Searches for Resonant and Non-resonant Phenomena in CMS

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On behalf of the CMS Collaboration

QCD@LHC, September 2\textsuperscript{nd} 2015
Outline

• Leptonic channels at 8 TeV
  – Dilepton (ee, \(\mu\mu\))
  – Multilepton
  – \(W'\)
  – Ditau

• Jet channels at 8 TeV
  – Dijet
  – Multijet

• Bosonic channels at 8 TeV
  – Diphoton
  – Diboson

• Preliminary results at 13 TeV data

- Searches for t/b quarks channel will be discussed a talk by F. Margaroli on Wed. in “Heavy Quarks” session
CMS Detector

**Pixels Tracker**
- Pixels (100 x 150 μm²)
  - ~1 m²: 66M channels
- Microstrips (50-100 μm)
  - ~210 m²: 9.6M channels

**ECAL**
- Crystal Electromagnetic Calorimeter (ECAL)
  - 76k scintillating PbWO₄ crystals

**HCAL**
- Preshower
  - Silicon strips
    - ~16 m²: 137k channels

**Solenoid**
- Steel Return Yoke
  - ~13000 tonnes

**Steel Yoke**
- Steel Return Yoke
  - ~13000 tonnes

**Muons**
- Superconducting Solenoid
  - Niobium-titanium coil carrying ~18000 A

**Hadron Calorimeter (HCAL)**
- Brass + plastic scintillator

**Muon Chambers**
- Barrel: 250 Drift Tube & 500 Resistive Plate Chambers
- Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers

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Total weight: 14000 tonnes
Overall diameter: 15.0 m
Overall length: 28.7 m
Magnetic field: 3.8 T

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September 2nd, 2015  H.D. Yoo, SNU
Dilepton (ee, μμ)

- Model independent shape-based search for a narrow resonance
  - Further interpretations of high mass dilepton
- Standard CMS high pT muon/electron id and event selection are used
- Dominant background
  - Drell-Yan, t\(\bar{t}\), tW, diboson
  - Jets misidentified as leptons (W+jets, QCD)
- Highest mass event: 1.79 TeV (ee), 1.87 TeV (μμ)

JHEP 04 (2015) 025
Dilepton (ee, μμ)

Limit on the resonance mass M:
- $M(Z'_{SSM}) > 2.90$ TeV, $M(Z'_{Ψ}) > 2.57$ TeV

**Interpretation using 2 non-resonant analyses**
- Large extra dimension
- Compositeness

Limits on $M_{S}$ scale as a function of the $n_{ED}$

JHEP 04 (2015) 025
Lepton Flavour Violation

- Decays of $Z \rightarrow e\mu$
  - New physics like massive Dirac or Majorana neutrinos or R-parity SUSY
- Oppositely charged $e$ and $\mu$
- Dominant background: $Z \rightarrow \tau\tau$

Br($Z \rightarrow e\mu$) < 7.3$\times$10$^{-7}$

CMS-PAS-EXO-13-005
Lepton Flavour Violation

- Decays of new heavy resonances
  - Resonant $\tilde{\nu}_\tau$ LSP production in RPV SUSY
  - LFV gauge boson ($Z'/a'$) exist and generate transitions between families
    - RPV: $M(\nu_\tau) > 1.3$ TeV
    - QBH: $M_{th} > 2.36 (3.6)$ TeV for $n_{ext} = 1 (6)$

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CMS-PAS-EXO-13-002

- $\tilde{\nu}_\tau$ LSP production in RPV SUSY
- LFV gauge boson ($Z'/a'$) exist and generate transitions between families
- RPV: $M(\nu_\tau) > 1.3$ TeV
- QBH: $M_{th} > 2.36 (3.6)$ TeV for $n_{ext} = 1 (6)$

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Excited Leptons

- Look for single production of excited lepton
  - Final state with $llZ$: Z boson is boosted
  - Relaxed isolation is applied

