Recent results from proton-proton collisions at CMS

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Outline

• Introduction to CMS
• Detector performance

• Results on Standard Model Physics:
  • QCD
  • Electroweak
  • B-Physics
  • Top
  • Higgs

• Results on Physics beyond the SM:
  • SUSY
  • Heavy bosons
  • Fourth generation
  • Leptoquarks
  • Extra dimensions
  • Model-independent searches
Introduction to CMS

Key:
- Cyan: Muon
- Red: Electron
- Green: Charged Hadron (e.g., Pion)
- Dashed Green: Neutral Hadron (e.g., Neutron)
- Blue: Photon

Transverse slice through CMS

Iron return yoke interspersed with Muon chambers

Silicon Tracker

Electromagnetic Calorimeter

Hadron Calorimeter

Superconducting Solenoid
Detector Performance

- **Tracker:**
  - **Pixels (1440 sensors, 66M pixels):**
    - 3 barrel layers, 2 discs / end cap
    - Size: 100 x 150 $\mu$m$^2$
  - **Strips (15148 sensors):**
    - 10 barrel layers, 12 discs / end cap
    - Width: 320 - 500 $\mu$m
Detector Performance

- **Calorimeters:**
  - ECAL: PbWO$_4$ crystals
  - HCAL: Cu + scintillator

- **Muon chambers:**
  - Drift Tubes
  - Cathode Strip Chambers
  - Resistive Plate Chambers
Detector Performance

- **Trigger & DAQ:**
  - **L1 Trigger:** 100kHz maximum rate. Uses multi-object algorithms.
  - **HLT:** 300Hz maximum rate. Single object + >200 multi-object triggers. Mitigates pile-up.

- Operational channels:
  - RPC: 98.5%
  - DT: 99.4%
  - CSC: 98.3%
  - HB: 99.9%
  - HE: 100.0%
  - HF: 99.9%
  - ES: 95.9%
  - EE: 98.6%
  - EB: 99.1%
  - STRIP: 97.8%
  - PIXEL: 96.9%
Detector Performance

- **Particle Flow:**
  - Use information from all the sub-detectors to build 5 kinds of particles: muons, electrons, photons, charged and neutral hadrons.
  - Use these to build jets, taus and MET. Systematics greatly reduced.

- **B-Tagging:**
  - Used to identify b-jets.
  - Uses track IP’s, SV’s & soft leptons.

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CMS Preliminary 2010, \( \sqrt{s} = 7 \text{ TeV}, 36 \text{ pb}^{-1} \)

- **Data:**
  - **MC (light)**
  - **MC (charm)**
  - **MC (bottom)**

- **Visible mass (GeV/c^2):**
  - **Number of events:**
    - **Data**
    - **Z \rightarrow \tau^+ \tau^-**
    - **QCD**
    - **W + jets**
    - **Z/\gamma \rightarrow \mu^+ \mu^-**
    - **tt + jets**
Results on Standard Model Physics
QCD

Inclusive jet production cross section

\[ \frac{d^2\sigma}{dp_T^2 \, dy} \]

\( \sqrt{s} = 7 \text{ TeV} \)

CMS preliminary, 34 pb\(^{-1} \)

Data for:

- \(|y| < 0.5 \times 3125\)
- \(0.5 \leq |y| < 1 \times 625\)
- \(1 \leq |y| < 1.5 \times 125\)
- \(1.5 \leq |y| < 2 \times 25\)
- \(2 \leq |y| < 2.5 \times 5\)
- \(2.5 \leq |y| < 3\)

NLO\(\otimes\)NP theory

Exp. uncertainty

Anti-\(k_T\) \(R=0.5\)

\(p_T\) (GeV)

\(10^{-1}\) \(10^{-2}\) \(10^{-3}\) \(10^{-4}\) \(10^{-5}\) \(10^{-6}\) \(10^{-7}\) \(10^{-8}\)

Inclusive prompt photon production cross section

\[ \frac{d^2\sigma}{dE_T \, d\eta} \]

\(\sqrt{s} = 7 \text{ TeV}, L_{\text{int}} = 35.9 \text{ pb}^{-1}\)

CMS Preliminary

\(p + p \rightarrow \gamma + X\)

