Upgrades towards new physics results in CMS

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On behalf of the CMS Collaboration

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**Outline**

**Motivation**
- LHC and CMS status and results
- Future CMS detector challenges

**CMS upgrades**
- LS1 and Phase 1 plans

**CMS physics potential at 14 TeV:**
- Precision Higgs physics
- Discovery potential: SUSY particles and exotic heavy resonances

**Summary**
LHC and CMS performance

Total delivered luminosity: ~33 fb⁻¹
Data taking efficiency ~93%
Efficiency after reconstruction 84%, after reprocessing 89%

Excellent LHC performance and very high data-taking efficiency of the CMS detector
A 3-year long sprint

- First MinBias / UE studies, particle multiplicities
- First incl. b x-section, 8/nb, $\delta \sim 15\%$
- First incl. jet x-section, PF jets, 60/nb, $\delta \sim 20-30\%$
- First incl. W/Z x-sections, 200/nb, $\delta \sim 4-6\%$, +11% lumi
- First incl. J/\Psi x-section, 100/nb, $\delta \sim 20\%$
- First top xsec, 3/pb, $\delta \sim 40\%$
- First single top xsec, t-chan., 36/pb, $\delta \sim 36\%$
- First m_{top}, 36/pb, $\Delta \sim 6.5$ GeV
- First ZZ xsec, 1.1/fb, $\delta \sim 40\%$
- Going more differential, e.g. Z/W + j,b,c
- First significant limit on $B_s \rightarrow \mu \mu$, $BR<1.9 \times 10^{-8}$
- First particle discovered by CMS: $\Xi_b$
- First spin parity analysis of the boson, 17/fb
- BSM searches continue, limits pushed
- First m_{top}, 36/pb, $\Delta \sim 6.5$ GeV
- First top xsec, 3/pb, $\delta \sim 40\%$
- First WW xsec, 36/pb, $\delta \sim 40\%$
- First limit on HWW
- First >2σ local excess at low $m_H$, 1.1-1.7/fb
- First q*, Z', W' limits, 3-36/pb, $>1.6, 1.1, 1.4$ TeV
- First SUSY limits, 36/pb, $q, g > 500-600$ GeV
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New boson with a mass of $\sim 125$ GeV...

We have discovered a SM-like scalar boson

\[ m_H = 125.7 \pm 0.3^{\text{stat}} \pm 0.3^{\text{syst}} \text{ GeV} = 125.7 \pm 0.4 \text{ GeV} \]

Combined signal strength: $\mu = 0.80 \pm 0.14$
Measurement of the signal strengths, couplings deviations, and $J^{PC}$ confirm the hypothesis that the new particle is the Higgs boson.

Spin/parity hypothesis tests
Several alternative specific models testes
European Strategy for Particle Physics

- Update formally adopted by CERN council at the European Commission in Brussels on 30 May 2013
- The discovery of the Higgs boson is the start of a major programme of work to measure this particle’s properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.
- Europe’s top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.
**LHC**

- Reach 1x design lumi by LS2, 2x design by LS3, and integrate 300fb-1 by 2022
- pile-up (PU) = 50-100

**HL-LHC**

- Lumi-level at 5x design and integrate 3000 fb-1
- use PU=140 for upgrade studies

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**CMS plan**

- Data: 2015 – 2017
- LS2: 2018 (Complete Phase 1)
- Data: 2019 – 2021
- LS3: 2022 – 2023 (Phase 2 Upgrade)
- Data

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**Phase 1 upgrade**

- 8 TeV
- splice consolidation
- button collimators, R2E project
- experiment beam pipe
- nominal luminosity 70%

- 13–14 TeV collision energy
- 25 ns, (PU)~25
- nominal luminosity
- dispersion suppression collimation, R2E project
- experiment upgrade phase 1
- cryogenics Point 4

- 1 x 10^{34} \text{ cm}^{-2}\text{s}^{-1}
- 25 ns, (PU)~25
- 2 x 10^{34} \text{ cm}^{-2}\text{s}^{-1}
- 25 ns, (PU)~50
- 5 x 10^{34} \text{ cm}^{-2}\text{s}^{-1}
- 25 ns, (PU)~128
- 2 x nominal luminosity
- radiation damage
- 10 x nominal luminosity
Experimental goals

**Physics:** precision measurements at the EWK scale while searching for new particles at the multi-TeV scale

**Detector:** extend and enhance detector capability, especially in the endcap region where effects of PU and radiation are most severe

**Pile-up:** maintain demonstrated robustness with 6x higher pile-up

**Trigger:** maintain low thresholds for precision Higgs measurements and high purity for broadband particle searches and rare processes

**Computing:** maintain maximum throughput at maximum efficiency

CMS upgrade plans target the experimental challenges that must be met to achieve these goals
The goal of the upgrades is to preserve the ability to reconstruct all Standard Model objects and Missing Et at higher luminosity than the original design, but which it now seems the LHC will reach.

