CMS Highlights

«ETTORE MAJORANA» FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE
INTERNATIONAL SCHOOL OF SUBNUCLEAR PHYSICS
54th Course: THE NEW PHYSICS FRONTIERS IN THE LHC–2 ERA

June 17, 2016

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Princeton University
LHC complex at CERN

The LHC is a 27km proton synchrotron 100m below the Swiss and French countryside near Geneva. It is designed to collide protons at center of mass energies up to 14 TeV.
LHC Physics Goals

- Discover or exclude the Higgs boson in the mass range ~100 to 1000 GeV
- Search for new phenomena up to ~10 TeV:
  - Supersymmetry
  - Dark Matter
  - Black Holes
  - Extra Dimensions
  - Unknown unknowns...

- 1984: First studies
- 1994: LHC approved
- 1996: Construction starts
- 2003: Start installation
- 2009: First collisions
- 2012: H125 Discovery
Run 1 Legacy

502 Run 1 publications (so far)

1 Higgs boson

Many precision SM measurements

Many BSM searches, a few bumps
CMS activity during the Year End Technical Stop (YETS)
The CMS Collaboration

4400+ members, 700+ students, ~1000 eng/tech, 200+ institutions from 40+ countries
CMS "nip and tuck" in LS1

3.8 T Solenoid
(problems with the cryo system in 2015 led to ¼ of the data being recorded with the field off)

12,500 tons
21 meters long
15 meters in diameter

Silicon Tracker
Recovery of tracker channels, new dry air plant

Silicon Tracker
Silicon pixel sensors (66M chs)
Silicon strip sensors (9.6M chs)

4 Layers of Muon Detectors
Completion of 4\textsuperscript{th} muon layer

Calorimeters
New HCAL photosensors

Electromagnetic: 76k PbWO\textsubscript{4} crystals
Hadronic: brass/scintillator sampling

New Beam Pipe
New Pixel Luminosity Telescope
New DAQ and upgraded trigger
CMS Solenoid

- Largest superconducting magnet ever build (12,000 tonnes, 7m dia)
- **3.8 T at center of CMS**
- Coils must be kept at a few Kelvin using liquid helium produced on site at CMS
- In 2015, CMS suffered contamination of the He filtration system, causing instabilities and leading to **25% of data taken @ 0T**
Cyrosystem Interventions

- Intense program to refurbish the cryogenic system in time for collisions in 2016
- Thorough cleaning to remove oil contaminant (Breox)
- Replacement of primary oil removal system

“Cold Box” performing better than ever:
He liquefaction rate better than previously ever achieved
The moment of truth... is it oil?

Eventually, 370g of oil removed from cryogenic system, all evidence consistent with this being the source of contamination.
New Oil Removal System Installed

Capacity increased significantly

Primary Oil Removal system

New oil coalescers

Commissioned, connected to the Coldbox

Old system
Early 2016 performance: perfect!

What we like to see: “brain dead signals” (Austin Ball)

A warm thanks to colleagues from CERN-TE dept, technical support from other CERN depts, CERN-EN,EP, CERN Management, CMS Magnet team and integration office, contractors (particularly Altead, ZEC service), CMS members for support and advice.
LHC and CMS: current status
LHC Performance in 2016: phenomenal

Fastest luminosity ramp to date
Record inst. lumi: $\sim 0.8 \times 10^{34} \text{ cm}^{-2} \text{/s}$
Still some room for improvement:
See talk by E. Métral @ LHCP 2016

Thank you, LHC!!
13 TeV dataset: 2015 and 2016

**Luminosity uncertainty:**
2.7% (CMS-LUM-15-001)

Now collected more luminosity in 2016 than in 2015 (> 3.5 fb⁻¹)

CMS collecting \(~400\text{pb}^{-1} / \text{day}\)

CMS Integrated Luminosity, pp, 2015, \(\sqrt{s} = 13\text{ TeV}\)
Data included from 2015-06-03 08:41 to 2015-11-03 06:25 UTC

LHC Delivered: 4.22 fb⁻¹
CMS Recorded: 3.81 fb⁻¹

Usable @ 3.8 T: 2.7 fb⁻¹
Usable @ 0 T: 0.6 fb⁻¹

CMS Offline Luminosity (Preliminary)