NLO pQCD JETPHOX

CT10 / BFG II, \(\mu_F = \mu_R = E_T\)

MPI and hadronization corrected

\(E_T\) [GeV]

\(10^{-5}\) \(10^{-4}\) \(10^{-3}\) \(10^{-2}\) \(10^{-1}\) \(10\) \(10^2\) \(10^3\) \(10^4\) \(3 \times 10^2\)
Electroweak

CMS preliminary

36 pb$^{-1}$ at $\sqrt{s} = 7$ TeV

- $\sigma \times B( W )$
- $\sigma \times B( W^* )$
- $\sigma \times B( W )$
- $\sigma \times B( Z )$
- $\sigma \times B( Z \to \tau \tau )$
- $\sigma \times B( W \gamma )$
- $\sigma \times B( Z \gamma )$
- $\sigma \times B( WW )$
- $R_{WZ}$
- $R_{W\perp}$
- $W_{\text{jet}} \to e\nu \alpha$
- $W_{\text{jet}} \to \mu \nu \alpha$
- $Z_{\text{jet}} \to e\nu \alpha$
- $Z_{\text{jet}} \to \mu \mu \alpha$
- $Z_{b\text{-jet}}/Z_{\text{jet}}(\to e\nu)$
- $Z_{b\text{-jet}}/Z_{\text{jet}}(\to \mu \mu)$

Ratio (CMS/Theory)

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B-Physics

- Quarkonia: cross-section, B-fraction.
- Inclusive cross-sections and angular correlations.
- Exclusive cross-sections ($B^+$, $B^0$, $B_s$).

CMS Preliminary, $\sqrt{s}=7$ TeV

- $pp \rightarrow B^{*} X$
  $P_T > 5$ GeV, $|y| < 2.4$
  $28.3 \pm 2.4 \pm 2.0 \pm 1.1 \mu b$
  ($6 \text{ pb}^{-1}$)

- $pp \rightarrow B^0 X$
  $P_T > 5$ GeV, $|y| < 2.2$
  $33.2 \pm 2.5 \pm 3.1 \pm 1.3 \mu b$
  ($40 \text{ pb}^{-1}$)

- $pp \rightarrow B_s X \rightarrow J/\psi \phi X$
  $8 < P_T < 50$ GeV, $|y| < 2.4$ ($x1000$)
  $6.9 \pm 0.6 \pm 0.5 \pm 0.3 \text{ nb}$
  ($40 \text{ pb}^{-1}$)

Theory: MC@NLO
CTEQ6M PDF, $\mu=(m_b^2+P_T^2)^{1/2}$, $m_b=4.75$ GeV

B-Meson Production Cross Section [\mu b]

\[
\begin{array}{c}
\text{CMS} \quad \sqrt{s} = 7 \text{ TeV, } L = 3.1 \text{ pb}^{-1} \\
\text{Data (p_T > 56 GeV)} \\
\text{Data (p_T > 84 GeV)} \\
\text{Data (p_T > 120 GeV)} \\
\text{Normalisation region}
\end{array}
\]

\[
\begin{array}{c}
\text{CDF} \quad \sqrt{s} = 1.96 \text{ TeV, } |y| < 0.6 \\
\text{PRD 71 (2005) 032001}
\end{array}
\]

\[
\begin{array}{c}
\text{JHEP 1103 (2011) 136}
\end{array}
\]


• Re-discovered single top with only 36 pb$^{-1}$


• Measurement of the pair cross-section at 7 TeV

• Properties:
  • Mass
  • Mass difference
  • Charge asymmetry

TOP-11-014
Higgs

- $H \rightarrow WW$: High sensitivity but low resolution (~30 GeV).
- $H \rightarrow \gamma\gamma$: Low sensitivity, high resolution (1-2 GeV). Challenging with increasing pile-up.
- $H \rightarrow ZZ$: Low sensitivity, high resolution (1-2 GeV) at low masses.
- Other channels: $H \rightarrow \tau\tau$; associated production ($VH \rightarrow Vbb$).

