPV, long lived particle

CMSSM or SMS as guidance

Single production mode and 1-or-2 steps’ decay with BR~100%, other SUSY particles are heavy

http://pauli.uni-muenster.de/~akule_01/nllwiki/index.php/NLL-fast
typical limits reach 700 GeV
a number of “holes” in the coverage left, corresponding to
compressed mass spectra resulting in experimental challenges
$m_{\tilde{t}} - m_{\tilde{\chi}} < m_w$

Hard ISR jet, high missing energy, and one or two soft lepton

CMS PAS SUSY-14-021
Unbinned max likelihood fit to $M_{ll}$: a small excess of 2.4σ with an edge at ~80 GeV
Non-SUSY: Exotica and B2G
CMS Searches for New Physics Beyond Two Generations (B2G)

95% CL Exclusions (TeV)

Vector-like Q'
$Z' \rightarrow \tau\tau$

JHEP 04 (2015) 025  CMS PAS EXO-12-046

SSM $Z'<2.9\text{TeV}$, RS $G<2.7\text{TeV}$ for $k/c=0.1$

Non-resonance also covered: CI, ADD
$W' \to l\nu, \tau\nu$


SSM $W' < 3.28 \text{TeV}$

$\sigma \times B$ (fb)

$M_{W'}$ (GeV)

$19.7 \text{ fb}^{-1}$ (8 TeV)

- Observed limit $W' \to ev$
- Observed limit $W' \to \mu \nu$
- Observed limit combined
- Expected limit combined
- Expected limit combined $\pm 1 \sigma$
- Expected limit combined $\pm 2 \sigma$
- SSM $W'$ NNLO
- PDF uncertainty
- $W_{KK}$ with $\mu = 10 \text{ TeV}$ NNLO
- $W_{KK}$ with $\mu = 0.05 \text{ TeV}$ NNLO

Cross section $\sigma \times B$ [fb]

$W' \to \tau\nu$

CMS Preliminary

Limits at 95% CL

$W' \to l\nu$

$\nu$

$\bar{q}$

$W'_{KK}$

$W'$/$W$

$1/\Lambda^2$

$\nu_L$

$\bar{q}_L$

$\nu$

-$\bar{q}$

$\Lambda^2$

$\chi$

$\chi$

$\nu$

$\bar{q}$

$\nu_L$

$\nu_L$

$\nu$

$\bar{q}_L$

$\Lambda^2$

$\chi$

$\chi$

$\nu$

$\bar{q}$

$\nu_L$

$\nu$

$\bar{q}$

$\Lambda^2$

$\chi$

$\chi$

$\nu$

$\bar{q}$

$\nu_L$

$\nu$

$\bar{q}$

$\Lambda^2$

$\chi$

$\chi$

$\nu$

$\bar{q}$

$\nu_L$

$\nu$

$\bar{q}$

$\Lambda^2$

$\chi$

$\chi$

$\nu$
Di-jet resonance


**gg, qq, gq resonance: narrow or wide**

Also for final states including b

Leading 2 jets as seeds \(\rightarrow\) 2 wide jets (DR<1.1)

SSM W’, Z’ < 2TeV
RS G <1.6TeV
Excited b* <1.2-1.6TeV
Di-jet angular distribution: Compositeness and ADD

\[ \chi_{\text{dijet}} = \exp(|y_1 - y_2|) \]


\[
\mathcal{L}_{qq} = \frac{2\pi}{\Lambda^2} \left[ \eta_{LL} (\bar{q}_L \gamma \mu q_L) (\bar{q}_L \gamma \mu q_L) + \eta_{RR} (\bar{q}_R \gamma \mu q_R) (\bar{q}_R \gamma \mu q_R) + 2 \eta_{RL} (\bar{q}_L \gamma \mu q_R) (\bar{q}_L \gamma \mu q_L) \right]
\]

Previous inclusive jet pt search:
Phys. Rev. D 87 (2013) 052017

\[ \Lambda_{LL}^+ < 9.9 \text{ TeV} \text{ and } \Lambda_{LL}^- < 14.3 \text{ TeV} \]
0, 1, 2 lepton category
b-tag category
CA8 CMS Top Tagging for ‘high mass’
CA15 HEPToptagger for ‘low mass’