CMS Integrated Luminosity Per Day, pp, 2016, \(\sqrt{s} = 13\text{ TeV}\)
Data included from 2016-04-22 22:48 to 2016-06-14 07:36 UTC

LHC Delivered, max: 392.2 pb⁻¹/day
CMS Recorded, max: 368.8 pb⁻¹/day

CMS Offline Luminosity (Preliminary)
CMS seeks to trigger on and reconstruct, with high efficiency and high purity, muons, electrons, taus, photons, hadrons (charged and neutral), and jets (light and heavy)
pile-up (PU)

At this high luminosity, multiple collisions per beam-crossing occur.

Experimental challenge to cope with high PU.

Reconstruction and analyses are designed to be robust against PU.

p → ≈ 10 cm → p

78 reconstructed vertices
L1 Trigger Performance

Muons

- Fully efficient above 20 GeV

Jets

- Stable against PU

Taus

- Fully efficient above 40 GeV

e/γ

- Fully efficient above 28 GeV
Muon and Tracker Performance

CMS Highlights - New Physics Frontiers in the LHC-2 Era

June 17, 2016
Jet energy scale calibrated using Z/photon + jet balancing, similar performance as in Run 1
Jet energy resolution robust against pile-up above 100 GeV
Missing Transverse Energy (MET)

Critical for new physics searches (think SUSY and Dark Matter)

“Out of the box” MET performance (final calibration not yet applied)

“Cleaning” procedure working well, removal of long MET tails
Taus and b tagging

Tau reconstruction and b-jet tagging well understood in MC
B-jet tagging efficiency of 80% for light quark efficiency of 3%
CMS Publication Status

Physics Papers:

- **Exotica**: 104
- **Standard Model**: 85
- **Higgs boson**: 67
- **Supersymmetry**: 64
- **Top quark**: 58
- **Heavy Ion**: 45
- **B physics**: 33
- **Forward physics**: 26
- **Beyond 2 gen**: 16

512 Publications submitted or published

Run 2 publications:
10 papers submitted

- $dN/d\eta$ – first 13 TeV paper (published)
- Search for dijet resonances (published)
- $t\bar{t}$ cross section in dileptons (published)
- Two-particle correlations “the ridge” (accepted)
- SUSY search in jets+MET (published)
- SUSY search in all-hadronic (Ref comments)
- SUSY search in 1 lepton (Ref comments)
- SUSY search in SS dilepton (Ref comments)
- Inclusive jets @ 13 TeV (submitted)
- Search for diphoton resonances (submitted to PRL Jun 13)

100 public results on 13 TeV so far!! (from 2015 data)


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**CMS Highlights - New Physics Frontiers in the LHC-2 Era**

June 17, 2016
Sensitivity: 13 vs. 8 TeV

Predicted cross-section ratios

(\sigma \cdot L)_{13 \, \text{TeV}} > (\sigma \cdot L)_{8 \, \text{TeV}}

ICHEP dataset (\sim 10/fb)

2015 dataset

2016 dataset (\sim 20/fb)
Recent Physics Highlights: 

*Standard Model Measurements*
Re-establishing H(125) @ 13 TeV

- First look at H(125) in Run 2
  - \( ZZ(4l): \sigma_{\text{fid}} = 2.48^{+1.48}_{-1.14} \text{ fb} \) [2.5\( \sigma \)]
  - \( \gamma\gamma: \mu = 0.69^{+0.47}_{-0.42} \) [1.7\( \sigma \)]
  - Results consistent with SM expectation
Revisiting a Higgs anomaly: ttH

- ~2σ excess for ttH search in Run 1
  - High priority to investigate in Run 2
  - Complicated analyses requiring careful control of $t\bar{t}$ backgrounds
- First look at ttH in 13 TeV data
  - Multilepton, bb, and $\gamma\gamma$ final states
  - All results consistent with SM

Run 1

Run 2

Higgs → Fermions @ 13 TeV

\[ pp \rightarrow q\bar{q}'H(\bar{b}b) \]

- Search for MSSM Higgs bosons decaying to tau pairs in 2.3fb\(^{-1}\)
- No signal found, limits already exceed Run 1 limits for large mass
Top Cross Section