![Higgs boson mass distribution](image)

**CMS Preliminary, $\sqrt{s} = 7$ TeV**

Combined, $L_{\text{int}} = 1.1$ fb$^{-1}$

**Limit $\sigma_{95\%}/\sigma_{SM}$**

- CL$_S$ Observed
- CL$_S$ Expected ± 1σ
- CL$_S$ Expected ± 2σ
- Bayesian Observed

**HIG-11-022**
Results on Physics Beyond the SM
SUSY

- Every SM particle has its super-partner with 1/2 difference in spin.

- Dominant at the LHC: squark-gluino associated production.

- Searches:
  - All hadronic + MET
  - Leptons (SS or OS) + jets + MET
CMS Preliminary

\[ \sqrt{s} = 7 \text{ TeV}, \int L dt = 1.1 \text{ fb}^{-1} \]

- 2011 Limits
- 2010 Limits

\( \tan \beta = 10, \ A_0 = 0, \ \mu > 0 \)

\( \tau = \text{LSP} \)

\( m_{1/2} (\text{GeV}/c^2) \)

\( m_0 (\text{GeV}/c^2) \)

- CDF \( \tilde{g}, \tilde{q}, \tan \beta = 5, \ \mu < 0 \)
- D0 \( \tilde{g}, \tilde{q}, \tan \beta = 3, \ \mu < 0 \)
- LEP2 \( \tilde{\chi}_1^\pm \)
- LEP2 \( \tilde{\ell}^\pm \)

1 Lepton

SS Dilepton

OS Dilepton

MT2

Jets+MHT

\( \tilde{\chi}_1^\pm \)

\( \tilde{\ell}^\pm \)

\( \tilde{g} (1000) \text{ GeV} \)

\( \tilde{g} (750) \text{ GeV} \)

\( \tilde{g} (500) \text{ GeV} \)

\( \tilde{g} (1000) \text{ GeV} \)

\( \tilde{g} (750) \text{ GeV} \)

\( \tilde{g} (500) \text{ GeV} \)

\( \tilde{g} (1000) \text{ GeV} \)

\( \tilde{g} (750) \text{ GeV} \)

\( \tilde{g} (500) \text{ GeV} \)
• MSSM $H \rightarrow \tau \tau$
Leptoquarks

• Why leptoquarks?
  • Remarkable symmetry between the 3 generations of quarks and leptons.
  • It’s natural to predict (GUT, compositeness, technicolor) particles that carry both baryon and lepton number.

• Properties:
  • Color-triplet bosons with weak isospin,
  • Can have spin 0 (scalar) or 1 (vector),
  • Fractional electric charge,
  • Couple to a quark and a lepton via Yukawa coupling $\lambda$, different for right/left handed,
  • Coupling to one generation only assumed due to absence of FCNC.
  • At the LHC expected to be produced in pairs from gluons (they have color!).
Leptoquarks

- So far in CMS only 34 pb$^{-1}$:
  - 1st generation LQ search: eejj & e$\nu$jj channels combined.
  - 2nd generation LQ search: only $\mu\mu jj$ channel.
Fourth Generation

- Why 4th generation? $m_t > 45$ GeV does not contradict LEP.
- $4 \times 4$ CKM matrix accommodates Belle & DØ new physics results + matter/anti-matter asymmetry
- With a 4th generation:
  - successful unification of gauge couplings, hierarchy problem solved.
  - Higgs mass less constrained by electroweak precision measurements.
Fourth Generation

- $M_{t'} - M_{b'} < M_W$ favored by electroweak measurements then look for $t' \rightarrow bW$. In this analysis both $W \rightarrow l\nu$.

- Select two isolated leptons with $p_T > 20$ GeV, two jets with $p_T > 30$ GeV (not matched to leptons, at least one b-tagged) and MET > 30 GeV. Cut Z mass window.

- Signal region: both $M_{lb} > 170$ GeV.

- Systematics: b-tagging (10%), trigger (2%), lepton selection (2%), jet & MET energy scale (8%), luminosity (4.5%).

