Searches for SUSY with the CMS experiment

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On behalf of the CMS Collaboration
SUSY (typical) topology

**HOW TO LOOK for SUSY:**

- If R-parity is conserved:
  - S-particles come in pairs
  - LSP is undetected $\rightarrow ME_T$

- Look for events with:
  - Large $ME_T$
  - Large hadronic activity
  - Low energy leptons
SUSY Production at LHC Run I

- SUSY production cross-section at 8 TeV

At 8 TeV, Standard Model probed with success down to cross-sections of 100 fb

- Gluinos & s-quarks:
  - Largest cross-section
  - Probe up to ~1 TeV

- 3rd generation s-quarks:
  - Intermediate cross-section
  - Probe up to ~500 GeV

- Charginos, neutralinos, s-leptons:
  - Smaller cross-section
  - Probe up to ~100-200 GeV
CMS SUSY searches reached a great sensitivity at 8 TeV:

- **EWK SUSY** excluded up to \( \sim 700 \text{ GeV} \) (95\% CL)
- **Gluino** excluded up to \( \sim 1.3 \text{ TeV} \) (95\% CL)
- **Stop** excluded up to \( \sim 750 \text{ GeV} \) (95\% CL)
Today On Run I Analyses

• Will only highlight the latest public results from CMS analyses performed on Run I data, with target to various SUSY signatures:
  ❖ An inclusive SUSY search: the $M_{T2}$ search
  ❖ $3^{rd}$ generation s-quark search
  ❖ Search for compressed SUSY
  ❖ First search for VBF SUSY

• For ALL CMS SUSY public results:
  ❖ [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS)
The $M_{T2}$ Search (SUS-13-019)

- An all hadronic analysis:
  - Veto leptons
  - At least two central jets
  - Large $M_{ET}$

- Event categorization:
  - Jet/b-jet multiplicity
  - $H_T (= \sum_{jets} p_T)$
  - $M_{T2}$

- Data-driven background prediction:
  - $Z(\nu\nu)+jets$ → Irreducible BG
  - Top & $W(l\nu)+jets$ → Lost Lepton
  - QCD multi-jet → Fake $M_{ET}$

➤ Use $M_{T2}$ as discovery variable
➤ SUSY = broad excess in $M_{T2}$ tails
The $M_{T2}$ Search – Results

• Observation is consistent with SM background, in all the search regions

➢ Interpretation in terms of exclusion limits on SUSY production cross-section
The $M_{T2}$ Search – Interpretation

- Interpretation of results in terms of exclusion limits (95% CL)
  - For a **full SUSY model**: cMSSM/mSUGRA
  - For **simplified SUSY models**:
    - Only two examples here

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Hadronic Stop Search (SUS-13-023)

- An all hadronic analysis:
  - Veto leptons
  - At least two central jets
  - Large $M_{E_T}$

- Dedicated top reconstruction
  - CORRAL
  - Efficient for diverse boost
  - Variable jet size clustering

- MVA to define search region
  - Separate training for each signal

- Data-driven/MC background prediction:
  - $ttZ(vv)+jets$ → Irreducible BG
  - $tt, W(l\nu), Z(vv)+jets$ → Electroweak BG
  - QCD multi-jet → Fake $M_{E_T}$
Hadronic Stop Search – Results

- Data found in agreement with SM background prediction
- Exclusion limits in simplified SUSY models with stop

CMS PAS SUS-13-023
Search for Compressed SUSY (SUS-14-021)

- **Target:** stop pair production
  - $m(\text{stop}) - m(\text{LSP}) < m(W)$
  - Four body decay

- **One high $p_T$ jet (from ISR)**
- **Large $M_{E_T}$**
- **At least one $\mu$**
- **Additional $e/\mu$**

- **Search channels:**
  - Single $\mu$ channel
  - Di-lepton channel

- **Data-driven background prediction**

- **Use $M_T$ as discovery variable**
  - From leading $\mu + M_{E_T}$
Search for Compressed SUSY – Results

- Data found in agreement with SM background prediction
- Exclusion limits in simplified SUSY models

**Single $\mu$ channel**

**Di-lepton channel**

Search for VBF SUSY with $s$-$\tau$ (SUS-14-005)