Inclusive $t\bar{t}$ cross section [pb]

- Tevatron combined 1.96 TeV ($L \leq 8.8$ fb$^{-1}$)
- CMS $e\mu$ 5.02 TeV ($L = 26$ pb$^{-1}$)
- CMS $e\mu$ 7 TeV ($L = 5$ fb$^{-1}$)
- CMS I+jets 7 TeV ($L = 2.3$ fb$^{-1}$)
- CMS all-jets 7 TeV ($L = 3.54$ fb$^{-1}$)
- CMS $e\mu$ 8 TeV ($L = 19.7$ fb$^{-1}$)
- CMS I+jets 8 TeV ($L = 19.6$ fb$^{-1}$)
- CMS all-jets 8 TeV ($L = 18.4$ fb$^{-1}$)
- CMS $e\mu$ 13 TeV ($L = 43$ pb$^{-1}$, 50 ns)
- CMS I+jets 13 TeV ($L = 2.2$ fb$^{-1}$, 25 ns)
- CMS all-jets 13 TeV ($L = 2.53$ fb$^{-1}$)

CMS Preliminary

June 2016

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

- NNPDF3.0
- MMHT14
- CT14
- ABM12*

Czakon, Fiedler, Mitrov, PRL 110 (2013) 252004

NNPDF3.0, $m_{top} = 172.5$ GeV, $\alpha_s(M_Z) = 0.118 \pm 0.001$ [$\alpha_s(M_Z) = 0.113$]
Summary of SM Cross Sections

All measurements consistent with the Standard Model prediction.
Toward a measurement of $m_W$

- First “W-like” measurement of $m_Z$
  - Remove one muon, treat like $W \rightarrow \mu \nu$
  - Three techniques using $p_T$, $m_T$, $E_{T\text{miss}}$
  - Exquisite control of muon momentum scale (at $10^{-4}$ level)
New technique to measure $m_t$

- Use ttbar events where b hadron from top quark decays to J/ψ
- top quark mass approximated by mass of J/ψ-lepton pair (only leptons used!)
- $M_t = 173.5 \pm 3.0 \text{ (stat)} \pm 0.9 \text{ (syst)} \text{ GeV}$
Recent Physics Highlights:

Status of Run 1 bumps @ 13 TeV
Search for diboson resonances

- **Run 1:** CMS $\sim 2\sigma$ excess near 1.8-2.0 TeV
- Repeat search at 13 TeV using most sensitive channels: $l\nu J$, JJ
- **Analysis categorized in dijet mass** for optimal sensitivity to WW, WZ, ZZ signals
- **13 TeV:** no excess observed in the region of interest near 2 TeV
  - More data needed to fully exclude Run 1 excess
Combination of Diboson Results

HVT (Heavy Vector Triplet) model

Not much at 2 TeV, something growing at 3 TeV in Run 2?

Graviton scenario

 CMS Highlights - New Physics Frontiers in the LHC-2 Era  
 June 17, 2016
Opposite-sign dileptons

- **Bumps in Run 1**
  - **Off-peak:** CMS saw excess ("the edge"), no excess in ATLAS
  - **On-peak:** ATLAS saw excess in high $H_T$ region, no excess in CMS

- **Important ‘first look’ channel for Run 2**
Opposite-sign dileptons: 13 TeV

- Off-peak selection similar to Run 1, on-peak analysis now includes a region targeting the ATLAS excess.
- **No significant signals are observed:**
  - Upper limits are below predicted yields scaling from the Run 1 excesses.
  - For gluino masses in the range 500-1100 GeV.
LFV Higgs Decays: $H \rightarrow \mu \tau$

- Sensitive probe of new physics, complementary to other LFV searches
- Hint ($2.4\sigma$) of a signal in Run 1, high priority for quick check in Run 2

Run 1: $B(H \rightarrow \mu \tau) = (0.84^{+0.39}_{-0.37}; < 1.51)\%$

- No sign of a signal in 2.3fb$^{-1}$ of 13 TeV data collected in 2015:

Run 2: $B(H \rightarrow \mu \tau) = (-0.76^{+0.81}_{-0.84}; < 1.20)\%$
Recent Physics Highlights: *Searches for New Physics @ 13 TeV*
Dark Matter Searches