Need new technology R&Ds to:

- Increase granularity
- Increase data bandwidth
- Increase processing power
- Improve radiation hardness
- Minimize material in tracking devices
Pileup in 2012

Learning to adapt

Pile-up in 2012 exceeded design specification
Mitigation via extensive use of particle flow and advanced analysis methods

Peak: 37 pileup events
BX=50 ns

Design value
25 pileup events
(L=10^{34}, BX=25 ns)
Pileup challenges

Reconstruction of hard collisions in high pileup environment requires detectors with very high granularity:

• efficient association of charged tracks to collision vertices
• reconstruction of charged and neutral particles in jets

Physics with high pileup requires full particle flow reconstruction assuring:

• precise jet energy correction
• robust missing energy measurement
• efficient lepton isolation

Very efficient reconstruction code is needed to stay within computing budget
**CMS upgrade program**

**LS1: consolidation**
- Complete Muon coverage (ME,RE4)
- CSC ME11, DT electronics
- HCAL Forward and Outer electronics
- DAQ1→DAQ2

**Phase 1 Upgrades**
- New Pixel detector, HCAL electronics and L1-Trigger upgrade
- GEMs for forward muon
- New beam pipe for pixel upgrade
- Install test slices of pixel, GE1/1, HCAL, L1-trigger
- Install ECAL optical splitters for L1-trigger

**Phase 2: being defined now**
- Tracker replacement, L1 Track-Trigger
- Forward: calorimetry, muons and tracking
- High precision timing for PU mitigation
- Further Trigger upgrade
- Further DAQ upgrade
Muon Upgrade
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Trieste, 27/09/2013

Maintenance and consolidation of existing detectors: to fix pending problems encountered during Run 1

DT consolidation
New trigger board and optical link rearrangement

ME1/1 upgrade..
Optimize use of region 2.1 < |h| < 2.4 (start using fine strip granularity of ME11a digital readout board and trigger card )

Completion of the 4th station..
..build, install and commission..
67 ME4/2 chambers
144 RE4 chambers

Improved trigger rate and efficiency

- L1 CSC trigger rates, $L=2 \times 10^{34}$
- no ME4/2, 2 stations
- with ME4/2, 3 stations

Target Rate 5 kHz

L1Mu Efficiency for Degraded and Upgraded Detector at High Luminosity

Detector and CSCTF threshold:
- ‘degraded’ ($p_T^{\text{CSCTF}} > 50 \text{ GeV/c}$)
- ‘upgraded’ ($p_T^{\text{CSCTF}} > 20 \text{ GeV/c}$)
New detectors in high eta region

Install triple-GEM detectors (double stations) in 1.6<|\eta|<2.1-2.4 endcap region:

- Restore redundancy in muon system for robust tracking and triggering
- Improve L1 and HLT muon momentum resolution to reduce or maintain global muon trigger rate
- Ensure ~ 100% trigger efficiency in high PU environment

GE1/1 Slice installation in 2016-2017
GE1/1 Full installation planned in LS2

GE2/1 possible installation in LS3
Hadron Calorimeter (HCAL) Upgrade
HCAL Upgrade

Improved longitudinal segmentation and trigger:
Replace the hybrid-photo detectors in the Barrel and Endcap with Silicon Photomultiplier
• New electronics to increase bandwidth (frontend, backend)
• Improved cluster separation, background rejection, Missing $E_T$ resolution and Particle Flow reconstruction

- HO replacement HPD $\rightarrow$ SiPM in LS1
- HF replacement PMT $\rightarrow$ MAPMT in LS1

Back-end electronics HF upgrade end of 2015, all HB/HE in LS2

• Hadronic showers spread out with increasing depth

Hadronic cluster width

50 pileup events

Barrel

Present (25 and 50 ns)

