CMS Search for Supersymmetry at the LHC

Teruki Kamon
on behalf of the CMS Collaboration
Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University

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[Credits]
- Images of Baryon Acoustic Oscillations with Cosmic Microwave Background by E.M. Huff, the SDSS-III team, and the South Pole Telescope team. Graphic by Zosia Rostomian (Lawrence Berkeley National Laboratory)
- Image of Neutrino Astrophysics, taken from https://astro.desy.de/
- Image of the LHC by CERN Photo
- Image of Bullet Cluster by NASA/Chandra X-ray Center
CHICAGO SEES FLOODS OF LHC DATA AND NEW RESULTS AT THE ICHEP 2016 CONFERENCE

“ATLAS and CMS have also looked for any signs of the direct production of new particles predicted by Supersymmetry and other exotic theories of physics beyond the Standard Model, but no compelling evidence of new physics has appeared yet. In particular, the intriguing hint of a possible resonance at 750 GeV decaying into photon pairs, which caused considerable interest from the 2015 data, has not reappeared in the much larger 2016 data set and thus appears to be a statistical fluctuation.”

“We're just at the beginning of the journey,” said CERN Director-General, Fabiola Gianotti. “The superb performance of the LHC accelerator, experiments and computing bodes extremely well for a detailed and comprehensive exploration of the several TeV energy scale, and significant progress in our understanding of fundamental physics.”
Examine pp collision events being consistent with models (or scenarios) that describe DM-SM particle interaction:

- Supersymmetry (SUSY)
  1) SUSY colored sectors
  2) SUSY electroweak sectors
  3) Summary & Remarks
Compact Muon Solenoid (CMS) Experiment

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

Schematic view of the CMS Detector with its main components.

Triggers
1) Tagging energetic jets (+ MET) from cascade decays
2) Tagging leptons
3) Tagging photons
4) Tagging with timing
5) ISR jet(s)
6) VBF dijet
7) ...

Particle IDs with Particle Flow

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CMS SUSY and X
Challenges with High Luminosity (= PU)

CMS Integrated Luminosity, pp

Data included from 2010-03-30 11:22 to 2016-08-07 05:35 UTC

CMS Preliminary 2016 Data 3.1fb⁻¹ (13 TeV)

MET, independent of PU

CMS Preliminary 2016

CMS-DP-2016-043

Muon reconstruction efficiency

Barrel Pixel Hit efficiency

CMS SUSY and X

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Fermion ↔ Boson
R parity conserving SUSY: Lightest neutralino (Lightest non-colored gaugino) $\tilde{\chi}_1^0 \to$ cold dark matter candidate

After EW symmetry breaking,

$$\tilde{\chi}_1^0 \in (\tilde{B}, \tilde{W}, \tilde{H}_d, \tilde{H}_u)$$

$$\tilde{\chi}_1^+ \in (\tilde{W}^+, \tilde{H}_u^+)$$

$$\tilde{\chi}_1^- \in (\tilde{W}^-, \tilde{H}_d^-)$$
“SUSY + Another Higgs” Menu

- MSSM Higgs (e.g., $A H^\pm$ and $H^+H^-$), Non-MSSM Higgs
- Colored Sectors
  - Gluinos
  - Heavier(?) 1$^{\text{st}}$/2$^{\text{nd}}$ generation scalar quarks (squarks)
  - Lighter(?) 3$^{\text{rd}}$ generation squarks (stop, sbottom)
- Charginos ($C_1, C_2$), Neutralinos ($N_1, N_2, N_3, N_4$), decaying into:
  - Leptons, Higgs, $W, Z$
- LSP?
  - Lightest Neutralino ($N_1$): Bino-like, Wino-like, Higgsino-like...
  - [Example] Higgsino LSP $\rightarrow$ chargino and neutralinos below 200 GeV, with mass splittings of order 10 GeV. It is very difficult for LHC to observe these particles.
  - Gravitino
- Sleptons
  - Selectrons and smuons - mass degenerate?
  - Special case: Stau is lighter.
- Displaced Tracks
- Long-Lived (LL)
- RPV + ???
SUS-16-012: Search for SUSY in Events with a Higgs Decaying to Two Photons Using the Razor Variables.

SUS-16-013: Search for RPV SUSY in 0l and 1l final states.

SUS-16-014: Search for supersymmetry in the multijet and missing transverse momentum channel in pp collisions at 13 TeV.

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SUS-16-026: Search for electroweak SUSY in the WH final state at 13 TeV.

SUS-16-028: Search for direct stop pair production in the single lepton final state at 13 TeV.

SUS-16-029: Search for direct stop pair production in the fully hadronic final state at 13 TeV.