- Search for dark matter ($\chi$) produced in association with initial state radiation: “monophoton”
- Results are cast in the context of a simplified model where dark matter particles $\chi$ are produced in the s-channel via a heavy mediator
  - Four parameters: $m_{DM}$, $M_{med}$, $g_q$, $g_{DM}$
Dark Matter: $b(\bar{b}), t(\bar{t}) + \text{MET}$

- First searches in CMS for dark matter produced in association with bottom or top quarks
  - Analysis searches in 1- and 2-tag samples
  - Sensitive to $b(b)+\text{DM}$ and $t(t)+\text{DM}$
  - Cross section limits set for scalar and pseudoscalar mediator assumptions
Dark Matter: monojet, mono-V

Jets can be “normal” or “merged” (from W/Z decays)

\[ \sigma(\text{mono-jet}) \geq 100 \times \sigma(\text{mono-W}) \]

\[ \sigma(\text{mono-jet}) \sim 30 \times \sigma(\text{mono-W}) \]

Limits on vector and axial-vector coupling scenarios: above 1 TeV; also limits on branching fraction into invisible under hypothesis of a SM Higgs as mediator.

Sensitivity approaching Run I (not quite there yet)
Dark Matter: monotop

- Search for dark matter ($\chi$) produced in association with a top quark via a flavor-changing neutral current ($V$): “monotop”
- The top quark is tagged through its all-hadronic decay mode via “jet substructure” techniques
Diphoton event with $m(\gamma\gamma) = 745$ GeV
Diphoton search (Dec 2015)

- Small excess seen near 750 GeV
  - 13 TeV: 2.6σ local significance @ 760 GeV
  - Combination with 8 TeV: 3σ @ 750 GeV
  - ATLAS sees ‘something similar’
  - CMS favors narrow width, but compatible with larger width implied by ATLAS result (and vice versa)
Does anyone care?

200 theory papers in 4 weeks!
435 as of June 17, 2016

Super luminal? First paper was uploaded less than one hour after the results were reported
Did anyone predict this?

\[ M(H^0) = \pi \left( \frac{1}{137} \right)^8 \sqrt{\frac{hc}{G}} \]

\[ 3987^2 + 4365^2 = 4472^2 \]

\[ \Omega(t) > 1 \]

\[ \Box \rightarrow \bigcirc \rightarrow \Box \rightarrow \bigcirc \]

1998
What could it be?

• **Excitement driven by several factors**
  • “Clean” channel
    • Photons well reconstructed in electromagnetic calorimeter
    • Precise mass resolution (~10 GeV), smooth background
  • Apparent coherence of ‘signal’ in ATLAS and CMS
  • Many possible interpretations, many possible decay channels, likely not a ‘lone wolf’ (other particles to find)

• **Most popular options so far:**
  • Electroweak (pseudoscalar) singlet
  • Heavy Higgs boson
  • New strong interactions (composite particle)

• **Preliminary conclusions**
  • Most likely outcome is still a data fluctuation, but would be revolutionary for the field if confirmed
  • Would require extra particles beyond the SM set
  • 3-4x more data expected by summer, >10x by end of 2016
Updated results (Mar 2016)

- Updated analysis relative to results shown in December
  - Data re-reconstructed with latest calibrations (resolution 30% better)
  - 0T data added to analysis (quite a challenge!)
    -> Together, expected sensitivity improves by 20%
  - Also added spin 0 interpretation

**CMS Preliminary** 2.7 fb⁻¹ (13 TeV, 3.8T)

**CMS Preliminary** 0.6 fb⁻¹ (13 TeV, 0T)
Updated results (Mar 2016)

- **New result compatible with previous result**
  - Local significance now $3.4\sigma$, slight increase coming from 0T data (1 event)
  - **Global significance $1.6\sigma$** accounting for mass range, spin, and width
  - Eagerly awaiting 2016 data!
### Bounds on other decay modes

