Dark matter search with top quarks

Sabine Crépé-Renaudin
Laboratoire de Physique Subatomique et de Cosmologie, Grenoble France
 Disclaimer

 ➔ Chose not to be exhaustive but more to show the strategy for the DM searches

 ➔ Very rich search field
  • will only show 13 TeV analysis results with at least 2015+2016 statistics
  • Not enough time to describes in detail the analysis strategies
Dark matter: observations

Evidence of dark matter

- From astrophysics and cosmology observations at **different scales**

  **Galaxy rotation**
  
  **Galaxy clusters via X-rays and gravitational lensing, collisions**

  
  **Nucleosynthesis**

  **Cosmic microwave background**

  **Large scale structure formation**

  ➔ **Results consistent: need of a new kind of matter**
Dark matter: what do we know about?

Properties

• It makes up 85% of the matter in the Universe
  • It is massive

• It interacts weakly with ordinary matter (at least through gravitation)
  • It is neutral

• It interacts weakly with itself

• It is stable (a minima very long-lived, order of the age of the universe)
  • \(\Rightarrow\) Ruled out SM Z and Higgs
  • Need a symmetry to prevent it to decay ex T-parity

• It is “cold” ie non relativistic
  • \(\Rightarrow\) ruled out SM neutrinos (also not enough massive)
Dark matter: which candidates ? Associated theories ?

Candidates
- WIMPs = Weakly Interacting Massive Particles
  - WIMP “miracle”: weak cross-section + particle mass ~1 TeV ~ relic density
    - Susy neutralinos
    - Kaluza-Klein photon
- Very Weak Interacting Massive Particles
  - gravitinos
  - Axions: to solve the strong CP problem, unstable but long lived
  - Sterile neutrinos: to explain neutrino masses
  - Kaluza Klein gravitons
  - …
- Could be also a more complex sector with several particles and interactions

Theories
- Supersymmetry
  - Symmetry: R-parity
- Extra dimensions
  - Symmetry: KK parity
- Little Higgs
  - Symmetry: T-parity
  - QCD axions
  - …
Dark matter: how to detect it?

Indirect detection
- Search for charged cosmic rays, gamma rays or neutrinos

Collider search
- Produce DM particles from SM particles collisions

Direct detection
- Use scattering of DM on a nucleus

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Dark matter search at LHC

Search for particles from (UV) complete theories

→ simulate particles decays, dark matter reconstructed as missing $E_T$
  • Supersymmetry
  • Extra dimensions
  • Little Higgs

Use of effective Field theory

→ more general search, many theories show common low energy behaviour

$q \rightarrow \chi$ mediator $M$

\[
\frac{g^2}{q^2 + M^2} \rightarrow \chi
\]

If $M \gg q$

\[
\frac{g^2}{M^2} = G_{\text{eff}}
\]

→ describe new interactions with few operators
Dark matter search at LHC: effective theory

Use of effective Field theory

- Mono X search: use of a radiated particle to trigger the event

\[
\begin{align*}
q & \xrightarrow{X} \chi \\
q & \xrightarrow{\chi} X
\end{align*}
\]

\(X = \gamma, \text{jet}, \ldots\)

\(\chi \chi = \text{MET}\)

\(\Rightarrow\) LHC Run-1 focus

- Advantages:
  - model independent
  - Allow to translate LHC results into (in)direct search frames (with some care on the hypothesis)

- Limitations:
  - EFT valid only if \(M \gg q\) \(\Rightarrow\) Run 1 LHC limits \(M \sim 1\) TeV \(\Rightarrow\) should not use energy > 1 TeV
  - Loose correlations that can be used in complete theory
Dark matter search at LHC: simplified models

Simplified models
- In between EFT and complete theory: add a single DM candidate (Dirac fermion) and a mediator
  
  - Allow to relax the $q^2$ limit but more model dependent
  - Allow to use other signatures to probe mediator and thus constrains the model

Common model and scenarios
- ATLAS/CMS + theory Dark Matter forum defined the DMSimp model (arXiv:1507.00966)
- Recommendations for benchmark scenarios (arXiv:1703.05703)
- Madgraph implementation (LO/NLO)
Complementarity

Combination of mono-jet, mono-photon and di-jets

- Note: couplings dependence is important

\[ g_{DM} = 1, \ g_q = 0.25, \ g_l = 0 \]

\[ g_{DM} = 1, \ g_q = 0.1, \ g_l = 0.1 \]
Complementarity

Combination of mono-jet, mono-photon and di-jets

- Sensitivity depends also on the mediator coupling type

Vector mediator

Axial-vector mediator

CMS Preliminary

LHCP 2017

CMS Preliminary

LHCP 2017
Comparison with direct detection

**ATLAS**

Vector mediator $g_q=0.25$, $g_i=0$

Vector mediator, Dirac DM $g_q=0.25$, $g_i=0$, $U_{pm}=1$

CMS Preliminary

CMS observed exclusion 95% CL

**CMS**

Vector mediator $g_q=0.25$, $g_i=0$

Axial-vector mediator $g_q=0.25$, $g_i=0$

CMS Preliminary

CMS observed exclusion 95% CL

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ATLAS Preliminary July 2017

DM Simplified Model Exclusions

Dijet

E_{T}^{miss}+X

Dirac DM $g_q=0.25$, $g_i=0$, $U_{pm}=1$

ATLAS limits at 95% CL, direct detection limits at 95% CL

E_{T}^{miss}+X

CMS observed exclusion 95% CL

OMNIT

PandaX

LUX
Collider Search: where does top quark join in?