- $ll\gamma$ final state: $M(l^*) < 2.45 (2.48)$ TeV for $e(\mu)$
- $llZ$ final state: $M(l^*) < 2.35 (2.38)$ TeV for $e(\mu)"

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CMS

Preliminary

**ee*→eeγ**

**ee*→eeZ→eej**

**ee*→eeZ→eee**

**ee*→eeZ→ee\mu\mu**

**ee*→eeZ→eell**

**\mu\mu*→\mu\gamma**

**\mu\mu*→\mu\muZ→\mu\mujj**

**\mu\mu*→\mu\muZ→\mu\mu\mu**

**\mu\mu*→\mu\muZ→\mu\mu\mu**

**\mu\mu*→\mu\muZ→\mu\mu\mu**

**\mu\mu*→\mu\muZ→\mu\mu\mu**

Excluded mass for $\Lambda = M_{l^*}$ (TeV)

- $f = f' = 1$

- $f = -f' = 1$

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CMS-PAS-EXO-14-015

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

CMS Preliminary

$ee^* \rightarrow ee\gamma$

- $ee^*(MC)$
- $\gamma$ fake
- electron fake
- data
- sys uncert.

- Signal: $M_{l^*}=200$ GeV
- Signal: $M_{l^*}=1000$ GeV

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September 2nd, 2015

H.D. Yoo, SNU

slide 8
Heavy Lepton Partners of Neutrinos

• Look for triplet state: $\Sigma^0$, $\Sigma^{+/ -}$
  – Type III seesaw
  – Can explain why the neutrino has a mass and it is small
  – 3 isolated leptons and large MET in the final state

CMS-PAS-EXO-14-001

$M > 280$ GeV
With $V_e = V_\mu = V_\tau = 10^{-6}$
**W’\rightarrow l\nu (e or \mu)**

- New heavy gauge bosons can appear in many BSM models
  - SSM, RS gravitons, composite Higgs, etc.
  - Signature based to cover all possible scenarios and interpret in many benchmark signal models
- **W’** couples to fermions as the SM **W**

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**PRD 91 (2015) 092005**

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**Graphical Abstract:**

**Graph 1:**
- Legend: CMS, W' \rightarrow \mu, v, M = 2000 GeV
- HNC CI \rightarrow \mu, v, \Lambda = 4000 GeV
- DM, \Lambda = 200 GeV, M_\chi = 300 GeV, \chi = +1

**Graph 2:**
- CMS, Observed limit e + E_T^miss
- Observed limit \mu + E_T^miss
- Expected limit combined

**Equation:**

\[ M(W'_{SSM}) > 3.28 \text{ TeV} \]
• Test a possible non-universal coupling
• Consider hadronic decay of the $\tau$-lepton
• Distribute the $M_T$ variable

CMS-PAS-EXO-12-011
Submitted to PRL
(arXiv: 1508.04308)
• Consider $\tau_e - \tau_\mu$ final states (e\(\mu\) channel)
• Main backgrounds: ttbar, dibosons, Drell-Yan, multijet from QCD

**Ditau**

**CMS-PAS-EXO-12-046**

- M($Z'_\text{SSM}) > 1.3 \text{ TeV}$
- M($Z'_\Psi > 0.8 \text{ TeV}$

$\Lambda_T > 2.8 \text{ TeV}$

`0.7`  `0.8`  `0.9`  `1.0`  `1.1`  `1.2`  `1.3`

0  500  1000  1500  2000  2500  3000

Events

10^0  10^1  10^2  10^3  10^4

Data  Bkg

$\Lambda_T > 2.8 \text{ TeV}$
Dijet

- Search for hint of new physics in the dijet mass spectra for narrow/wide resonances
- Geometrically close jets (dR < 1.1) combined into wide jets: use to measure $m_{jj}$
- Highest dijet mass is at 5.15 TeV

![Graph showing dijet mass spectra](image)

