CERN – A Gateway to Science and Technology
CMS detector performance
New 13TeV results
and
some of its Upgrade perspectives
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some of its Upgrade perspectives

Ludwik Dobrzynski
Laboratoire Leprince Ringuet - Ecole polytechnique - CNRS - IN2P3

Split - 14 September 2015
CERN – The European Organization for Nuclear Research
The Mission of CERN

Innovation

Education

CERN

uniting people

Research
The Mission of CERN

- **Push forward** the frontiers of knowledge

  E.g. the secrets of the Big Bang …what was the matter like within the first moments of the Universe’s existence?
Push forward the frontiers of knowledge

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Develop new technologies for accelerators and detectors

Information technology - the Web and the GRID
Medicine - diagnosis and therapy
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  Medicine - diagnosis and therapy

- **Train** scientists and engineers of tomorrow
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  Medicine - diagnosis and therapy

- **Train** scientists and engineers of tomorrow

- **Unite** people from different countries and cultures
CERN was founded 1954: 12 European States
“Science for Peace”
Today: 21 Member States

**Member States:** Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, the Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom

**Candidate for Accession:** Romania

**Associate Member in Pre-Stage to Membership:** Serbia

**Applicant States for Membership or Associate Membership:** Brazil, Croatia, Cyprus, Pakistan, Russia, Slovenia, Turkey, Ukraine

**Observers to Council:** India, Japan, Russia, Turkey, United States of America; European Commission and UNESCO
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- 2300 staff
- 1600 other paid personnel
- 10500 scientific users
Budget (2014) ~1000 MCHF

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CERN – building bridges across continents
Age Distribution of Scientists
- and where they go afterwards

Survey in March 2009

Today:
~3000 PhD students in LHC experiments
Age Distribution of Scientists
- and where they go afterwards

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They do not all stay: where do they go?
Survey in March 2009

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They do not all stay: where do they go?
Knowledge and Technology Transfer
CERN: Particle Physics and Innovation

- **Interfacing** between fundamental science and key technological developments
- **Interfacing** between fundamental science and key technological developments

- **CERN Technologies and Innovation**

  - Accelerating particle beams
  - Detecting particles
  - Large-scale computing (Grid)
Combining Physics, ICT, Biology and Medicine to fight cancer

Hadron Therapy

Accelerating particle beams
~30'000 accelerators worldwide
~17'000 used for medicine

>70'000 patients treated worldwide (30 facilities)
>21’000 patients treated in Europe (9 facilities)

Leadership in Ion Beam Therapy now in Europe and Japan
Combining Physics, ICT, Biology and Medicine to fight cancer

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**Imaging**

- PET Scanner

- Clinical trial in Portugal for new breast imaging system (ClearPEM)

- Detecting particles

**CERN Technologies and Innovation**

Example – Medical Applications
Breaking the Wall of Communication
25 years ago: the Web was born
Breaking the Wall of Communication
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Breaking the Wall of Communication
25 years ago: the Web was born

... and today?
The LHC Data Challenge

- Experiments were anticipated to produce about **25 Million Gigabytes** of data each year (~30 million CDs!).
- LHC data analysis requires a computing power equivalent to ~**100,000 of today's fastest PC processors**.
- => Requires many cooperating computer centres, as CERN can only provide ~20% of the capacity.

GRID Computing
The Worldwide LHC Computing Grid
WLCG:
An International collaboration to distribute and analyse LHC data

Integrates computer centres worldwide that provide computing and storage resource into a single infrastructure accessible by all LHC physicists
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CERN Education Activities

**Scientists at CERN**
Academic Training Programme

**Young Researchers**
CERN School of High Energy Physics
CERN School of Computing
CERN Accelerator School

**Physics Students**
Summer Students Programme

**CERN Teacher Schools**
International and National Programmes

NEW:
Asia-Europe-Pacific School of High-Energy Physics
Fukuoka, Oct 2012
India, 2014

Latin American School
Natal, Brazil, 2011
Arequipa, Peru, 2013

The 2013 European School of High-Energy Physics
CERN School of Physics
Hungary, June 2013
Discovery Science
Scientific Challenge:
to understand the very first moments of our Universe after
the Big Bang

Big Bang

13.8 Billion Years (Planck Telescope)

$10^{28}$ cm

Today
Atom
Proton
Big Bang
Radius of Earth
Earth to Sun
Radius of Galaxies
Universe
Hubble
ALMA
VLT
AMS
Big Bang