![Generated vs. Reconstructed M_{1b2}](image)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tt \rightarrow \ell^+\ell^-$</td>
<td>$1.35 \pm 0.67$</td>
<td>Data</td>
</tr>
<tr>
<td>Fake leptons</td>
<td>$0.0^{+0.4}_{-0.0}$</td>
<td>Data</td>
</tr>
<tr>
<td>DY $\rightarrow e^+e^-$ or $\mu^+\mu^-$</td>
<td>$0.07^{+0.13}_{-0.07}$</td>
<td>Data</td>
</tr>
<tr>
<td>DY $\rightarrow \tau^+\tau^-$</td>
<td>$0.11 \pm 0.11$</td>
<td>Simulation</td>
</tr>
<tr>
<td>Di-boson</td>
<td>$0.02 \pm 0.02$</td>
<td>Simulation</td>
</tr>
<tr>
<td>Single top</td>
<td>$0.07 \pm 0.04$</td>
<td>Simulation</td>
</tr>
<tr>
<td>Total prediction</td>
<td>$1.62^{+0.80}_{-0.70}$</td>
<td>Data</td>
</tr>
</tbody>
</table>

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Fourth Generation

- No excess beyond SM.
- 95% CL Limits:
  - expected: $M_{t'} > 415$ GeV
  - observed: $M_{t'} > 422$ GeV

EXO-11-050
Fourth Generation

- Other searches:

![Graph 1](image1.png)

![Graph 2](image2.png)

![Graph 3](image3.png)

![Graph 4](image4.png)

EXO-11-051

EXO-11-036

EXO-11-054

EXO-11-054

arXiv: 1109.4985 (hep-ex)
Extra Dimensions

- **Hierarchy Problem:**
  - SM interactions can be unified at the energy scale of $10^{16}$ GeV.
  - $G_N \ll \alpha$: gravity too weak to be unified at the same scale.
  - Natural energy scale: Planck scale ($M_P = 1.2 \times 10^{19}$ GeV).

- **Possible solution: extra dimensions.**
  - ADD model (Arkani-Hamed, Dimopoulos and Dvali):
    - $n$ “large” extra-dimensions of size $d \gg 1/M_P$. At short distances $F \sim 1/r^{2+n}$. Then $M_P^2 \sim M_D^{2+n} d^n$.
    - For 1 TeV scales $d \sim 1$ mm if $n=2$.
  - RS-I model (Randall and Sundrum):
    - one “wrapped” extra-dimension.

\[ ds^2 = e^{-2kr_c \xi} \eta_{\mu\nu} dx^\mu dx^\nu + r_c^2 d\xi^2 \]

- From both massive Kaluza Klein gravitons appear.
**Extra Dimensions**

- ADD: emission of a KK graviton. Signature: 1 jet + MET
  - Selection: 1 or 2 jets, $p_T(j_1) > 110$ GeV, $|\eta(j_1)| < 2.4$, $p_T(j_2) > 30$ GeV, $\Delta\phi(j_1,j_2) < 2$

---

![Graphs](https://example.com/graphs.png)

- CMS Preliminary
- $L dt = 1.1$ fb$^{-1}$ at $\sqrt{s} = 7$ TeV
- Events / 25 GeV
- $p_T(Jet)$ [GeV/c]
- $\Delta\phi(Jet_1, Jet_2)$
- $E_{Tmiss}$ [GeV]
- $M_D$ (TeV)
- $\sigma$ (pb)

- ADD, $\delta = 2$
- ADD, $\delta = 4$
- ADD, $\delta = 6$

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• **Di-photons:**
  - Off-shell ADD KK graviton
  - On-shell RS-I KK graviton

**EXO-11-038**
Extra Dimensions

- **Photon + MET**

- **Di-muon**

EXO-11-058

EXO-11-039
Many theories predict the existence of heavier gauge bosons $W'$ and $Z'$:

- Sequential Standard Model
- GUT’s
- Extra Dimensions (KK bosons)
- Little, Littlest Higgs Model
- Technicolor

Typical decays:
- $Z'$ to quark or lepton pair (even top pair)
- $W'$ to lepton neutrino or quarks (even bt)
- $W'$ to $WZ$
- $W_R \rightarrow \nu_R$

CMS top pair search:
- All-jets decay channel
- Divide event in 2 hemispheres
- Type 1: 3 sub-jets merged in one
- Type 2: The 2 $W$ sub-jets merged in one + 1 b-jet

