Dark Matter Searches at CMS

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https://indico.triumf.ca/conferenceDisplay.py?confId=1647

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Missing Transverse Momentum (MET) and Dark Matter Particles

- **MET**
  - the form in which the dark matter particles would appear in CMS
  - the imbalance in the transverse momentum of all visible particles
    - the transverse momentum that must have been carried by invisible particles

- **MET reconstruction**
  - requires hermetic detector
  - entails reconstruction of all particles with electromagnetic or strong interactions with precision
  - susceptible to many types of imperfections, e.g., hot calorimeter cells, detector noise, beam-halo particles
Possible dark matter particle pair-production and its signature at LHC

Heavier unstable new particles are produced
Their decay chains end with dark matter particles

e.g. SUSY models

Signature: large MET + jets (+ leptons) (+ photons)

Dark Matter particles are directly produced in pairs after initial-state radiation (ISR)

Signature: large MET + mono-jet (or mono-photon)
Large Hadron Collider (LHC)

Proton-proton runs in the last 3 years

<table>
<thead>
<tr>
<th>Year</th>
<th>$\sqrt{s}$ [TeV]</th>
<th>$\int \mathcal{L} dt^{a}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>7</td>
<td>44.2 pb$^{-1}$</td>
</tr>
<tr>
<td>2011</td>
<td>7</td>
<td>6.1 fb$^{-1}$</td>
</tr>
<tr>
<td>2012</td>
<td>8</td>
<td>23.3 fb$^{-1}$</td>
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$a$ Delivered luminosity at CMS

CMS at LHC Point 5 (P5)
The CMS detector is located underground cavern, ~100 meters below the surface
CMS Collaboration

- 3275 physicists
- 790 engineers and technicians
- 179 institutes
- 41 countries

http://cms.web.cern.ch/content/people-statistics

summer 2012, in a surface building at P5
(CMS-PHO-COLLAB-2012-004)
CMS DETECTOR

- **Total weight**: 14,000 tonnes
- **Overall diameter**: 15.0 m
- **Overall length**: 28.7 m
- **Magnetic field**: 3.8 T

**STEEL RETURN YOKE**
- 12,500 tonnes

**SILICON TRACKERS**
- Pixel (100x150 μm) ~16m² ~66M channels
- Microstrips (80x180 μm) ~200m² ~9.6M channels

**SUPERCONDUCTING SOLENOID**
- Niobium titanium coil carrying ~18,000A

**MUON CHAMBERS**
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

**PRESHOWER**
- Silicon strips ~16m² ~137,000 channels

**FORWARD CALORIMETER**
- Steel + Quartz fibres ~2,000 Channels

**CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)**
- ~76,000 scintillating PbWO₄ crystals

**HADRON CALORIMETER (HCAL)**
- Brass + Plastic scintillator ~7,000 channels
Online Event Selection and Offline Event Reconstruction at CMS

### Online Event Selection
- LHC makes bunches of protons (10^{11} protons in each bunch) cross each other at CMS at 20~40 MHz
- L1 Trigger (custom hardware processors, underground P5)
  - selects interesting events based on signals from muon systems and calorimeters, reducing the event rate to 100 kHZ
- HLT, High-Level Trigger (computing farm, surface building at P5)
  - reconstructs full events and selects interesting events, reducing the event rate further down to 300~500 Hz, the recording rate of the storage system

### Offline Event Reconstruction (on grid, ~60 computing sites worldwide)
- Global Event Description, GED
- Visible particles (muons, electrons, charged hadrons, photons, neutral hadrons)
  - reconstructed and identified by particle-flow (PF) algorithm, which uses all CMS detector subsystems, i.e., trackers, calorimeters, muon systems
- Jets
  - defined as sets of particles clustered by jet-clustering algorithms, e.g., anti-\( k_T \)
  - corrected for detector effects (jet energy corrections, JEC)
  - can be tagged to indicate possible origins, e.g., b-quarks, tau leptons, boosted-W bosons, boosted-top quarks.
- MET (missing transverse momentum)
  - reconstructed from all jets to which JEC is applied and all remaining visible unclustered particles reconstructed by the PF algorithm
  - cleaned for detector noise, cosmic rays, beam halos and corrected for pile-up events, detector mis-alignment
High luminosity, high pile-up events