<table>
<thead>
<tr>
<th>final state $f$</th>
<th>$\sigma$ at $\sqrt{s} = 8\text{ TeV}$</th>
<th>implied bound on $\Gamma(S \to f)/\Gamma(S \to \gamma\gamma)_{\text{obs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>observed</td>
<td>expected</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>$&lt; 1.5 \text{ fb}$</td>
<td>$&lt; 1.1 \text{ fb}$</td>
</tr>
<tr>
<td>$e^+e^-, \mu^+\mu^-$</td>
<td>$&lt; 1.2 \text{ fb}$</td>
<td>$&lt; 1.2 \text{ fb}$</td>
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<tr>
<td>$\tau^+\tau^-$</td>
<td>$&lt; 12 \text{ fb}$</td>
<td>$&lt; 15 \text{ fb}$</td>
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<tr>
<td>$Z\gamma$</td>
<td>$&lt; 11 \text{ fb}$</td>
<td>$&lt; 12 \text{ fb}$</td>
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<td>$ZZ$</td>
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<td>$Zh$</td>
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<td>$hh$</td>
<td>$&lt; 39 \text{ fb}$</td>
<td>$&lt; 42 \text{ fb}$</td>
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<tr>
<td>$W^+W^-$</td>
<td>$&lt; 40 \text{ fb}$</td>
<td>$&lt; 70 \text{ fb}$</td>
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<tr>
<td>$t\bar{t}$</td>
<td>$&lt; 450 \text{ fb}$</td>
<td>$&lt; 600 \text{ fb}$</td>
</tr>
<tr>
<td>invisible</td>
<td>$&lt; 0.8 \text{ pb}$</td>
<td>-</td>
</tr>
<tr>
<td>$b\bar{b}$</td>
<td>$\lesssim 1 \text{ pb}$</td>
<td>$\lesssim 1 \text{ pb}$</td>
</tr>
<tr>
<td>$jj$</td>
<td>$\lesssim 2.5 \text{ pb}$</td>
<td>-</td>
</tr>
</tbody>
</table>

Here $r = \sigma_{13\text{ TeV}}/\sigma_{8\text{ TeV}}$. Using run 2 data only would be safer. Run 2 $jj$?

Even invisible modes are constrained
Searches relevant for $X(750)$

- $pp \rightarrow X \rightarrow Z\gamma$
  - $ll\gamma$: EXO-16-010 (13 TeV), HIG-16-014 (8 TeV), EXO-16-021 (8+13 TeV combination)
  - $qq\gamma$: EXO-16-020

- $pp \rightarrow X \rightarrow ZZ$
  - 4 lepton: HIG-15-004
  - 2l 2\nu: HIG-16-001

- $pp \rightarrow X \rightarrow ZH(125)$
  - $H(125) \rightarrow bb$: B2G-16-003

- $pp \rightarrow X \rightarrow HH$
  - $bbbb$: HIG-16-002
  - $b\tau\tau$: HIG-16-013 (13 TeV), HIG-15-013 (8 TeV)
  - WWbb: HIG-16-011

- $pp \rightarrow X \rightarrow WW$
  - $l\nuqq$: B2G-16-004

- $pp \rightarrow X \rightarrow t\bar{t}$
Searching for $X(750) \rightarrow jj, bb$?

Difficult, but not impossible with “data scouting” technique (keep only relevant part of each event -> allows for $\sim 2$kHz rate)...

... scouting with $b$ tagging also possible
• If X(750) is real it decays to photons, and thus can be photoproduced
  • CT-PPS is a dedicated proton spectrometer able to deduce the mass of the recoil system in CMS
  • Acceptance happens to peak in an ‘interesting’ mass region ;-)  
• Advanced by one year the integration of CT-PPS into CMS data acquisition
  • Originally foreseen in YETS 16-17  
• CT-PPS status
  • Successful Roman Pot insertion tests performed in 2015 and 2016 (15σ achievable)
  • Expected mass resolution \( \sim 1-2\% \)
Summary

• Year-end technical stop was a productive time for CMS
  • Cleaned and improved magnet cryogenic system
  • Installed hardware for Stage 2 trigger upgrade, with commissioning ongoing
• CMS has entered “physics production mode” @ 13 TeV
  • 100 results on Run 2 data so far (50/50 SM vs. searches)
  • Highlights: diphoton excess and related searches, Dark Matter searches, SUSY searches, Higgs physics, standard model precision measurements
• LHC delivering data at record rate, CMS recording data at > 90% efficiency
• We will have the answer on X(750) in the next months!