Proton

Atom

Radius of Earth

Radius of Galaxies

Earth to Sun

Universe

cm

Hubble

ALMA

VLT

AMS

Super-Microscope

LHC
Study physics laws of first moments after Big Bang increasing Symbiosis between Particle Physics, Astrophysics and Cosmology
The Large Hadron Collider
LHC - Large Hadron Collider

7 TeV + 7 TeV

Luminosity = $10^{34}$ cm$^{-2}$sec$^{-1}$

Primary targets:
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

The LHC results will determine the future course of High Energy Physics
Collision of proton beams... observed in giant detectors

The large Hadron Collider

Present LHC Injectors
- Linac2 (p, 50 MeV, 1978)
- PSB (1.4 GeV, 1972)
- PS (28 GeV, 1959)
- SPS (450 GeV, 1976)
Enter a New Era in Fundamental Science

Start-up of the Large Hadron Collider (LHC), one of the largest and truly global scientific projects ever, is the most exciting turning point in particle physics.

Exploration of a new energy frontier
Proton-proton collisions at $E_{\text{CM}}$ up to 14 TeV
The discovery of the **Higgs particle** – the most important result from LHC (currently)

4.07.2012

First observations of a new particle in the search for the Standard Model Higgs boson at the LHC

Published: Physics Letters B 716, 17 Sep 2012
The design goals of CMS:

1. A very good and redundant muon system
2. The best possible ECAL consistent with 1)
3. A high quality central tracking to achieve 1) and 2)
4. A financially affordable detector

- 3.8T solenoid 13m long, 6m diameter
- High eta HCAL coverage
- Silicon based inner tracking system supplementing all types of reconstruction.

Powerful reconstruction of: μ, e/γ, τ-jets, jets, MET (+tracks, vertices)
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Powerful reconstruction of:
\( \mu, e/\gamma, \tau\)-jets, jets, MET (+tracks, vertices)
The real CMS detector

- 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)

Courtesy of A. Abdelalim
2009 running:
• Hard to see anything apart from min bias in the displays.
• Serious analysis to find muons in the barrel.

What a run!
2012 Data at 8 TeV. Event with:
Raw $\Sigma E_T \sim 2$ TeV
14 jets with $E_T > 40$ GeV
Estimated pile up $\sim 50$
This starts being a not so easy environment...

2012 Data at 8 TeV. Event with:
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14 jets with ET $> 40$ GeV
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This starts being a not so easy environment...
Conditions in Run II could be similar to these.

2012 Data at 8 TeV. Event with:
Raw $\Sigma ET \sim 2$ TeV
14 jets with $ET > 40$ GeV
Estimated pile up $\sim 50$
CMS: Event processing

Level-1: dedicated hardware, data available with reduced granularity, no tracker data

HLT: computer farm, ~13kCPU, all data, algorithm paths seeded by L1, with reconstruction similar to offline (up to 450 paths: physics obj. and complex alg.)

CMS trigger reduce # of p-p interactions from: \(2 \cdot 10^7\) Hz (input) through \(\leq 100\) kHz down to: ~300-500 Hz “core data” – main Physics program (+ ~300-600 Hz “parked” for later analysis + 1kHz “scouting”)

More than 12 billion of data events in 2010-2012

Reconstruction: Standalone detector based reconstruction but also Particle Flow (attempts to reconstruct individually each particle in the event, prior to the jet clustering, based on information from relevant sub-detectors. → better reconstruction of the jets, \(E_T\), MET, tau)
Reconstructed events
- 20 billion simulated events
- 12 billion data events

Data volume
- More than 25PB moved to Tier-1s
- 70PB moved to Tier-2s

- Improvements in the reconstruction code to cope with pile up
- Reconstruction time per event reduced by maintaining the physics performance.
  - Non-linear with PU $\rightarrow$ explodes

Quite a challenge:
All things equal, 2015 computing needs increase x10
CMS in action: H→4 lepton
CMS in action: H -> 4 lepton

CMS preliminary

Events / 3 GeV

- Data
- $m_H = 126$ GeV
- $Z \gamma^*$, ZZ
- $Z + X$

$\sqrt{s} = 7$ TeV; $L = 5.1$ fb$^{-1}$

$\sqrt{s} = 8$ TeV; $L = 19.7$ fb$^{-1}$

2 Zs

$\ell^+ \ell^- \ell^+ \ell^-$
CMS in action: $H \rightarrow 2\gamma$

$\gamma_1 = 86 \text{ GeV}$

$\gamma_2 = 56 \text{ GeV}$
CMS in action: H→2γ

γ_1= 86 GeV

γ_2= 56 GeV
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."
Highlights of results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
• Excellent performance of CMS detector during Run I
  • Tracking, vertexing
  • Lepton identification
  • Jet and MET reconstruction
  • Triggering capabilities

• And final physics performance!

2013-2014: Detector open for maintenance and upgrade
CMS: First look at 13 TeV data

Paolo SPAGNOLO on behalf of the CMS Collaboration

August 31 2015
CMS detector for Run2

Improvements during Long Shut Down LS1

Tracker:
~1 m² Pixels (66M channels)
~200 m² Si microstrips (9.6M channels)

Iron Yoke

4th muon station

4 stations of muon detectors

Tracker / Pixel: Cold Operation

DAQ and HLT: New computers Improved Trigger

ECAL: Electromagnetic calorimeter - 76K PbWO₄ crystals
12,500 tons
21 m long
15 m diameter

HCAL: hermetic Brass/Scintillator sampling hadronic calorimeter
HCAL new photosensors

new Beam Pipe

new Luminosity telescopes

3.8 T Solenoid

Tracker / Pixel: Cold Operation

Tracker / Pixel: Cold Operation
First Physics collision @ 13 TeV
First CMS publication @ 13 TeV

First paper from LHC @13 TeV


**Pseudorapidity distribution of charged hadrons in proton-proton collisions at $\sqrt{s} = 13$ TeV**

$$\frac{dN_{\text{ch}}}{d\eta}|_{\eta|<0.5} = 5.49 \pm 0.01 \text{ (stat)} \pm 0.17 \text{ (syst)}$$

- measured in CMS in a special early run @13 TeV taken on June 7th (~1h30’) with $B = 0$ T
- $dN/d\eta$ vs $\sqrt{s}$ gives an handle on the relative weight of soft and hard scattering contribution
- both EPOS (better) and PYTHIA8 compatible with data
Di-muon spectroscopy: standard candles resonances and first $B$ mesons
Di-muon spectroscopy: standard candles

Events / GeV

Energy spectrum of di-muon events with invariant mass from 1 GeV to 10 GeV. The CMS preliminary data shows peaks at various masses, including φ, ψ', ω, J/ψ, B_s, Y, and Z. The trigger paths for these events are labeled accordingly.

20 pb⁻¹ (13 TeV)

Trigger paths:
- φ
- J/ψ
- ψ'
- B_s
- Y
- low mass double muon + track
- double muon inclusive
Top pair cross-section measurement

Integrated lumi= 42 pb$^{-1}$
- all validated data from 50 ns run

Selection
- At least 2 good (OS) leptons (1e and 1$\mu$)
- $p_T$(lept)> 20 GeV and $|\eta| < 2.4$
- If more than 2 good leptons, the two with the highest $p_T$ are retained
- Di-lepton invariant mass > 20 GeV
- At least 2 jets (anti-kT R = 0.4)
- $p_T$(jets)> 30 GeV and $|\eta| < 2.4$

From Run1 data NEW RESULTS
(CMS TOP 13-004)

$\sigma_{t\bar{t}} = 174.5 \pm 2.1$ (stat)$^{+4.5}_{-4.0}$ (syst) $\pm 3.8$ (lumi) pb at $\sqrt{s} = 7$ TeV

$\sigma_{t\bar{t}bar} = 245.6 \pm 1.3$ (stat)$^{+6.6}_{-5.5}$ (syst) $\pm 6.5$ (lumi) pb at $\sqrt{s} = 8$ TeV

Allow to extract the pole mass from NNPDF30 PDF to be $m_{t,\text{pole}} = 173.6^{+1.7}_{-1.8}$ GeV

$\text{inclusive } \sigma_{t\bar{t}}(13\text{ TeV}) = 772 \pm 60$ (sta) $\pm 62$ (sys) $\pm 93$ (lum) pb
Di-jet resonance search

- Observed limits at 95% CL on cross section of qq, qg, gg resonances
- Get worse when there are gluons in the final state because radiation increases and resolution degrades
- Extend to 7 TeV in di-jet mass for the first time
- Plateaus at high mass due to absence of events

Confirms Run2 is already more sensitive than Run1 for M> 5 TeV

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CMS PAS EXO-15-001

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Search for narrow resonances using the dijet mass spectrum with 42 pb$^1$ of pp collisions at $p_{\text{s}} = 13$ TeV. The CMS Collaboration