SUS-16-030: Search for SUSY with a customized top tagger at 13 TeV.
Probing a TeV scale at LHC13 😊

No hints of NP (yet) in very diverse search programs 😞

[Simplified Models]

MSSM (>100 parameters) - impossible to have more than 100 measurements at the LHC. Consider a way to test a minimal scenario or simplified scenario, first.

[R-parity]
- R-parity conserving SUSY (with a DM candidate)
- R-parity violating SUSY (with a DM candidate from somewhere else)
“Squarks & Gluinos” PASEs

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SMS Diagrams for Squarks/Gluinos
Squarks/Gluinos Searches

\[ 3 \leq N_{\text{jet}} \leq 4 \]

\[ H_T^{\text{miss}} > 500 \text{ GeV} \]

\[ H_T > 500 \text{ GeV} \]

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CMS SUSY and X

SUS-16-014
Close look at Squarks Results

[Q] Do we still care of the extremly compressed mass scenario?
Closer Look at Bottom Squarks Results

CMS Preliminary

pp → b̄b̄, b̄ → b ū\bar{\chi}^0_1

13 TeV

CMS SUSY and X
Closer Look at Bottom Squarks Results

CMS Preliminary

pp → b¯b, b → b ¯χ₁⁺

13 TeV

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SUS-14-001 (8 TeV)
Compressed Bottom Squark: ISR vs. VBF

Monojet: SUS-14-001

VBF: SUS-14-019

CMS SUSY and X

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Define search bins by $M_R$ and $R^2$

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Gluios with 4 Top Quarks

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Top Squarks

Stop decay $\leftrightarrow$ Stop mixing & neutralino/chargino composition & $\Delta m = m_\tilde{t} - m_{\tilde{\chi}_1^0}$

<table>
<thead>
<tr>
<th>LSP</th>
<th>Allowed stop decays</th>
<th>Why</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\chi}_1^0 = \tilde{B}_3$</td>
<td>$\tilde{t}_L \rightarrow t_L \tilde{\chi}_1^0, \tilde{t}_R \rightarrow t_R \tilde{\chi}_1^0$</td>
<td>U(1) couples L to L and R to R SU(2) only acts on L</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 = \tilde{W}_3$</td>
<td>$\tilde{t}_L \rightarrow t_L \tilde{\chi}_1^0$</td>
<td>Only couples to down-type</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 = \tilde{H}_d^0$</td>
<td>none</td>
<td>Higgs couple L to R (mass term)</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 = \tilde{H}_u^0$</td>
<td>$\tilde{t}_L \rightarrow t_R \tilde{\chi}_1^0, \tilde{t}_R \rightarrow t_L \tilde{\chi}_1^0$</td>
<td></td>
</tr>
</tbody>
</table>

CMS SUSY and X

Off-shell $W$, off-shell top, on-shell top
“Top Squark” PASes

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Top Squark Results

Searches with 0l + 1l

CMS SUSY and X

pp → \tilde{t}\tilde{t}, \tilde{t} → t\tilde{\chi}_1^0

ICHEP 2016

13 TeV

CMS Preliminary

LSP mass [GeV]

m_\tilde{\chi}_1^0 [GeV]

- SUS-16-014, 0-lep (H_T^{miss}), 12.9 fb^{-1}
- SUS-16-015, 0-lep (M_{T2}), 12.9 fb^{-1}
- SUS-16-016, 0-lep (\alpha_t), 12.9 fb^{-1}
- SUS-16-029, 0-lep stop, 12.9 fb^{-1}
- SUS-16-030, 0-lep (top tag), 12.9 fb^{-1}
- SUS-16-028, 1-lep stop, 12.9 fb^{-1}
- Combination 0-lep and 1-lep stop, 12.9 fb^{-1}

- 0-lep (MVA) 19.5 fb^{-1}
- 0-lep + 1-lep + 2-lep (Razor) 19.3 fb^{-1}
- 0-lep (Razor) + 1-lep (MVA) 19.3 fb^{-1}
- SUS-13-039 (monojet stop) 19.7 fb^{-1} (\tilde{t} \to c\chi_1^0)
- 0-lep (hadronic stop) 19.4 fb^{-1}

m_W m_{top} vs stop mass [GeV]

m_t [GeV]
Top Squark Results

2. Searches with 2l

No sensitivity for $\Delta M < 50$ GeV (8 TeV)

Soft OS dileptons + Low N(jet)

$\Delta M < 20$ GeV

SUS-16-025

SUS-14-021

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CMS SUSY and X
Top Squark Results

② Searches with 2l

Sensitivity for $\Delta M < 20$ GeV (13 TeV)

Soft OS dileptons + Low N(jet) $\Delta M < 20$ GeV

CMS Preliminary

SUS-16-025
Compressed Top Squark

Vs.