Narrow width 1%
Wider width 10%
Vector-like Quark

has only vector couplings with the W and Z bosons, thereby evading many electroweak precision tests, e.g. in LH model \( pp \rightarrow T'T' \rightarrow bW: tZ: th \)

\( T' \rightarrow th: 100\% \)

arXiv: 1503.01952

\( T' \rightarrow th \) full hadronic: Top and H tagging

\( bW: tZ: th \quad 50\%: 25\%: 25\% \)


1 or more lepton category

Boosted H tagging

For the first time
**Di-boson Resonance: W-/ H-tagging**


- Recombine jet constituents with C/A or kt while vetoing wide angle ($R_{cut}$) and softer ($z_{cut}$) constituents. Does not recreate subjets but prunes at each point in jet reconstruction

**W-tagging:**
Pruning, CA8, Nsubjettiness

**H-tagging:**
jet/subjet b-tagging

**Tuned parameters:**
$R_{cut}$ and $z_{cut}$

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$$

**TTbar control region** - Scale Factor
Di-boson Resonance: \(VV \rightarrow \ell\nu j, llj, jj\)

Di-boson Resonance: VH

VH: lvbb, lττ, full had

CMS PAS EXO-14-010
arXiv:1502.04994
arXiv:1506.01443
### Run2 and future

<table>
<thead>
<tr>
<th>Year</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Shutdown/Technical stop</td>
<td>Protons physics</td>
<td>Commissioning</td>
<td>Ions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 2015 Phase

<table>
<thead>
<tr>
<th>Phase Description</th>
<th>Days</th>
<th>Physics Efficiency</th>
<th>Integrated Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial low luminosity luminosity run</td>
<td>7</td>
<td>20%</td>
<td>few pb-1</td>
</tr>
<tr>
<td>50 ns intensity ramp-up</td>
<td>21</td>
<td>20%</td>
<td>0.5 fb-1</td>
</tr>
<tr>
<td>25 ns phase beta* = 80 cm</td>
<td>70</td>
<td>30%</td>
<td>8 fb-1</td>
</tr>
</tbody>
</table>

Run2 Start on June/03, 2015, with stable beams at energy 6.5TeV
Run2 and future

<table>
<thead>
<tr>
<th>Year</th>
<th>Peak lumi E34 cm$^{-2}$s$^{-1}$</th>
<th>Days proton physics</th>
<th>Approx. int lumi [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>1.3</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>2016</td>
<td>1.5</td>
<td>160</td>
<td>35</td>
</tr>
<tr>
<td>2017</td>
<td>1.7</td>
<td>160</td>
<td>45</td>
</tr>
<tr>
<td>2018</td>
<td>1.7</td>
<td>40</td>
<td>10</td>
</tr>
</tbody>
</table>

beyond 2025 and up to 2035: HL-LHC  3000fb-1

Mike Lamont, Moriond 2015
Collider Reach

http://collider-reach.web.cern.ch

Run2 1fb-1, already surpass Run1 at ~3TeV
10fb-1 start overtake Run1

Run2 100fb-1 Z’ 3TeV→5-6TeV
CMS Exotics Projecture

CMS projection \( \sqrt{s} = 14 \text{ TeV} \) \( \geq 2 \) leptons

CMS projection \( \sqrt{s} = 14 \text{ TeV} \) \( \geq 1 \) leptons
Summary

- New Physics Searches at the CMS:
  - top down: guided by SUSY and other models
  - bottom up: possible corners/final state combination
- Higgs becomes a tool for new physics search
- Rich results from Run1, hints for Run2. A few excesses here and there to follow.
- Run2 will definitely tell us more

Thank you!
Higgs invisible decay

Combined $\text{Br}(H \rightarrow \text{inv}) < 55\% \ (44\%)$ at 95\% C. L.

VBF result recently updated to <57\% from previous <65\%

Impact on DM Nucleon Xsec in Higgs portal models
at least 2 leptons, large missing transverse momentum, and 2 jets with a large pseudorapidity gap
Can only highlight some recent results
Results of the edge-search counting experiment for event yields in the signal regions. The statistical and systematic uncertainties are added in quadrature, except for the flavor-symmetric backgrounds. Low-mass refers to $20 < m_{ll} < 70$ CMS.GeV, on-Z to $81 < m_{ll} < 101$ CMS.GeV, and high-mass to $m_{ll} > 120$ CMS.GeV.