Inelastic proton-proton cross section at 8 TeV: ~70 mb
for example, if the luminosity is 7 nb⁻¹/s,
490M (= 7 nb⁻¹ x 70 mb) interactions per second
20M times proton bunches cross each other per second (when bunch spacing is 50 ns)
The average numbers of interaction per crossing (pile-up events) would be 24.5 (=490/20)

note: nb⁻¹/s = 10³³ cm⁻²/s

https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults
The image above is the CMS event display showing 29 vertices reconstructed, which correspond to 29 distinct proton-proton collisions in the same bunch crossing.

Charged particles produced in the interesting collision are easy to identify from the vertices.

CMS develops various techniques to mitigate the effect of neutral particles produced in the pile-up events.
Supersymmetry (SUSY) searches at CMS

- SUSY
  - a hypothetical extension of space-time symmetry
  - solves several outstanding problems in particle physics
    - stabilizes radiative corrections to Higgs boson mass
    - unifies the three gauge couplings
    - provides a dark matter candidate
  - a broken symmetry as the exact symmetry contradicts the real world
  - has many parameters (>100), most of which are for its breaking mechanism
    - impractical to constrain by experimental data
  - further hypotheses can reduce the number of parameters, which could be explored at LHC
    - e.g., $m_0 - m_{1/2}$ plane in CMSSM

- SUSY searches at CMS
  - SUSY models predict that SUSY particles will be pair-produced at LHC and each of their decay chains will end with a LSP
    - the final states will contain large MET, jets, and possibly leptons and photons
  - CMS selects events with such final states. Some analyses use discriminating variables such as $\alpha_T$, $M_{T2}$, razor variables
  - CMS evaluates if the rate of such events exceed the SM predictions
    - the SM predictions are estimated by data-driven methods, MC simulation
  - No such excess has been observed by now
  - The results have been interpreted in terms of CMSSM, other SUSY models, and Simplified Models (SMS)
    - exclusion limits have been placed on parameters of the models
**CMS limits in CMSSM (Constrained MSSM)**

- CMSSM was one of the popular SUSY models in interpreting the results of CMS SUSY analyses in 7 TeV data
- CMSSM adds five new parameters to SM
  - $m_0$, $m_{1/2}$, $\tan \beta$, $A_0$, sign($\mu$)
- In most of its parameter spaces, LSP is a neutralino, a dark matter candidate
- The right figure summarizes the exclusion limits of several CMS SUSY analyses on the $m_0 - m_{1/2}$ plane for $\tan \beta = 10$, $A_0 = 10$ GeV, and positive $\mu$

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**Dark matter relic density**

- the corresponding neutralino relic density $\Omega_\chi h^2$ on the $m_0 - m_{1/2}$ plane can be calculated under certain assumptions (arxiv:1202.6580)
- which can be compared with the cold dark matter relic density derived from cosmological observations
  - $\Omega_{\text{cdm}} h^2 = 0.112 \pm 0.006$ [Phys. Rev. **86**, 010001 (2012)]
Interpretation of SUSY results in Simplified Model Spectra (SMS)

- A **simplified model** is defined by a few new particles and their production and decay
  - New particles have the same names as the SUSY particles
    - e.g., gluinos, squarks, stops, neutralinos, charginos, LSP (neutral)
  - New particles are produced in pairs. Each decay chain ends with LSP

- SUSY analysis results are used to set upper limits on the product of the production cross section and branching fraction (\(\sigma \times BR\)) as a function of new particle masses