315 GeV

VBF
SUS-14-019
“Electroweakino” PASes

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Electroweakinos – SMS Diagrams
Electroweak Sector

- **Wino-Chargino and Bino-LSP**
  - Up to ~1000 and ~600 GeV for light slepton case
  - Up to 400 and 120 GeV for W and Z cases

- **Weaker limits for**
  - heavy slepton
  - being Higgsinos
  - small mass difference (compressed mass spectra)
Electroweak Sector

$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$

- $\tilde{\chi}_2^0 \tilde{\chi}_1^0 \rightarrow (H \tilde{\chi}_1^0)(W \tilde{\chi}_1^0)$
- $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow (Z \tilde{\chi}_1^0)(W \tilde{\chi}_1^0)$

Dimuon (3 GeV) + MET (50 GeV) trigger (offline: $p_T > 5$ GeV and MET > 125 GeV) $\rightarrow$ Soft OS dilepton in compressed mass spectra ($\Delta M < 20$ GeV).

- Wino-Chargino and Bino-LSP
  - Up to $\sim 1000$ and $\sim 600$ GeV for light slepton case
  - Up to 400 and 120 GeV for W and Z cases
- Weaker limits for
  - heavy slepton
  - being Higgsinos
  - small mass difference (compressed mass spectra)
Electroweak Sector

CMS SUSY and X

SUS-16-025
Generic M(II) Searches

[SUS-16-021] These categories are based on several observables related to the lepton pair and the hadronic system in order to optimize signal efficiency and background rejection. A fit is employed to search for a possible kinematic edge position in the strong, non-resonant search. In addition, signal regions are included for which excesses were reported by the ATLAS and CMS collaborations using 8 TeV and 13 TeV data. The observations in all signal regions are consistent with the expectations from the standard model, and the results are interpreted in the context of simplified models of supersymmetry.

[SUS-16-021 – Table 6] ATLAS-like Z+jets+MET

<table>
<thead>
<tr>
<th>Total background</th>
<th>6.1$^{+4.0}_{-2.2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>8.0</td>
</tr>
</tbody>
</table>
M(II) Endpoint via Bottom Squark Decays?

SUS-14-014

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32
Bottom Squark Decays

CMS Preliminary

12.9 fb⁻¹ (13 TeV)

pp → bb̄, b̄ → ̄χ₂⁻ + Z, Z → b̄b, ̄χ₂⁻ → ̄χ₂⁻ lν, ̄χ₂⁻ → ̄χ₁⁻ lν, ̄χ₂⁻ → ̄χ₁⁻ lν, ̄χ₂⁻ → ̄χ₂⁻ lν

mₐ = 0.5(mₐ + mₐ); NLO+NLL exclusion

Expected limit, ± 1 (2) σₑₑ

Observed limit, ± 1 σₑₑ

95% CL upper limit on σ [pb]

CMS Preliminary

Events / 5.0 GeV

Signal Region
mₐ = 132.0 ± 3.9 GeV
fitted Nₐ = 147.6 ± 78.9

SUS-16-021
“Photons + MET” PASes

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“Photon(s) + MET” Results

- $p_T(\gamma 1) > 180$
- $S_T(\gamma s, MET) > 80$
- $m_T(\gamma 1, MET) > 300$
Summary of Run 2 in 2016

- For MANY more results, see the public result pages: http://cms-results.web.cern.ch/cms-results/public-results/publications/

- We still search for physics beyond the SM (SUSY, DM \( \chi \), more) at TeV scale ... one of the main motivations for the LHC experiments.

- [13 TeV] CMS covers a large variety of possible final states even with Large pile-up \( <PU> \sim 25-50 \), closing in on challenging scenarios such as compressed SUSY, setting stringent limits on many SUSY scenarios (with a few anomalies?)
**Remarks on Run2 and Beyond**

LHC and beyond will be powerful in producing heavy objects.

- **Run2 at 13 TeV** - the LHC14 is probing a TeV physics: null results on BSM.
- **Run2 at 13 TeV** - Exciting! Understanding the limitations of the LHC13 will be an important step toward the next energy frontier (e.g., 100 TeV)

<table>
<thead>
<tr>
<th>Hadron Collider ($\sqrt{s}$)</th>
<th>Gluino/Squark Mass Reach (M)</th>
<th>$M/\sqrt{s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron (2 TeV)</td>
<td>~400 GeV</td>
<td>0.20</td>
</tr>
<tr>
<td>LHC (8 TeV)</td>
<td>~1.7 TeV</td>
<td>0.21</td>
</tr>
<tr>
<td>LHC (14 TeV)</td>
<td>~2.8 TeV*</td>
<td>0.20*</td>
</tr>
<tr>
<td>FCC (100 TeV)</td>
<td>~20 TeV*</td>
<td>0.20*</td>
</tr>
</tbody>
</table>

(*) just use a naïve scaling

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**CMS SUSY and X**