<table>
<thead>
<tr>
<th>Residuals</th>
<th>95% CL upper limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>gluon-gluon</td>
</tr>
<tr>
<td>2000</td>
<td>quark-gluon</td>
</tr>
<tr>
<td>3000</td>
<td>quark-quark</td>
</tr>
</tbody>
</table>

**PRD 91 (2015) 052009**

- String res. < 5.0 TeV
- Excited quarks < 3.5 TeV
- Scalar diquarks < 4.7 TeV
- $W'$ (SSM) < 2.2 TeV
- $Z'$ (SSM) < 1.7 TeV
- RS(g, c=0.1) < 1.6 TeV
Multijet

- Pair produced resonances decaying to jets: \( X \rightarrow YY, Y \rightarrow jj \)
  - Exclude top squark masses for decays to light (heavy) jets in range
  - \( 200 < m(jj) < 350 \) (385) GeV

PLB 747 (2015) 98
Diphoton

- Look a signature of an excited state of the graviton in the RS model
  Simple final state, large background
- Background: SM diphoton, photon+jet or di-jet processes (jets identified as photons)
- Limits on $M(G_{RS})$: $1.45 - 2.78$ TeV for $0.01 < k/M_{Pl} < 0.1$

CMS-PAS-EXO-12-045
Diboson

- Massivie resonances in dijet (multijet) searches with W, Z tagging
  - Used jet-substructure for boosted signature
  - GRS→WW (left), WZ (middle), WH→llbb (right) resonances

JHEP 08 (2014) 173

CMS PAS EXO-14-010

CMS, L = 19.7 fb⁻¹, √s = 8 TeV

• Small excess around 1.8 TeV (1.5σ in VV, ~2.0σ in VH)
  - Enhanced in exclusive decay modes
Status of LHC Run II

- Run II operation with 50ns completed successfully
  - Start 25ns operation from August
  - Performance studies are on-going

**CMS Integrated Luminosity, pp, 2015, \( \sqrt{s} = 13 \) TeV**

Data included from 2015-06-03 08:41 to 2015-08-25 05:56 UTC

- LHC Delivered: 205.76 \( \text{pb}^{-1} \)
- CMS Recorded: 175.17 \( \text{pb}^{-1} \)

CMS Preliminary Calibration
First 13 TeV Collision!!

- LHC collides protons at 13 TeV
  - Physics run started from June 3rd!!!
Resonances

Special Triggers

In certain mass regions and with different $p_T$ cuts

$\mathbf{B}_s^0 \rightarrow \mathbf{J/}\psi \ \phi$

with displaced $\mathbf{J/}\psi + \text{track trigger}$

\begin{align*}
\text{Mass:} & \quad 5.369 \pm 0.001 \text{(stat.) GeV} \\
\text{PDG:} & \quad 5366.7 \pm 0.4 \text{ MeV}
\end{align*}
Z Boson Resonance

**Z → ee**

**Z → μμ**

**Z → ττ**

Z – Boson as standard physics candle
Dijet Search at 13 TeV

- With 42/pb expect to exceed the sensitivity of 8 TeV analyses only for narrow resonances with masses $\approx 5$ TeV
- The dijet mass distribution is fitted using 4-parameter function

CMS PAS EXO-15-001
Dilepton Search at 13 TeV

- Two isolated leptons are required
- Highest mass events are observed at around 1 TeV for dielectron and dimuon channels
- Run 1 sensitivity will be reached after about 2/fb
Dielectron Event at ~3 TeV

In the additional 25 pb\(^{-1}\) data @13 TeV and 50 ns processed last Wednesday:

An event with a di-electron mass of 2.9 TeV has been observed

The event consists in two perfectly balanced electrons and no other significant activity

M = 2.9 TeV !!!
Summary

• Many searches for new physics are delivered with Run I data and stay tuned with new 13 TeV results from CMS
CMS After Long Shutdown 1

Tracker: ~1 m² Pixels (66M)
~200 m² Si microstrips (2M)
New Photosensors
Tracker / Pixel: Cold Operation Channel Recovery