Upgrade
Pixel Upgrade

Pixel Detector

Barrel Pixel Detector (BPIX)

Forward Pixel Detector (FPIX)

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New pixel layout

Extra layer in barrel (BPIX) and end-cap (FPIX)
L4↑ reduce gap to TIB, L1↓ reduce impact of multiple scattering on dxy/dz resolution

- New pixel readout chip (ROC) to minimize data loss due to latencies and limited buffering
- To reduce material (IP and γ conversion) use two-phase CO2 cooling and light-weight mechanical support, electronic cards and connections out of the tracking volume -> in LS1
- smaller diameter beam pipe → inner pixel layer closer to the interaction region → in LS1

- Install few Pilot-Modules in existing FPIX for DAQ running in 2015/16
- Full installation in 2016-2017

Year End Technical Stop
Tracking and b-tagging performance

Efficient seeding + robust tracking in increasing track density with less multiple scattering and photon conversions → Better tracking efficiency, I.P and primary vertex resolution:

Improvement of b-tagging efficiency with new pixel detector

Improvement in tracking efficiency w/ new pixel detector, in ttbar events, vs PU

Primary vertex resolution improved by factor ~1.5 - 2

b-jet efficiency ~1.3x better@ 10^{-2} udg-rej.
2 b-jets → (1.3)^2 ~1.69
Trigger upgrade

- Electromagnetic Calorimeter
- Hadron Calorimeter
- Muon Detectors
- Not shown (off-detector) • Muon Trigger • Calorimeter Trigger
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Upgrade plan
Factor of ~6 increase in rate with no change to existing menu:
• Deploy **PU subtraction and isolation**, improve muon reco, **increase flexibility** of global L1 trigger (expanded menu)
• Improved calorimeter trigger with higher granularity, better algorithms, and integration of calorimeter and muon data for muon isolation
• track-stub finding & better coverage for overlap regions
• Improved global trigger with more powerful object algorithms

Features
➢ Calorimeter and muon trigger cards in µ–TCA crates
➢ High bandwidth optical links
➢ FPGAs with extensive memory

In-situ commissioning in parallel with existing system post LS1.
Available for data taking in 2016
Trigger performance: Higgs & SUSY

Significant signal efficiency gains in Higgs analyses with leptons with the upgraded trigger.

Signal efficiency for stop searches also improves, especially in RPV scenarios with and without upgraded trigger.
LHC after LS1

In addition to the increase in production cross section, a multi-TeV particle produced via gluon fusion will see an increase in the parton luminosity by one or two orders of magnitude relative to 7 TeV collisions.

We are about to explore a new territory!
CMS Physics program priorities

The discovery of a SM-like scalar boson at \( m_H \sim 125 \text{ GeV} \) defines the physics priorities

- With LHC 13/14 TeV data until \(~2022 (\sim 300 \text{ fb}^{-1})\)
  - Measure SM-like scalar boson properties
    - mass, \( J^{PC} \)
    - individual couplings with 5-15% precision
  - Search for new physics at a higher mass scale (new energy region)
    - SUSY
    - Exotics

Analysis of various physics channels to evaluate performance improvements
- select a few exemplar Higgs decay channels (\( \sqrt{s}=14 \text{ TeV} \))
- standard CMS Monte Carlo for signal samples & some backgrounds
- no tuning for 14 TeV data, use analyses as developed for 7-8TeV
- upgraded & current detector with \(<\text{PU}>=50\)
- Compare signal selection efficiency with upgraded detector vs. current detector
Expected Phase 1 improvements

Full simulation @ 14 TeV and 50 PU demonstrates substantial improvements in key channels

Significant gain in signal reconstruction efficiency:

- $H \rightarrow 4\mu$: +41%
- $H \rightarrow 2\mu 2e$: +48%
- $H \rightarrow 4e$: +51%

Total efficiency improvement: factor of 2.5 (4.5% → 11%)

Improved jet and MET → 25% improvement in $m_{\tau\tau}$ resolution
Scalar boson signal with 300 fb$^{-1}$

- Upgraded detector performances assumed the same as 2012 detector
- Three scenarios (assumptions for all future analysis):
  - **Scenario 1**: same systematics as in 2012
  - **Scenario 2**: theory systematics scaled by a factor $\frac{1}{2}$, other systematics scaled by $1/\sqrt{L}$
  - **Scenario 3**: same exp. systematics as in 2012, w/o theory uncertainty

With 300 fb$^{-1}$ the precision on the signal strength is expected to be 6-15% per channel.
To test for possible deviations in the data from the rates expected in the different channels for the SM Higgs boson, factors “k” corresponding to the coupling modifiers are introduced and fit to the data.