- SMS allows us to explore wider kinematic phase space of final states than particular models predict

- The upper limits can be compared with predictions of particular SUSY (or non-SUSY) models
  - This comparison can be used to set limits on new particle masses

Example simplified models
Interpretation of SUSY results in Simplified Model Spectra (SMS)

- An interpretation of a CMS SUSY result in a SMS

\[ \tilde{t} \rightarrow t \tilde{\chi}_1^0 \]

top squark pair-production with the final states containing large MET, jets, b-jets, and an isolated lepton

The color scale shows the upper limit on \( \sigma \times \text{BR} \) (the product of the cross section and the branching fraction)

The lines show the contour at which the reference cross sections calculated in SUSY NLO+NLL intersect with the upper limit, indicating the lower mass limits in the reference theory.
Direct dark matter production and its signature at collider

Instead of being at the end of decay chains, dark matter particles could be directly produced in pairs.

The DM pair-production event can be tagged if it occurs after ISR (initial-state radiation).

As the coupling between SM and DM can be evaluated, results can be compared with direct detection results.
The event rates did not exceed the standard model and background expectation in the analysis of 19.5 fb\(^{-1}\) of data at \(\sqrt{s}=8\) TeV.

**The dark matter-nucleon cross section limit:**
- The following assumptions were made in the limit setting:
  - The mediator is heavy (an effective contact operator)
  - The dark matter particles are Dirac fermions
  - The interaction is vector or axial-vector interaction
- The lower limits were set on the cutoff \(\Lambda\)
- The upper limits were set on the dark matter-nucleon cross section
  - The vector interactions correspond to the spin-independent interactions
  - The axial-vector interactions correspond to the spin-dependent interactions
- The limits were compared with the limits from the direct detection results
Dark matter searches in monojet events in CMS

Limits on $\Lambda$

\[ \mathcal{O}_V = \frac{(\bar{\chi} \gamma_{\mu} \chi)(\bar{q} \gamma^\mu q)}{\Lambda^2} \]

Limits on $\Lambda$ as functions of dark matter particle mass when the mediator is heavy

Limits on $\Lambda$ as functions of the mediator mass when the mediator is light for two different dark matter particle masses each for three different mediator widths
A monojet event
EX0-12-048

CMS Experiment at LHC, CERN
Data recorded: Fri Oct 5 20:41:32 2012 CEST
Run/Event: 204553 / 26729384
Lumi section: 31

Jet 0,
et = 921.98
eta = -0.463
phi = 2.508

MET 0,
pt = 913.68
eta = 0.000
phi = -0.657
Summary

- Dark matter was searched for in proton-proton collision data at $\sqrt{s}=7$ and 8 TeV collected with the CMS detector at LHC before the Long Shutdown 1.

- If produced at LHC, dark matter will be invisible to the CMS detector; their existence can be inferred by large MET.

- CMS SUSY search results were summarized as exclusion limits on a $m_0-m_{1/2}$ plane in CMSSM. The limits can be compared with calculated corresponding neutralino relic density on the plane and the cold dark matter density derived from cosmological observations.

- CMS SUSY search results were interpreted in Simplified Models (SMSes), in which LSPs are dark matter candidates. In each SMS, upper limits were placed on the product of the production cross section and branching fraction. With the benchmark theory, exclusion limits were set on the masses of the produced new particles in the SMS.

- Direct productions of the pairs of dark matter particles can be tagged by the initial-state radiation (ISR). The CMS monojet analysis searched for events with only the final state of ISR and large MET and placed upper limits on the dark matter-nucleon cross sections, which can be compared with direct detection results.

- Analyses of $\sqrt{s}=8$ TeV data collected in 2012 are still ongoing. Further, after the Long Shutdown 1, the CMS will collect proton-proton collision data at higher energy and at higher rate. The dark matter searches in CMS will continue.

Tai Sakuma, 15 April, 2013
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