**Abstract**

A search for narrow dijet resonances in proton-proton (pp) collisions at $p_{\text{s}} = 13$ TeV is presented. The dijet mass distribution of the two leading jets is measured with the CMS detector. The data used correspond to an integrated luminosity of 42 pb$^1$ from Run 2 of the LHC. The pseudorapidity separation of the two jets is required to satisfy $|\Delta h_{jj}| < 1.3$ with each jet inside the region $|\eta| < 2.5$. The highest observed dijet mass is 5.4 TeV. The spectrum is well described by a smooth parameterization and no significant evidence for new particle production is observed. Upper limits at the 95% confidence level are set on the resonance cross section. By comparing these generic limits with theoretical predictions for the cross section of several models of new particles, lower limits are set on the mass of string resonances, excited quarks, axigluons, colorons, scalar diquarks and color octet scalars. For resonance masses greater than 5 TeV this search is expected to be more sensitive than those in Run 1 of the LHC at $p_{\text{s}} = 8$ TeV. A lower mass limit of 5.1 TeV is set for string resonances which extends previous exclusions from Run 1.

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**Figure:**

- **Image 1:** Highest Mass di-jet event $M = 5.4$ TeV.
- **Image 2:** CMS Experiment at LHC, CERN.
  - Data recorded: Sun Jul 12 01:52:51 2015 CDT
  - Run/Event: 251562 / 310157776
  - Lumi section: 347
  - Dijet Mass: 5.4 TeV
Event display of the highest mass di-photon candidate ( $M = 730$ GeV)

**Photon selection**

$p_T > 100$ GeV and $|\eta| < 2.5$ with at least one candidate in the ECAL Barrel with $|\eta| < 1.4442$

isolated photons with shape in ECAL compatible with prompt photon
Muon + MET resonance Search

Muon selection

Good-quality isolated high-$p_T$ muon with $p_T > 55 \text{ GeV}$ and $|\eta| < 2.4$

Event selection

- Single high-$p_T$ muon accompanied by a large missing transverse energy ($E_T^{\text{miss}}$).
- Events containing additional muons with $p_T > 25 \text{ GeV}$ are vetoed
- Kinematic selection: $0.4 < p_T(\mu)/E_T^{\text{miss}} < 1.5$
  
$\Delta \Phi(\mu, E_T^{\text{miss}}) > 2.5$

Transverse mass distributions for muon + $E_T^{\text{miss}}$ events using 42 pb$^{-1}$ of pp collisions at $\sqrt{s} = 13 \text{ TeV}$

CMS Preliminary

Early Alignment used in data

last bin includes overflow
Di-muon resonance search

M = 920 GeV

CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 10:18:52 2015 FET
Run/Event: 251562 / 367325039
Lumi section: 414
Di-muon resonance search

2 isolated muons muons are required to satisfy:

\( p_T > 48 \text{ GeV} \) and \( |\eta| < 2.4 \)

MC samples: aMC@NLO for Drell-Yan, POWHEG for ttbar and dibosons

Highest mass event = 920 GeV

Early alignment of Muon system and Tracker used in data contribution from di-jets negligible and not shown
Di-electron resonance search

2 electrons in ECAL with $E_T > 35$ GeV and at least one electron in the ECAL barrel

\[ |\eta| < 1.4442 \text{ or } 1.566 < |\eta| < 2.5 \text{ with one electron within } |\eta| < 1.4442 \]

Cumulative distribution

Highest mass event ~ 1 TeV
Run1 Limit for SSM Z' < 2.9 TeV
Run1 sensitivity will be reached after about 2 fb$^{-1}$
M = 2.9 TeV !!!
Di-electron resonance search

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 !!!
Di-electron resonance search

$M = 2.9$ TeV !!!
Conclusions

• Successful operation in 2010 - 2012 runs at $\sqrt{s}$- 7 and 8 TeV
• A major discovery: Higgs boson
• Large number of analysis and publications from many CMS physics groups
• The 13 TeV campaign is expected to be highly fruitful.
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Physics: exciting times

CMS EX0 2015-001

Shown this week at LHCP

ATLAS Preliminary
$\sqrt{s}$=13 TeV, 80 pb$^{-1}$

- Data
- Background fit to data
- QCD MC
- $q'^* (4.5$ TeV)

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.
Conclusion (2)

• CMS is (~continuously) improving and upgrading to take advantage of the increasing LHC energy and luminosity
  – The LS1 projects are nearly complete
  – Upgrades to tracking and trigger will happen during Run 2
  – Further upgrades during LS2 to improve calorimeter granularity, trigger
  – R&D is underway for upgrades for HL-LHC

The CMS upgrade program aims to fully exploit the LHC physics potential