<table>
<thead>
<tr>
<th></th>
<th>Low-mass</th>
<th></th>
<th>On-Z</th>
<th></th>
<th>High-mass</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Central</td>
<td>Forward</td>
<td>Central</td>
<td>Forward</td>
<td>Central</td>
<td>Forward</td>
</tr>
<tr>
<td>Observed</td>
<td>860</td>
<td>163</td>
<td>487</td>
<td>170</td>
<td>818</td>
<td>368</td>
</tr>
<tr>
<td>Flavor-symmetric</td>
<td>$722 \pm 27 \pm 29$</td>
<td>$155 \pm 13 \pm 10$</td>
<td>$355 \pm 19 \pm 14$</td>
<td>$131 \pm 12 \pm 8$</td>
<td>$768 \pm 28 \pm 31$</td>
<td>$430 \pm 22 \pm 27$</td>
</tr>
<tr>
<td>Drell–Yan</td>
<td>8.2 ± 2.6</td>
<td>2.5 ± 1.0</td>
<td>116 ± 21</td>
<td>42 ± 9</td>
<td>2.5 ± 0.8</td>
<td>1.1 ± 0.4</td>
</tr>
<tr>
<td>Total estimated</td>
<td>730 ± 40</td>
<td>158 ± 16</td>
<td>471 ± 32</td>
<td>173 ± 17</td>
<td>771 ± 42</td>
<td>431 ± 35</td>
</tr>
<tr>
<td>Observed—estimated</td>
<td>$130^{+48}_{-49}$</td>
<td>$5^{+20}_{-20}$</td>
<td>$16^{+37}_{-38}$</td>
<td>$-3^{+20}_{-21}$</td>
<td>$47^{+49}_{-50}$</td>
<td>$-62^{+37}_{-39}$</td>
</tr>
<tr>
<td>Significance</td>
<td>2.6 $\sigma$</td>
<td>0.3 $\sigma$</td>
<td>0.4 $\sigma$</td>
<td>&lt;0.1 $\sigma$</td>
<td>0.9 $\sigma$</td>
<td>&lt;0.1 $\sigma$</td>
</tr>
</tbody>
</table>
RS Graviton: $\gamma \gamma$
CMS PAS EXO-12-45

19.5 fb$^{-1}$ (8 TeV)

$M_{\gamma \gamma}$ (GeV)

Events / 20 GeV

Data
SM Diphoton
Photon+Jet
Jet+Jet
DY, W$\gamma$, Z$\gamma$

CMS Preliminary

RS G <2.78 TeV for $k/c=0.1$

WZ-$llv$ resonance

$M_{W',\rho_{TC}}$ (GeV)

$\sigma \cdot B$ (pb)

Observed 95% CL
Expected 95% CL
Expected ± 1σ
Expected ± 2σ
$\sigma_W$
**Excited quark: q+γ**

\[ L_{\text{int}} = \frac{1}{2\Lambda} \overline{q} R \sigma^{\mu
u} \left[ g_s f_s \frac{\lambda}{2} G^a_{\mu
u} + g f_{\tau} T^{\mu\nu} + g' f' Y B_{\mu
u} \right] q_L + \text{h.c.} \]


Focus on \( \Lambda = M q^* \)

And \( f_s = f = f' \sim O(1) \)

---

Bkg fit by

\[ \frac{d\sigma}{dm} = \frac{P_0(1 - m/\sqrt{s})^p_l}{(m/\sqrt{s})^{p_2 + p_3 \ln(m/\sqrt{s})}} \]
Excited lepton: $l^* + \gamma$

$$\mathcal{L}_{CI} = \frac{g^2}{2 \Lambda^2} j^\mu j_\mu$$
$$\mathcal{L}_{GM} = \frac{1}{2 \Lambda} f_R^* \sigma^{\mu \nu} \left( 8f f' W_{\mu \nu} + g' f' B_{\mu \nu} \right) f_L + h.c.$$
Fat Jet at CMS: an incomplete history