- **Target:** VBF SUSY with $s$-$\tau$

  - At least two isolated leptons
    - $\mu\mu$, $e\mu$, $\mu\tau_h$, $\tau_h\tau_h$
    - Same/Opposite Sign

  - At least two jets
    - VBF-like
    - $\Delta\eta > 4.2$ & $\eta_1 \times \eta_2 < 0$
    - Large $M_{jj}$

  - Large $ME_T$

  - Data-driven background prediction

- **Use** $M_{jj}$ as discovery variable
- **VBF SUSY =** broad excess
Search for VBF SUSY with s-τ — Results

- Data found in agreement with SM background prediction
- Exclusion limits in simplified SUSY models with s-τ
SUSY Searches at 13 TeV

- SUSY cross-section increase is much larger than center-of-mass energy ratio!
  - x50 for 1.5 TeV gluino-gluino
  - x10 for 750 GeV stop-stop
2015: a very important year

• By the end of 2015, expect to collect $\gtrsim 3 \text{ fb}^{-1}$ at 13 TeV

• About same amount of SM events as in whole Run I dataset
  ❖ Most of background estimates are data-driven
  ❖ About same statistical uncertainty on SM background

• SUSY signal has much larger cross-section ($\times 10^{-50}$)
  ➢ Will push our sensitivity to the borders of natural SUSY
    ❖ Gluino mass $\lesssim 1.5$ TeV
    ❖ Stop mass $\lesssim 700$ GeV

❖ Papucci, Ruderman, Weiler, arxiv:110.6926
Using all available luminosity collected at 13 TeV (42 pb^{-1})

Still too few data in order to reach same sensitivity as in Run I

Early data have been used to validate SUSY key observables
  - To validate data-driven background estimation techniques

Will use $M_{T2}$ inclusive search as a reference in the next slides
  - For (my) convenience, since already presented today

Validation has been performed by all SUSY Early Analyses
The $M_{T2}$ Search

- An all hadronic analysis:
  - Veto leptons
  - At least two central jets
  - Large $M_{E_T}$

- Event categorization:
  - Jet/b-jet multiplicity
  - $H_T (= \sum_{jets} p_T)$
  - $M_{T2}$

- Use $M_{T2}$ as discovery variable
  - SUSY = broad excess in $M_{T2}$ tails

Data-driven background prediction:
- $Z(\nu\nu)+jets$ \rightarrow Irreducible BG
- Top & $W(l\nu)+jets$ \rightarrow Lost Lepton
- QCD multi-jet \rightarrow Fake $M_{E_T}$
The $M_{T2}$ Search at 13 TeV: Z/$\gamma$

- $Z(\nu\nu)$+jets events, with genuine $M_{E_T}$ → Irreducible background
  - Estimated from a control sample of $\gamma$+jets events
  - Reweight by expected ratio $R(Z/\gamma)$ in MC
  - Ratio is validated on data in $Z(\ell\ell)$+jets control region

![Graphs showing $M_{T2}$ distributions with $H_T > 450$ GeV and $\geq 2j, \geq 0b$.]
The $M_{T2}$ Search at 13 TeV: lost lepton

- Top and $W(l\nu)+$jets events, with genuine $M_{ET}$ from $\nu$
  - Largely rejected by lepton veto
  - Entering search regions if lepton is ‘lost’
  - Estimate from a control sample of one-lepton events

![Graphs showing $M_{T2}$ distributions for $0$ b-tag and $2$ b-tag events.](image-url)
Summary

• A selection of SUSY searches performed at 8 TeV using data collected by the CMS experiment has been presented.

• Validation of SUSY key observables at 13 TeV has been presented, using $M_{T2}$ search as reference analysis.
  - Data and MC are found in good agreement.

• Run II could be the key to disclose SUSY at the LHC…

• … Let’s cross our fingers!

The end.
Backup
The CMS Experiment at the LHC

CERN Accelerator Complex
Overview

• Introduction
  ➢ Why SUSY?
  ➢ How to look for SUSY

• SUSY Searches at 8 TeV
  ➢ Highlights from searches with Run I data
  ➢ Selection of latest results

• SUSY Searches at 13 TeV
  ➢ First look at Run II data
  ➢ What’s next?
The Standard Model at LHC Run I

• Undeniable success of Standard Model

![Graph showing production cross sections for various processes like W+jets, Z+jets, di-boson, tt+jets, ttZ, ttH. The graph includes data from 7 TeV and 8 TeV CMS measurements compared to theory predictions and CMS 95% CL limit. The graph indicates a production cross section of 100 fb at the top right corner.]
Why SUSY?