Iron Yoke
4 stations of muon detectors
4th Muon Station

New Beampipe

New Detectors for Luminosity

ECAL: Electromagnetic calorimeter - 76K PbWO₄ crystals

14,000 tons
21 m long
15 m diameter

HCAL: hermetic Brass/Scintillator sampling hadronic calorimeter

New Computers
Improved Trigger

DAQ and HLT:

3.8 T Solenoid
Detector Commissioning

- All sub-detectors ready for data-taking
- Active channel fraction higher than Run 1

**Active Detector Fraction Run 1 to Run 2**

<table>
<thead>
<tr>
<th>Detectors</th>
<th>End Run 1 (Feb 2013)</th>
<th>Start Run 2 (Jul 2015)</th>
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<tbody>
<tr>
<td>Pixel</td>
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<td>Strip</td>
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<td>EB+EE</td>
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<td>CSC</td>
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Luminosity Ratio

ratios of LHC parton luminosities: 13 TeV / 8 TeV

In gg fusion:
for $\sqrt{s} = 1$ TeV, x6;
for $\sqrt{s} = 2$ TeV, x15;
for $\sqrt{s} = 3$ TeV, x45;
for $\sqrt{s} = 4$ TeV, ~x200.

In qq, ~x2 less
LHC Operation

Energy increase 8 TeV to 13/14 TeV
Injection upgrade

LHC

Energy increase 8 TeV to 13/14 TeV
Injection upgrade

HL-LHC

Peak luminosity [cm^{-2}s^{-1}]

\[ P_U = \begin{cases} 100 \text{@25ns} \\ 200 \text{@50ns} \end{cases} \]

\[ P_U = \begin{cases} 50 \text{@25ns} \\ 100 \text{@50ns} \end{cases} \]

\[ P_U = \begin{cases} 25 \text{@25ns} \\ 50 \text{@50ns} \end{cases} \]

F. Zimmermann, CMS Upgrade Workshop, 11/2011

Integrated luminosity [fb^{-1}]

Luminosity leveled at 5x10^{34} cm^{-2}s^{-1} in HL-LHC

LS- Long Shutdown

Interaction region upgrade

Phase 1 Upgrade

Phase 2 Upgrade

8x10^{33} Hz/cm^2
30 fb^{-1}

2x10^{34} Hz/cm^2
300 fb^{-1}

10^{35} Hz/cm^2
3000 fb^{-1}
The restart of the CMS magnet after LS1 was more complicated than anticipated due to problems with the cryogenic system in providing liquid Helium.

Inefficiencies of the oil separation system of the compressors for the warm Helium required several interventions and delayed the start of routine operation of the cryogenic system.

Currently the magnet can be operated, but the continuous up-time is still limited by the performance of the cryogenic system requiring more frequent maintenance than usual.

A comprehensive program to re-establish its nominal performance is underway. These recovery activities for the cryogenic system will be synchronized with the accelerator schedule in order to run for adequately long periods.

A consolidation and repair program is being organized for the next short technical stops and the long TS at the end of the year.
Sensitivity at 2 TeV: Electron Excess

- An excess with $2.8\sigma$ @ 2.1 TeV visible on the eejj invariant mass in the search for $W_R$ (not observed the excess in mumujj)
- Similar excess (@ 650 GeV) is observed in both eejj and evjj channel in leptoquarks searches (dominated by evjj)
Sensitivity at 2 TeV: Dijet

- CMS observed ~2.0σ (local) and ATLAS also did small excess (but not much like CMS)
- This is the ONLY place where both experiments observed with limit > expectation!!

![Graph showing gg resonance mass (GeV)](image)

![Graph showing σ x A (pb)](image)
Z’ Projection at 14 TeV

- Projection of discovery reach at 14 TeV with 300, 1000, 3000/fb
- Used in Snowmass white paper
- Studies are based on generator level extrapolations and scaling of 8 TeV results

Important to understand the future expectation to decide the detector upgrade plan

CMS-NOTE-13-002 (2013)