7TeV Z’-&gt;ttbar: Proposed Jet Pruning, C-A 0.8 Jet, TTbar control

7TeV WZ/ZZ resonance:
Jet mass, mass drop
JHEP 1302 (2013) 036

Dijets and V+jets,
jet mass and substructure at 7 TeV:
Comprehensive overview of various jet grooming techniques
JHEP 1305 (2013) 090

8TeV WW/WZ/ZZ resonance:
W-tagging, Pruning, CA8, Nsubjettiness

W-tagging Summary: JHEP 1412 (2014) 017

Top tagging …….
Efficiency of reconstructing either the simulated $W$ or simulated decaying quarks from the $W$ with a single generator level CA8 jet or two generator level AK5 jets. Matching of generator level jets to the simulated $W$ and simulated quarks are required within $\Delta R < 0.1$.

Efficiency of the pruned jet mass cut and the $\tau_2/\tau_1$ cut combined with the pruned jet mass cut on WW signal samples as a function of $p_T$. 

Efficiency of reconstructing either the simulated $W$ or simulated decaying quarks from the $W$ with a single generator level CA8 jet or two generator level AK5 jets. Matching of generator level jets to the simulated $W$ and simulated quarks are required within $\Delta R < 0.1$. 
Fraction of jets passing the pruned jet mass and tau2/tau1 cuts in data and simulation as a function of pT. The data over simulation ratio is shown for the combination of the pruned jet mass and tau2/tau1 cuts.
The typical width of the Gaussian core is about 3%–5% of the nominal mass in the ll+V-jet channel or 4%–6% for the lv+V-jet channel.
CMS, $L = 19.7$ fb$^{-1}$, $\sqrt{s} = 8$ TeV

- **VV dijet**

- $\sigma \times B(G_{RS} \rightarrow WW)$ (pb)
  - Observed
  - Expected (68%)
  - Expected (95%)
  - $G_{RS} \rightarrow WW (k/M_p = 0.1)$

- $\sigma \times B(G_{RS} \rightarrow ZZ)$ (pb)
  - Observed
  - Expected (68%)
  - Expected (95%)
  - $G_{RS} \rightarrow ZZ (k/M_p = 0.1)$

- High-purity single W/Z-tag

- $\sigma \times B(q^* \rightarrow qW)$ (pb)
  - Observed
  - Expected (68%)
  - Expected (95%)
  - $q^* \rightarrow qW$
Higgs Tagging: a bit beyond W-tagging

1. Mass of the H-jet as the main discriminating variable against QCD jets

**Boosted H-boson:**

- b-quarks merged into a single jet
- reconstructed with CA algorithm with $R=0.8$
- traditional dijet searches cannot be performed
- **use jet substructure techniques**

**H-tagged jet** $\Rightarrow 110 < m_{\text{jet}}^{\text{pruned}} < 135$ GeV

Jet substructure: jet pruning

- removes the softest components of a jet
- improves discrimination by pushing the jet mass for QCD jets towards lower values while maintaining the jet mass for the H-jet at the H-mass
- studied in detail for W-tagging: JME-13-006

2. Discriminate b-quark initiated jets from light quark or gluon jets

**Combined b-tagging:**

**Subjet b-tagging**  
**Fat jet b-tagging**

- use CSV b-tagging algorithm
- the jet is split into 2 subjets by undoing the last iteration of the pruned jet clustering
- **subjet b-tagging:** apply b-tagging to the subjets if $\Delta R > 0.3$
- **fat jet b-tagging:** when the subjets are too close ($\Delta R < 0.3$) apply b-tagging to the CA8 jet
- studied in detail in BTV-13-001

worse performance because JTA cones overlap
CMS PAS EXO-14-010 Final $M_{WH}$ distribution

- Good data/MC agreement in the muon channel
- Excess of 3 events in the electron channel with $M_{WH} > 1.8$ TeV where less than 0.3 are expected
Long Lived Particles

- Stopped in the calorimeter: **R-hadrons** using the time intervals between LHC beam crossings
- Displaced dilepton: $H \to XX, X \to l^+ l^-$; $\tilde{q} \to q\tilde{x}^0, \tilde{x}^0 \to l^+ l^- \nu$
- Displace dijet: $H \to XX, X \to q\bar{q}$; $\tilde{q} \to q\tilde{x}^0, \tilde{x}^0 \to jj\mu$

Set limits on lifetime of the long-lived particle