- **The fine-tuning problem:**
  \[ (m_H)^2 = (m_{H,0})^2 + (\Delta m_H)^2 \]

- **Solution:**
  - For every fermion, add scalar with same mass/coupling
  - Additional diagram that cancels $\Delta m_H$
  - Double degrees of freedom of theory

\[ \Lambda_{UV} \leq \Lambda_{Planck} \]
How SUSY would look like?

- Neutralinos: $\chi^0_i$  
  \[ (i = 1, \ldots, 4) \]
- Charginos: $\chi^{\pm}_i$  
  \[ (i = 1, 2) \]

- New fundamental symmetry
  
  $Q \, |\text{fermion}\rangle = |\text{boson}\rangle$  \&  $Q \, |\text{boson}\rangle = |\text{fermion}\rangle$

- Stability of mass hierarchy problem
- Facilitation of Great Unification Theory
- Candidate for Dark Matter
SUSY (typical) topology

HOW TO LOOK for SUSY:

- If R-parity is conserved:
  - S-particles come in pairs
  - LSP is undetected $\rightarrow$ $\text{ME}_T$

- Look for events with:
  - Large $\text{ME}_T$
  - Large hadronic activity
  - Low energy leptons
Natural SUSY:

- Higgsino $\lesssim 300$ GeV
- Stop $\lesssim 700$ GeV
- Gluino $\lesssim 1.5$ TeV

Could be $>> 1$ TeV

Papucci, Ruderman, Weiler, arxiv:110.6926
Transverse mass – $M_T$

- Projection of the mass $M$ on the transverse plan

$$M_T^2 = (E_{T,1} + E_{T,2})^2 - (p_{T,1} + p_{T,2})^2$$

- $M_T \leq M$

$\Rightarrow$ **End-point** at parent mass

Discovery of W boson at UA1 (1983)
What is $M_{T2}$?

- The $M_{T2}$ recipe:
  - Two decay chains
  - One LSP in each decay
The $M_{T2}$ Recipe

- The $M_{T2}$ recipe:
  - Two decay chains
  - One LSP in each decay

- Can generalize definition of transverse mass $M_T$:

$$M_{T2}(m_c) = \min \left[ \max(M^{(1)}_T, M^{(2)}_T) \right]$$

- SUSY-like: $M_{T2} \lesssim M_{ET}$
- QCD-like: $M_{T2} \rightarrow 0$
The $M_{T2}$ Search at 13 TeV: invisible $Z$

- $Z(\nu\nu)+$jets events, with genuine $M_{E_T} \rightarrow$ Irreducible background
- Estimated from a control sample of $\gamma+$jets events
- Reweight by expected ratio $R(Z/\gamma)$ in MC

![Graph 1: MT2 vs. Events](image1)

![Graph 2: Photon Purity](image2)
The $M_{T2}$ Search at 13 TeV: $Z/\gamma$

- $Z(\nu\nu)$+jets events, with genuine $M\vec{E}_T \rightarrow$ Irreducible background
- Estimated from a control sample of $\gamma$+jets events
- Reweight by expected ratio $R(Z/\gamma)$ in MC
- Ratio is validated on data in $Z(ll)$+jets control region
The restart of the CMS magnet after LS1 was more complicated than anticipated due to problems with the cryogenic in providing liquid Helium.

Inefficiencies of the oil separation system of the compressors for the warm Helium required several interventions and delayed the start of routine operation of the cryogenic system.

Currently the magnet can be operated, but the continuous up-time is till limited by the performance of the cryogenic system, requiring more frequent maintenance than usual.

A comprehensive program to re-establish its nominal performance is underway.

The recovery activities for the cryogenic system will be synchronized with the accelerator schedule in order to run for adequately long periods.

A consolidation and repair program for the cryogenic system is being organized for the next technical stop at the end of the year.

The Collaboration appreciated the priority being given to this issue by CERN’s Technology Department, which is responsible for the maintenance and operation of the CMS magnet external cryogenic system.