Supersymmetry
- Naturalness requires SUSY to have « light » stop (~TeV)
- Stop decays in top + MET, or similarly to top decay unless compressed scenario
- R-parity conservation $\Rightarrow$ stop produced by pair
- Top quarks found also in gluinos decays

Simplified models

Mediator: (axial)vector, (pseudo)scalar

$\bar{t}t + DM$

(pseudo)scalar, 2HDM + (pseudo)scalar

Single top + DM FCNC

FCNC, coloured charged scalar
Supersymmetry: stop search

Top squarks

- Susy = symmetry between fermion and bosons
  - $t_\sim L$ and $t_\sim R$ superpartners of $t_L$ and $t_R$,
  - mix in 2 mass eigenstates $t_\sim 1$ (the lightest) and $t_\sim 2$
- Significant mass-splitting between the 2 stops is possible due to the large top-quark Yukawa coupling + renormalisation group equations drive third-generation squarks masses to values significantly lower than those of the other generations.

DM particle

- The charginos $\chi^-\pm$ and neutralinos $\chi^0$ are the mass eigenstates formed from the superposition of the charged and neutral SUSY partners of the Higgs and electroweak gauge bosons
  - higgsino, wino and bino
- Neutralino is often considered as the Lightest Supersymmetric Particle (LSP)
Supersymmetry: stop search

Search for stop pairs

- Decays depend on the susy parameters via the particle mass hierarchy, the mixing between $t^\pm_L$ and $t^\pm_R$ and the nature of the neutralino (which mixture of higgsino, wino and bino)

Example of mass spectra considered in the ATLAS 1 lepton analysis

- Analyses divided
  - with respect to final states (0, 1, 2 leptons) as for any top pair analysis
  - and subdivided according to decay chain
Supersymmetry: stop search

Decay chain

- Different diagrams are taken into account to cover the largest possible space in the parameter phase space

Example: considered decay chain in the pure bino LSP hypothesis (from ATLAS 1 lepton analysis)

- Note: in the boundary regions, sensitivity decrease because of the kinematics
Susy Stop pair search: summary

Latest summary plots with references of papers
Gluinos searches

Top quarks appear also in gluinos/b squark decays

- Results obtained with an analysis using final states with two same-sign or three leptons and jets
  [arXiv:1706.03731]
Simplified model: top pair + DM

Fermionic DM particle produced through the exchange of a spin-0 mediator

- colour-neutral scalar $\phi$ or pseudo-scalar particle $a$
- Final state top pair + MET

- Not far from susy searches but kinematics different
- More complex models derived from 2HDM could be also considered:
  - Choice of DM forum: 2HDM (type II) + pseudo-scalar $\Rightarrow$ close kinematics, need however to add heavy pseudo-scalar $A$ decays

Couplings

- couplings of the mediator to the SM fermions are constrained by precision flavour measurements
  - Minimal Flavour Violation assumed: same structure as in the Standard Model.
  - Interaction between $\phi/a$ and SM matter $\propto$ fermion mass via Yukawa coupling $\Rightarrow$ top

Parameters:

- $m(\phi/a)$, $m(\chi)$, $g_\chi$, and the flavour-universal $g_q$ coupling, to reduce parameter number: $g_\chi = g_q = g$
- Minimal width assumed taking into account only couplings and considered particles mass
Simplified model: top pair + DM - CMS

→ CMS 0,1,2 L combination CMS-PAS-EXO-16-049

Limits on coupling

Scalar

Pseudo-scalar
Simplified model: top pair + DM - ATLAS


Vs mediator mass

Vs DM mass

- Comparison (2L) with direct detection spin independent

Direct detection not competitive for pseudo-scalar mediator
Single top + DM

Models

• "Non resonant": FCNC producing a top quark + a vector boson that decays to DM

\[ \begin{array}{c}
  \text{g} \\
  \text{u} \\
  \text{V} \\
  \text{t}
\end{array} \]

Couplings:

- \( g_\chi^V \) and \( g_\chi^A \) \( V= \text{vector, } A=\text{axial-vector} \)
- \( g_u^V, g_u^A, g_d^V, g_d^A \), are 3 \( \times \) 3 flavour matrices
  - \( g_u^V - g_u^A = g_d^V - g_d^A \) to preserve SU(2)_L
  - Choice: \( g_u^V = g_d^V \equiv g_q^V \), and \( g_u^A = g_d^A \equiv g_q^A \)

• "Resonant": coloured charged scalar \( \phi \) that decays to a top quark and a DM fermion \( \psi \)

\[ \begin{array}{c}
  \text{d} \\
  \phi \\
  \text{t}
\end{array} \]

Couplings:

- \( \phi \) to down-type quarks: \( a_q \) (scalar) and \( b_q \) (pseudo-scalar)
- \( \phi \) to DM \( \psi \): Similarly, \( a_\psi \) and \( b_\psi \)
- Hypothesis: \( a_q = b_q = 0.1 \) and \( a_\psi = b_\psi = 0.2 \).
Single top +DM

Analysis

- CMS, hadronic top decay [arXiv:1801.08427]
- Top-tagging: BDT with substructure variable to distinguish top from light jet (quark/gluon)

Non resonant: vector couplings

Non resonant: axial-vector couplings

- Limits also given for couplings vs m(V)
Simplified model: (axial-)vector mediator

Model:

\[ \mathcal{L}_{\text{vector}} = g_q \sum_{q=u,d,s,c,b} Z_q^i \bar{q}^i q + g_{DM} Z_{DM}^i \bar{q}^i q + g_{SM} Z_{SM}^i \bar{q}^i q \]

\[ \mathcal{L}_{\text{axial-vector}} = g_q \sum_{q=u,d,s,c,b} Z_q^i \bar{q}^i q + g_{DM} Z_{DM}^i \bar{q}^i q + g_{SM} Z_{SM}^i \bar{q}^i q \]

Scenarios:

- Free parameters: \( m(\chi), m(\text{med}), g_{DM}, g_q, g_l \)
- Minimal width computed according to couplings and considered particles mass
  - mediator decays considered = ones strictly necessary to maintain model self-consistency

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>( g_q )</th>
<th>( g_{DM} )</th>
<th>( g_l )</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1: vector model with only couplings to quarks</td>
<td>0.25</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>V2: vector model with small couplings to leptons</td>
<td>0.1</td>
<td>1.0</td>
<td>0.01</td>
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<tr>
<td>A1: axial-vector model with only couplings to quarks</td>
<td>0.25</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>A2: axial-vector model with equal coupling to quarks &amp; leptons</td>
<td>0.1</td>
<td>1.0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Chosen to show the complementarity of the DM production analyses (mono X) and the mediator-to-visible analyses (di X)
Top pair

Analysis

• ATLAS, lepton+jets final state, resolved and boosted regimes \textbf{arXiv:1804.10823}

• Not competitive with dijets limits, because of the BR
  ➔ will be more interesting to look at (pseudo-)scalar mediators
Summary and conclusion

DM search is a very active field

Beyond search using complete model like Susy, strategy evolved from run1 to run 2 from EFT to quite general simplified models

- Allow to show complementarity between collider search and direct detection experiments
- Allow to take advantage of the wide analyses sensitivities at LHC to constrain models using the analyses without DM particle in the final state
- Common benchmark model defined at DM forum help to focus in interested regions

Top quark is an interesting tool in that frame

- Already a lot of results and more to come
C'EST TOUT POUR AUJOUR D'HUI
TO GO FURTHER...
Susy Stop pair search: summary

Other scenarii
**Susy CMS summary**

Selected CMS SUSY Results* - SMS Interpretation

<table>
<thead>
<tr>
<th>CMS Preliminary</th>
<th>( \sqrt{s} = 13 \text{TeV} )</th>
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<tbody>
<tr>
<td>( L = 12.9 \text{ fb}^{-1} )</td>
<td>( L = 35.9 \text{ fb}^{-1} )</td>
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</tbody>
</table>

For decays with intermediate mass,\
\[
m_{\text{intermediate}} = x \cdot m_{\text{Mother}} + (1-x) \cdot m_{\text{LSP}}
\]

*Observed limits at 95% C.L. - theory uncertainties not included

Only a selection of available mass limits. Probe "up to" the quoted mass limit for \( m_{\text{LSP}} = 0 \) GeV unless stated otherwise

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*Top LHC France 2018 Workshop*  
*Sabine Crépé-Renaudin*
### ATLAS SUSY Searches - 95% CL Lower Limits

**December 2017**

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell ), ( \mu ), ( \tau )</th>
<th>Jets</th>
<th>( M_{\text{miss}} )</th>
<th>Mass Limit</th>
<th>( \sqrt{s} = 7, 8, 13 \text{ TeV} )</th>
<th>Reference</th>
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*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.*
Bullet cluster
Bullet cluster

Hot gaz (X-ray)
Bullet cluster

Mass (gravitational lensing)
Bullet cluster