With 300 fb\(^{-1}\) the uncertainties on the Higgs couplings are expected in the range

\[ \sigma (k_Y) \sim 4\text{-}8\% \]
\[ \sigma (k_f) \sim 6\text{-}15\% \]
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Studies for 14 TeV: currently simple scaling based on existing public results

Analyses are assumed unchanged; results are rough estimates of expected reach.

SUSY limits at a glance

EWKinos ~200-400 GeV

Stop, sbottoms ~200-600 GeV

Squarks, gluinos ~600-1300 GeV

Focus on “natural SUSY”:
3rd generation light
Gluinos in the TeV region
Direct production of EWKinos

Studies for 14 TeV: currently simple scaling based on existing public results

Analyses are assumed unchanged; results are rough estimates of expected reach.

SUSY: where we stand now
Discovery potential: Stops search..

Strategy: same analysis at 8 TeV but:

\[ N_{\text{bkg/sign}} \text{ scaled by: } R_{\text{bkg/sign}} = \frac{\sigma(14\text{ TeV})}{\sigma(8\text{ TeV})} \times \frac{300 \text{ fb}^{-1}}{20 \text{ fb}^{-1}} \]

(Background scaled by a constant factor based on ttbar 14 TeV / 8 TeV ratio = (965 fb / 249 fb) = 3.9 plus a factor of 15 due to lumi)

Pessimistic Systematics same for 2012

Optimistic: uncertainties on bkg reduced by \( 1/\sqrt{R_{\text{bkg}}} \)

Driven by statistical precision from samples: fix 10% relative uncertainty

Can discover (5σ) stops up to 750-950 GeV with LSP 300-450 GeV

Search in final state with ℓ + jets + MET
Two approaches:
“conservative” and “optimistic” similar to stop scenarios
Analysis methods assumed unchanged

5σ discovery reach:
Gluino up to 1.9 TeV for LSP <0.9 TeV
Sbottom: ~600–700 GeV for LSP 350–500 GeV
EWK-ino: ~500–600 GeV and LSP 150–300 GeV
EXOTICA: $W'$ and $Z'$ projections

$W' \rightarrow e\nu$

Simple scaling of existing 8 TeV results
Assume flat 65% efficiency

Exclude up to $\sim 5.6$ TeV

$Z' \rightarrow \mu\mu$

$Z' \rightarrow ll$ generator-level studies
Efficiencies from data
Electron: $E$ smearing as in 8 TeV, but estimate effect of electron showers saturating in ECAL
Muon: smear as in 8 TeV

Discovery ($5\sigma$) up to $\sim 5$ TeV
CMS have exceeded the design performances during the first LHC run, showing that precision physics can be made under these conditions.

- The experience gained and a sound program of upgrades gives us confidence that the experiments will meet the physics expected with 300 fb\(^{-1}\), collected at \(\sqrt{s}=14\) TeV and instantaneous luminosities up to \(2\times10^{34}\) cm\(^{-2}\) s\(^{-1}\).
  - LHC detectors must remain sensitive to EWK-scale physics
  - While maximizing sensitivity to new particles at the multi-TeV scale

- LHC upgrades present several challenges
  - Trigger rate, pile-up, radiation
- CMS upgrade plans are designed to deal with these challenges head-on
- Uncertainty on Higgs couplings reach \(\sim 4\%-10\%\)
- SUSY and Exotic discovery potential ranging from up to \(\sim 6\) TeV
- LHC has an exciting physics program for the next twenty years!
BACKUP
LV1 trigger performance

The threshold shown for each trigger is the offline transverse energy at which the trigger reaches 95% (85% for tau) of its plateau efficiency.
CMS Upgrade impact on Higgs

<table>
<thead>
<tr>
<th>Channel</th>
<th>Key Features</th>
<th>Upgrades addressing future challenge:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>di-photon mass</td>
<td>Tracker, trigger, endcap calo, precision timing</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>Lepton reco/iso</td>
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Upgrades will specifically address dominant systematic uncertainties impacting Higgs precision measurements and searches for additional Higgs bosons