Complementarity of the mono-X and SUSY searches

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**Summary of CMS SUSY Results** in SMS framework

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

<table>
<thead>
<tr>
<th>m(mother)-m(LSP)=200 GeV</th>
<th>m(LSP)=0 GeV</th>
</tr>
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<tbody>
<tr>
<td>SUS 13-019 L=19.5 fb</td>
<td></td>
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<td>SUS 13-008 SUS 13-013 L=19.5 fb</td>
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*Observed limits, theory uncertainties not included

**CMS Preliminary**

Only a selection of available mass limits

Probe *up to* the quoted mass limit
ATLAS SUSY Searches* - 95% CL Lower Limits

### Inclusive Searches

- **Scalar charm, \( \tilde{c} \rightarrow \chi_1 \ell \nu \)**
- **GMSB (\( \tilde{q} \) NLSP)**
- **GMSB (\( \tilde{g} \) NLSP)**
- **Gravitino LSP**

### First search direct production

- **Mixed LSP, \( \tilde{t}_1 \rightarrow \tilde{b}_1 \tilde{W}^- \tilde{\chi}^0_1 \)**
- **GMSB, \( \tilde{b} \rightarrow c \tilde{t}_1 \tilde{\chi}^0_1 \)**
- **GMSB, \( \tilde{g} \rightarrow c \tilde{t}_1 \tilde{\chi}^0_1 \)**

### EW direct

- **Direct \( \tilde{t}_1 \rightarrow \tilde{b}_1 \tilde{W}^- \tilde{\chi}^0_1 \)**
- **Stable, stopped \( \tilde{b}_1 \rightarrow R\) hadron**
- **GMSB, \( \tilde{g} \rightarrow c \tilde{t}_1 \tilde{\chi}^0_1 \)**

### Long-lived particles

- **Left-handed neutrino, \( \tilde{\nu}_L \rightarrow X \tilde{\nu}_R \)**

### Other

- **Scalar charm, \( \tilde{c} \rightarrow \chi_1 \ell \nu \)**

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**Model**

- **MSUGRA/CMSSM**
- **GMR**
- **GMSB**
- **GMSB (\( \tilde{q} \) NLSP)**
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- **Gravitino LSP**

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<tr>
<th>Model</th>
<th>Jets ( E_T^{miss} )</th>
<th>( T_{1/2} )</th>
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*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1\( \sigma \) theoretical signal cross section uncertainty.*
SUSY and DM complementarity

SUSY searches $\rightarrow$ Stuff $+$ MET (assuming LSP DM)
SUSY and DM complementarity

SUSY searches $\rightarrow$ Stuff + MET (assuming LSP DM)

- Stuff generally (but not always) means $\geq 2$ particles
- Vast majority of searches are NOT SUSY specific
  - Simply looking for a heavy state that decays to MET + ....
  - Majority of searches target decay products
SUSY and DM complementarity

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SUSY searches $\rightarrow$ General DM searches
SUSY and DM complementarity

Mono-X searches $\rightarrow$ Singular stuff $+$ MET
SUSY and DM complementarity

Mono-X searches → Singular stuff + MET

- Mono-X searches are a continuation of the ‘SUSY’ analyses to lower multiplicity
- Jets \((g, q, b, t's)\), \(W^\pm, Z^0, \gamma, h^0\)
- Difference is that searches (mostly) aim to target initial state radiation (ISR)
Question: How many LHC monojet searches have there been (7, 8 and 13 TeV)?
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ANSWER: 1
When is a Mono-X really a Mono-X?

- Early ATLAS mono-jet conf note vetoed events with 2 jets
  - CMS only vetoed a third jet
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<td>$p_T(j_1) &gt; 100$ GeV</td>
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<td>$pp \rightarrow \tilde{\chi}\tilde{\chi} j \ (+N j)$</td>
<td>0.005</td>
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<tr>
<td>$pp \rightarrow \tilde{\chi}\tilde{\chi} j j \ (+N j) , p_T(j_2) &gt; 30$ GeV</td>
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- Results show that jet-vetoes should be handled with care.
  - CMS ‘mono-jet’ @ 13 TeV allows ANY jet multiplicity
- Only ATLAS $Z \rightarrow \ell^+\ell^-$ now has explicit jet veto
  - Kill $t\bar{t}$ background
Differences

• Almost no ‘pure’ mono signatures
  • More just lower multiplicity in general
  • Very large signal region overlaps with SUSY searches

• Taking ATLAS and CMS together
  • Almost no kinematical gaps between mono-X and SUSY searches
  • One set of searches can be viewed as the continuation of the other

• Difference is more in terms of models investigated
  • ATLAS mono-jet and mono-photon are now listed under both DM and SUSY searches
  • CMS also includes mono-jet under SUSY search
Which Mono-X should we concentrate on?

Assuming ISR signal, which Mono-X is best?

- All possibilities currently targeted,
  - Jets \((g, q, b, t's), W, Z, \gamma, h^0\) ?
  - Dominant background is normally \(X+ (Z \rightarrow \nu \bar{\nu})\)
Which Mono-X should we concentrate on?

Ignoring systematics, want to maximise,

$$\sigma_{\text{stat}} = \frac{S}{\sqrt{S + B}}$$

• For jets, $S \propto g^2 s$,
  $B \propto g^2 s$

• For $\gamma$, $S \propto g^2 e$,
  $B \propto g^2 e$

• Significance, $\sigma_{\text{stat, jet}} \propto g s$,
  $\sigma_{\text{stat, } \gamma} \propto g e$

Monojet usually provides best sensitivity to ISR signal

• Constructive interference motivated mono-$W$

• Models break $\text{SU}(2)_L$ (Bell, Cai, Dent, Leane, Weiler; 2015)
  (Haisch, Kahlhoefer, Tait; 2016)

• Exceptions $\rightarrow$ Mono-X produced 'internally', via decay or heavy flavour interaction
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How realistic is the ISR DM signal???

Original motivation were the effective models → integrate out heavy mediator.

\[
\frac{1}{p^2 - M^2_\Omega} - \frac{1}{M^2_\Omega} \left( 1 + O\left(\frac{p^2}{M^2_\Omega} + \ldots\right) \right)
\]
How realistic is the ISR DM signal???

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\[
\frac{1}{p^2 - M_\Omega^2} \rightarrow - \frac{1}{M_\Omega^2} (1 + O(p^2/M_\Omega^2 + ...)
\]

- We have an unavoidable SM interaction
- We want a model that is theoretically consistent
  - Gauge Invariance
  - Unitarity
How realistic is the ISR DM signal???

- Gauge Invariance
  - Dilepton resonance searches
  - Electroweak precision observables
- Relatively small regions of parameter space where,
  - Relic abundance is satisfied
  - LHC monojet search is most constraining
- t-channel models
  - This is essentially SUSY!!!!
- Is the monojet actually worth looking at?

Kahlhoefer, Schmidt-Hoberg, Schwetz, Vogl; 2015
Co-annihilation

SUSY → Bino has small $g_1$ coupling

- Small annihilation cross-section
- Generically predicts DM over-abundance
- Co-annihilation is one mechanism to reduce this
- Requires small mass splitting between co-annihilating states

Model independent → Co-annihilation codex
(Joachim tomorrow)


Baer, Choi, Kim, Roszkowski; 2014
Compressed Spectra

- Co-annihilating particle may have far larger LHC cross section
- Small mass splitting means that visible particles are soft
- Natural to ask whether ISR helps
Is this a Monojet signal?

Do the visible decay products stay soft under ISR boost?

In rest frame of decaying particle,

$$P_{LSP} = P_{vis} = \frac{M^2 - m^2}{2M}$$

As a function of mass difference, $$\delta M = M - m$$,

$$P_{LSP} = P_{vis} = \delta M - \frac{\delta M^2}{2M}$$

In boosted frame, $$E = \gamma M$$ for decaying particle,

$$P'_{LSP} \sim \gamma \delta M \pm \gamma \beta m, \quad P'_{vis} \sim \gamma \delta M \pm \gamma \beta \delta M$$

Boosts only act multiplicatively on soft particle momenta $$\rightarrow$$ Monojet has potential.
Monojet searches for SUSY

For compressed SUSY spectra, monojet is the most constraining

Monojet searches for SUSY

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CMS Stop Search (JHEP 06 (2015) 116)

\[
\tilde{t}\tilde{t} \text{ production, } \tilde{t} \rightarrow t \tilde{\chi}_1^0 / c \tilde{\chi}_1^0
\]
Monojet searches for SUSY

For compressed SUSY spectra, monojet is the most constraining

CMS Sbottom Search (JHEP 06 (2015) 116)
Monojet searches for SUSY

For compressed SUSY spectra, monojet is the most constraining

ATLAS Squark Search (JHEP 10 (2015) 054)
Monojet searches for SUSY

- These are the only SUSY monojet studies so far (+ ATLAS sbottom)

- My opinion,
  - All compressed (but prompt) scenarios will be most constrained by monojet
  - As mass scale increases, sensitivity of multijet susy search and monojet will converge

- Once again emphasise that this is not SUSY specific!

Dreiner, Kraemer, JT; 2012
ISR searches for electroweak SUSY

Of particular interest is the neutralino/chargino system

- **Neutralinos**, \( \mathcal{L} = -\frac{1}{2} \tilde{\nu}^0 \tilde{\nu}^0 + \text{h.c.} \)

\[
\mathbf{M}_{\tilde{\nu}^0} = \begin{pmatrix}
M_1 & 0 & -c_\beta s_W m_Z \\
0 & M_2 & c_\beta c_W m_Z \\
-c_\beta s_W m_Z & c_\beta c_W m_Z & 0 \\
s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu \\
s_\beta s_W m_Z & -s_\beta c_W m_Z & 0
\end{pmatrix}
\]

- **Charginos**, \( \mathcal{L} = -\frac{1}{2} (\tilde{\chi}^+ \mathbf{X}^T \mathbf{X} \tilde{\chi}^- + \mathbf{X} \tilde{\chi}^- \tilde{\chi}^+) + \text{h.c.} \)

\[
\mathbf{X} = \begin{pmatrix}
M_2 \\
\sqrt{2} c_\beta m_w \\
\sqrt{2} s_\beta m_w \\
\mu
\end{pmatrix}
\]

Compressed if,

- \( \mu \ll M_1, M_2 \) (Higgsino)
- \( M_2 \ll M_1, \mu \) (Wino)
- \( M_1 \sim M_2 \) (mixed)
Monojet,
- Cross-sections are too small to go beyond LEP with collected data
- At 300 fb$^{-1}$ LHC,
  - Gaugino < 200 GeV, Higgsino < 150 GeV
  - Assuming 1% systematic (using data driven $Z \rightarrow \nu\nu$)

(Schwaller, Zurita; 2013)
Improvements?

Improving the LHC reach for SUSY gauginos has received significant attention

- Can we target the soft decay products?
- Looking at distributions, this seems very challenging
  - MET softer than SM background
  - Leptons softer than SM background

(Gori, Jung, Wang; 2013)
Improvements?

Use hard ISR to trigger and transform distributions
(Gori, Jung, Wang; 2013)
Problem Solved?

- Reach is improved but compression hole still not filled
  - Relies on soft leptons
    \[ 7 < p_T(\ell) < 50 \text{ GeV} \]
  - Invariant mass
    \[ 12 < m_{\ell\ell} < \Delta m_{\tilde{\chi}_2-\tilde{\chi}_1} \]
- How realistic are these cuts?
  - No ATLAS or CMS analysis with \( 2\ell, p_T < 10 \text{ GeV} \)
  - ISR associated topology not investigated so far

\[ \text{(Gori, Jung, Wang; 2013)} \]
Go even further?

Why is this difficult,

- Reconstruction of soft leptons
- Meson ($J/\psi$, $\Upsilon$) backgrounds for $m_{\ell\ell} < 12$ GeV
- Jet fakes???
- Double parton scattering

Theory study (Higgsinos) (Han, Kribs, Martin, Menon; 2014)

- None seem to be a showstopper
- Interesting to look at soft $m_{\ell\ell}$

This is a refining of the original monojet idea
Further compression

As we go to very compressed scenarios < 2 GeV, decays are no longer prompt

Signatures include,

- Displaced vertices
- Disappearing tracks
- Charged tracks
- Stopped heavy particles

Neither mono-X nor exclusively SUSY but I think should be considered more in a general DM context.
Example: Stau Co-annihilation

Stau co-annihilation is well known from the CMSSM (mSUGRA).

- Lifetime of stau varies with compression
- Different lifetimes sensitive to different searches
- No displaced vertex search for solitary same flavour leptons ($e\mu$ is CMS)
- Moving away from SUSY, are we missing potential signatures?
  - Soft leptons, jets, photons
- Can displaced vertex be improved in combination with monojet?
  - Disappearing track uses a jet trigger

(Evans, Shelton; 2016)
HSCP: (CMS; JHEP01 (2015) 068)
DT: (CMS; JHEP01 (2015) 096)
e$\mu$: (CMS; PRL.114.061801)
Motivation for other mono-X

If monojets are most sensitive for ISR, are other mono signatures still motivated?

- Higgs portal models heavily investigated
  - Simplest realisation difficult for LHC when $m_{DM} > \frac{1}{2} m_{h^0}$
- Extend to a Two Higgs Doublet Model
  - Resonant production of s-channel heavy Higgs
  - Example here is pseudo-scalar Higgs portal

(Nomura, Thaler; 2009), (No; 2015)

Many other examples

- Best choice for experimental interpretation?
Conclusion

Mono-X and SUSY searches are clearly very complementary

- One is essentially a continuation of the other
- Both search strategies could be classed as ‘General DM searches’

Nice if more SUSY signatures are investigated

More importantly → are we missing potential signals?

- ISR + soft stuff
  - Experimentally very challenging
- Long lived states?

All Mono-X states should be investigated

- Is the effective ISR interpretation always so useful?
- Perhaps other interpretations (and focus) are better for non monojet signals?