EXO-11-006

CMS Preliminary, 886 pb$^{-1}$ at $\sqrt{s} = 7$ TeV

Combined type 1+1 & 1+2

- Observed (95% CL)
- Expected (95% CL)
- ± 1σ Expected
- ± 2σ Expected

- KK Gluon, Agashe et al
- Topcolor $Z'$, 3.0% width, Harris et al
- Topcolor $Z'$, 1.2% width, Harris et al

Upper Limit $\sigma_{Z} \times BR(Z' \rightarrow t\bar{t})$ (pb)

$t\bar{t}$ Invariant Mass (TeV/c$^2$)
Heavy Bosons

- $W' \rightarrow e\nu / W' \rightarrow \mu\nu$
- $0.4 < p_T(e/\mu)/\text{MET} < 1.5$
- $\Delta\phi(e/\mu,\text{MET}) > 2.5$
- Limits from fits to $M_T$ distributions

$$M_T = \sqrt{2 \cdot p_T^e \cdot E_{\text{T}}^{\text{miss}} \cdot (1 - \cos \Delta\phi_{e,\nu})}$$
• **W' → WZ**
  - Z: \( p_T(\mu, \mu) < (15, 15) \text{ GeV} \); \( p_T(e, e) < (20, 10) \text{ GeV} \)
  - W: \( p_T(\mu/e) > 20 \text{ GeV} \); MET > 30 GeV
  - Optimize \( H_T \) cut for each signal MC mass

\[ \int L \, dt = 1.15 \text{ fb}^{-1} \]

\[ \text{W'} \text{ Limit} = 784 \text{ GeV} \]

\[ \sigma \cdot \text{BR (pb)} \]

\[ \text{Events / 10 GeV} \]

\[ \text{M}_{WZ} (\text{GeV}) \]

\[ \text{Lepton Pt Sum: } H_T (\text{GeV}) \]

\[ \text{CMS Preliminary 2011 } \sqrt{s} = 7 \text{ TeV} \]
Model-independent Searches

- Resonance decaying to dileptons:
  - $p_T > 35$ GeV (40 GeV for ee in EC)
  - Vertex with 4 tracks + cosmic protection
  - Main background: Drell-Yan (MC)
  - $t\bar{t}$bar & QCD estimated from data

![Graphs and plots showing model-independent searches for dileptons and di-muons.](image-url)
Model-independent Searches

- **Heavy Stable Charged Particles:**
  - Using detector information: EXO-11-022
    - Tracker: dE/dx and p compatible with slow.
    - Muons: time of flight.
  - Stopped HSCP: EXO-11-020
    - Created at collision, decays later.
    - Dedicated trigger to select bunch crossings with no collisions. 1 jet $p_T > 70$ GeV.

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![Graph showing model independent cross-section vs. HSCP decay time](image1)

![Graph showing tracks vs. mass](image2)

![Graph showing theoretical predictions](image3)
Model-independent Searches

- Other searches:
  - Long lived resonances decaying to leptons:
    - $H \rightarrow XX \rightarrow 4$ displaced leptons.  
    - $\text{BR} < 1.9 \times 10^{-8}$ (4.6 $\times 10^{-9}$)
    - $1.2(0.3) \sigma$ away from BG only hypothesis.
  - $B_{s(d)} \rightarrow \mu\mu$ (rare $b$-decay):
    - $\text{BR} < 1.9 \times 10^{-8}$ (4.6 $\times 10^{-9}$)
    - $1.2(0.3) \text{s away from BG only hypothesis.}$
  - Combination with LHCb: $\text{BR} > 1.1 \times 10^{-8}$
    - $\sim 3 \times \text{SM}$

EXO-11-004

BPH-10-019

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CMS Preliminary $\sqrt{s}=7$ TeV $L=1.1$ fb$^{-1}$

CMS Preliminary $\sqrt{s}=7$ TeV $L=1.2$ fb$^{-1}$
Conclusions

• CMS has shown an excellent performance since start-up in 2009.

• SM physics results in agreement with expectation.

• Wide range of beyond the SM searches. None found... yet. Tevatron sensitivity surpassed.

• I had to leave out many results:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults