SEARCHES FOR DARK MATTER PRODUCTION AT THE LHC
MITCHELL WORKSHOP ON COLLIDER AND DARK MATTER PHYSICS 2015
Searches for Dark Matter (&SUSY)

Direct Searches

DM?

Indirect Searches
Searches for Dark Matter (&SUSY)

- Direct Searches
- DM?
- Indirect Searches
Characterizing Dark Matter Searches

complete theory vs. simple interpretations

SUSY

Example:
Effective Field Theory
Simplified models
Characterizing Dark Matter Searches

complete theory vs. simple interpretations

Example:
Effective Field Theory
Simplified models
Supersymmetry

Extension of the Standard Model: Introduce a new symmetry
Spin $\frac{1}{2}$ matter particles (fermions) $\Leftrightarrow$ Spin 1 force carriers (bosons)

**Standard Model particles**

- Quarks
- Leptons
- Force particles

**SUSY particles**

- Squarks
- Sleptons
- Susy Force particles

New Quantum number: R-parity:

\[ R_p = (-1)^{B+L+2s} \]

- SUSY particles are produced in pairs
- The lightest SUSY particle (LSP) is stable

R-parity conservation:

- +1 SM particles
- -1 SUSY particles
What do we call a “SUSY search”? 

The definition is purely derived from the experimental signature. Therefore, a “SUSY search signature” is characterized by:

- Lots of missing energy, many jets, and possibly leptons in the final state

RP-Conserving SUSY is a very prominent example predicting this famous signature but …

**Missing Energy:**
- from LSP

**Multi-Jet:**
- from cascade decay (gaugino)

**Multi-Leptons:**
- from decay of charginos/neutralinos
What is its experimental signature?

... by no means is it the only New Physics model predicting this experimental pattern. Many other NP models predict this genuine signature.

Model examples are Extra dimensions, Little Higgs, Technicolour, etc but a more generic definition for this signature is as follows.

**Missing Energy:**
- Nwimp - end of the cascade

**Multi-Jet:**
- from decay of the Ns (possibly via heavy SM particles like top, W/Z)

**Multi-Leptons:**
- from decay of the N’s
Inclusive SUSY Searches in 2013

ATLAS Preliminary
\[ \int \mathcal{L} \, dt = 20.1 - 20.7 \, fb^{-1} \] \[ \sqrt{s} = 8 \, TeV \]

MSUGRA/CMSSM: \( \tan(\beta) = 30, \ A_0 = -2m_0, \ \mu > 0 \)

\[ \text{Msq} = 1800 \, \text{GeV} \]

\[ \text{Mg} = 1400 \, \text{GeV} \]

95% CL limits. \( \sigma_{\text{SUSY}} \) not included.

- Expected 0-lepton, 2-6 jets
- Observed ATLAS-CONF-2013-047
- Expected 0-lepton, 7-10 jets
- Observed ATLAS-CONF-2013-054
- Expected 0-1 lepton, 3 b-jets
- Observed ATLAS-CONF-2013-061
- Expected 1-lepton + jets + MET
- Observed ATLAS-CONF-2013-062
- Expected 1-2 taus + jets + MET
- Observed ATLAS-CONF-2013-066
- Expected 2-SS-leptons, 0 - \( \geq 3 \) b-jets
- Observed ATLAS-CONF-2013-067
Inclusive SUSY Searches in 2013

The LHC has pushed the mass scale in constraint SUSY models to a new level!
Inclusive SUSY Searches in 2013

Bottom line today:
Impressive variety of powerful SUSY searches have been executed but only limits (at least so far).

The LHC has pushed the mass scale in constraint SUSY models to a new level!
Global Fit to indirect and direct constraints on SUSY!

Other “fitter” groups find very similar results: e.g.

Fittino group: arXiv:1204.4199
CMSSM: Evolution with time

- 2008 Pre-LHC
- 2011 post-LHC + Xenon100
- 2012 post-LHC Higgs discovery
- 2012 post-LHC-2011+2012
Constrained SUSY models like the CMSSM are severely put under pressure by the LHC limits!

Experiments define new benchmarks and less complex SUSY models in order to present the interpretation of their searches.

Aided by the discovery of a Higgs boson, the focus of the experimental search strategy and corresponding interpretation shifts towards other scenarios like “Natural SUSY” (i.e. 3rd generation squark searches).
What the individual searches are sensitive to is much more simple…

Simplified model spectrum (SMS) with 3 particles, 2 decay modes

86% of all hadronic production in LM1 consists of “simple” decay chains.

This makes it particularly amenable to being approximated well with a 3-particle OSET.
SMS: a few interesting features

$\tilde{q}q \rightarrow q\tilde{\chi}^0\tilde{\chi}^0$

$\sigma^{\text{NLO+NLL}} \pm 1 \sigma$ theory

$\tilde{q}_L + \tilde{\chi}^0_0, \tilde{u} + \tilde{d} + \tilde{s} + \tilde{c}$

$\tilde{u}_L$ only

CMS, 11.7 fb$^{-1}$  
$\sqrt{s} = 8$ TeV

$95\%$ CL upper limit on $\sigma$ (pb)

$\sigma \pm 1\sigma$ expected limit

$\tilde{q}q \rightarrow q\tilde{\chi}^0\tilde{\chi}^0$

$m_{\tilde{\chi}_L^{\max}} \approx 0.8$ TeV: Best limit in plane

$m_{\tilde{s}}^{\max} \approx 0.3$ TeV: LSP mass above which there is NO limit anymore

Assumes $100\%$ BR for decay chain considered.
How to summarize SMS limits?

Approach taken in the 2012 and 2013 Experimental SUSY PDG reviews [OB & Paul De Jong]:


<table>
<thead>
<tr>
<th>Model</th>
<th>Assumption</th>
<th>(m_{\tilde{q}})</th>
<th>(m_{\tilde{g}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMSSM</td>
<td>(m_{\tilde{q}} \approx m_{\tilde{g}})</td>
<td>1400</td>
<td>1400</td>
</tr>
<tr>
<td></td>
<td>all (m_{\tilde{q}})</td>
<td>-</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>all (m_{\tilde{g}})</td>
<td>1300</td>
<td>-</td>
</tr>
<tr>
<td>Simplified model (\tilde{g}\tilde{g})</td>
<td>(m_{\tilde{\chi}_1^0} = 0)</td>
<td>-</td>
<td>900</td>
</tr>
<tr>
<td></td>
<td>(m_{\tilde{\chi}_1^0} &gt; 300)</td>
<td>-</td>
<td>no limit</td>
</tr>
<tr>
<td>Simplified model (\tilde{q}\tilde{q})</td>
<td>(m_{\tilde{\chi}_1^0} = 0)</td>
<td>750</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(m_{\tilde{\chi}_1^0} &gt; 250)</td>
<td>no limit</td>
<td>-</td>
</tr>
<tr>
<td>Simplified model (\tilde{g}\tilde{g}, \tilde{q}\tilde{q})</td>
<td>(m_{\tilde{\chi}<em>1^0} = 0, m</em>{\tilde{\chi}<em>1^0} \approx m</em>{\tilde{g}})</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td></td>
<td>(m_{\tilde{\chi}<em>1^0} = 0, m</em>{\tilde{q}})</td>
<td>1400</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(m_{\tilde{\chi}<em>1^0} = 0, m</em>{\tilde{g}})</td>
<td>-</td>
<td>900</td>
</tr>
</tbody>
</table>

This was an appropriate approach for the rather limited amount of inclusive searches and corresponding SMS interpretations available in 2011 (7 TeV).
How to summarize SMS limits?

Approach taken in the 2012 and 2013 Experimental SUSY PDG reviews [OB & Paul De Jong]:


This was an appropriate approach for the rather limited amount of inclusive searches and corresponding SMS interpretations available in 2011 (7 TeV).

It is a challenge to do justice to the many searches and limits that have been established so far - even more so to put it all together into the/a "bigger picture".
What are representative SMS limits on the different particles?

Note: The following results are a May 2015 update to PDG review September 2013.

Direct squark production – chosen limits

CMS arXiv:1502.04358
Signature: Jets + \( E_T^{\text{miss}} \) with \( M_{T_2} \)
Limit assumes all 1\(^{st}\) & 2\(^{nd}\) gen squarks to be mass degenerate [or only one light squark]!

ATLAS arXiv:1308.2631
Signature: 2 b-jets + \( E_T^{\text{miss}} \)

ATLAS arXiv:1407.0583
Signature: 1Lepton + jets + \( E_T^{\text{miss}} \)
**Direct squark**

\[ m_{SUSY} = m_{\tilde{q}} \]

\[ \tilde{q} \to q\chi_1^0 \]

CMS arXiv:1502.04358

\[ \tilde{u}_L \to u\chi_1^0 \]

CMS arXiv:1502.04358

\[ \tilde{b} \to b\chi_1^0 \]

ATLAS arXiv:1308.2631

\[ \tilde{t} \to t\chi_1^0 \]

ATLAS arXiv:1407.0583

BR=100%

all limits are observed nominal
95% CLs limits
RP conserved
Gluino mediated squark production – limits chosen

ATLAS arXiv:1405.7875
Signature: 0L + 2-6 Jets + $E_T^{\text{miss}}$

CMS arXiv:1502.00300
Signature: : 0L + Razor + b-tag

Signature: 0/1 Leptons + 3 b-tag + $E_T^{\text{mis}}$
**Direct squark**

\[ m_{SUSY} = m_{\tilde{q}} \]

- \( \tilde{q} \rightarrow q\chi_1^0 \) 
- \( \tilde{u}_L \rightarrow u\chi_1^0 \)
- \( \tilde{b} \rightarrow b\chi_1^0 \)
- \( \tilde{t} \rightarrow t\chi_1^0 \)

---

**Gluino mediated**

\[ m_{SUSY} = m_{\tilde{g}} \]

- \( \tilde{g} \rightarrow q\bar{q}\chi_1^0 \)
- \( \tilde{g} \rightarrow b\bar{b}\chi_1^0 \)
- \( \tilde{g} \rightarrow t\bar{t}\chi_1^0 \)

---

CMS arXiv:1502.04358
ATLAS arXiv:1308.2631
ATLAS arXiv:1407.0583
ATLAS arXiv:1407.0600

- All limits are observed nominal
- 95% CLs limits
- RP conserved
- BR=100%
Compressed stop – mind the gap!

ATLAS arXiv:1407.0608
Mono-jet & c-tag combined

ATLAS: arXiv:1407.0583
1L + E_{t}^{mis} & b-tag

CMS arXiv:1308.1586
1L + E_{t}^{mis} and BDT & b-tag
**Direct squark**

\( m_{SUSY} = m_{\tilde{q}} \)

- \( \tilde{q} \rightarrow q\chi_1^0 \) (CMS arXiv:1502.04358)
- \( \tilde{u}_L \rightarrow u\chi_1^0 \) (CMS arXiv:1502.04358)
- \( \tilde{b} \rightarrow b\chi_1^0 \) (ATLAS arXiv:1308.2631)
- \( \tilde{t} \rightarrow t\chi_1^0 \) (ATLAS arXiv:1407.0583)

**Direct stop in “gap”**

\( m_{SUSY} = m_{\tilde{t}} \)

- \( \tilde{t} \rightarrow c\chi_1^0 \) (ATLAS arXiv:1407.0608)
- \( \tilde{t} \rightarrow bff'\chi_1^0 \) (ATLAS arXiv:1407.0583)
- \( \tilde{t} \rightarrow Wb\chi_1^0 \) (CMS arXiv:1308.1586)

**Gluino mediated**

\( m_{SUSY} = m_{\tilde{g}} \)

- \( \tilde{g} \rightarrow q\bar{q}\chi_1^0 \) (ATLAS arXiv:1405.7875)
- \( \tilde{g} \rightarrow b\bar{b}\chi_1^0 \) (CMS arXiv:1502.00300)
- \( \tilde{g} \rightarrow t\bar{t}\chi_1^0 \) (ATLAS arXiv:1407.0600)

BR=100%

All limits are observed nominal

95% CLs limits

RP conserved
**Direct squark**

$m_{SUSY} = m_{\tilde{q}}$

- $\tilde{q} \rightarrow q\chi^0_1$
- $\tilde{u}_L \rightarrow u\chi^0_1$
- $\tilde{b} \rightarrow b\chi^0_1$

**Direct stop in “gap”**

$m_{SUSY} = m_{\tilde{t}}$

- $\tilde{t} \rightarrow c\chi^0_1$
- $\tilde{t} \rightarrow \bar{b}f\chi^0_1$

**Gluino mediated**

$m_{SUSY} = m_{\tilde{g}}$

- $\tilde{g} \rightarrow b\chi^0_1$
- $\tilde{g} \rightarrow t\chi^0_1$
- $\tilde{g} \rightarrow q\chi^0_1$

---

**Signature**

2 lepton + $E_T^{miss}$
**Direct squark**

\[ m_{\text{SUSY}} = m_{\tilde{q}} \]

- \( \tilde{q} \to q\chi_1^0 \)
  - CMS arXiv:1502.04358
- \( \tilde{u}_L \to u\chi_1^0 \)
  - CMS arXiv:1502.04358
- \( \tilde{b} \to b\chi_1^0 \)
  - ATLAS arXiv:1308.2631
- \( \tilde{t} \to t\chi_1^0 \)
  - ATLAS arXiv:1407.0583

**Direct stop in “gap”**

\[ m_{\text{SUSY}} = m_{\tilde{t}} \]

- \( \tilde{t} \to c\chi_1^0 \)
- ATLAS arXiv:1407.0608
- \( \tilde{t} \to bff'\chi_1^0 \)
- ATLAS arXiv:1407.0583
- \( \tilde{t} \to Wb\chi_1^0 \)
  - CMS arXiv:1308.1586

**Direct slepton**

\[ m_{\text{SUSY}} = m_{\tilde{l}} \]

- \( \tilde{l}_R \to l^+\chi_1^- \)
  - ATLAS: arXiv:1403.5294
- \( \tilde{l}_L \to l^+\chi_1^- \)
  - ATLAS: arXiv:1403.5294

**Gluino mediated**

\[ m_{\text{SUSY}} = m_{\tilde{g}} \]

- \( \tilde{g} \to q\bar{q}\chi_1^0 \)
  - ATLAS arXiv:1405.7875
- \( \tilde{g} \to b\bar{b}\chi_1^0 \)
  - CMS arXiv:1502.00300
- \( \tilde{g} \to t\bar{t}\chi_1^0 \)
  - ATLAS arXiv:1407.0600

**Generallities**

- All limits are observed nominal
- 95\% CLs limits
- RP conserved

**SUSY & DM Searches @ LHC**

- O. Buchmüller

**CMS & ATLAS arXiv References**

- arXiv:1402.04358
- arXiv:1405.7875
- arXiv:1308.2631
- arXiv:1407.0583
- arXiv:1407.0600
- arXiv:1403.5294

**Legend:**

- Red line: CMS
- Blue line: ATLAS
- Green line: ATLAS (additional references not specified)
Direct chargino/neutralino production

$X_2^0 X_1^+$ production

$X_1^+ X_1^-$ production

**light slepton “easy”**

**heavy slepton “hard(er)”**

Add $Z(l^+l^-)+2$jets topology in bins of $E_t^{\text{miss}}$ to increase sensitivity for “heavy” slepton case

---

**ICHEP 2014**

$s = 8$ TeV

**CMS Preliminary**

CMS arXiv:1405.7570

---

**ATLAS arXiv:1403.5294**
**Direct squark**

- $m_{SUSY} = m_{\tilde{q}}$
- $\tilde{q} \rightarrow q\chi_1^0$
- $\tilde{u}_L \rightarrow u\chi_1^0$
- $\tilde{b} \rightarrow b\chi_1^0$
- $\tilde{t} \rightarrow t\chi_1^0$

CMS arXiv:1502.04358
ATLAS arXiv:1407.0608

**Direct stop in “gap”**

- $m_{SUSY} = m_{\tilde{t}}$
- $\tilde{t} \rightarrow c\chi_1^0$
- $\tilde{t} \rightarrow bff'\chi_1^0$
- $\tilde{t} \rightarrow Wb\chi_1^0$

ATLAS arXiv:1407.0608

**Direct slepton**

- $m_{SUSY} = m_{\tilde{\ell}}$
- $\tilde{\ell}_R \rightarrow \ell\chi_1^0$
- $\tilde{\ell}_L \rightarrow \ell\chi_1^0$

ATLAS arXiv:1403.5294

**Gluino mediated**

- $m_{SUSY} = m_{\tilde{g}}$
- $\tilde{g} \rightarrow q\bar{q}\chi_1^0$
- $\tilde{g} \rightarrow bb\chi_1^0$
- $\tilde{g} \rightarrow t\bar{t}\chi_1^0$

ATLAS arXiv:1405.7875

---

All limits are observed nominal 95% CLs limits RP conserved
**Direct squark**

$m_{SUSY} = m_{\tilde{q}}$

- $\tilde{q} \rightarrow q \chi_1^0$
- $\tilde{u}_L \rightarrow u \chi_1^0$
- $\tilde{b} \rightarrow b \chi_1^0$

**Direct stop in “gap”**

$m_{SUSY} = m_{\tilde{t}}$

- $\tilde{t} \rightarrow c \chi_1^0$
- $\tilde{t} \rightarrow b f f' \chi_1^0$
- $\tilde{t} \rightarrow W b \chi_1^0$

**Direct slepton**

$m_{SUSY} = m_{\tilde{\ell}}$

- $\tilde{\ell}_R \rightarrow \ell \chi_1^0$
- $\tilde{\ell}_L \rightarrow \ell \chi_1^0$

**Gluino mediated**

$m_{SUSY} = m_{\tilde{g}}$

- $\tilde{g} \rightarrow q\bar{q}\chi_1^0$
- $\tilde{g} \rightarrow b\bar{b}\chi_1^0$
- $\tilde{g} \rightarrow t\bar{t}\chi_1^0$

**Direct**

$m_{SUSY} = m_{\chi_1^0}$

- $\chi_1^+ \chi_1^-$
- $\chi_1^\pm / \chi_2^0$
- $\chi_1^\pm / \chi_2^0 (light \ \tilde{t})$
- $\chi_1^\pm / \chi_2^0 (heavy \ \tilde{t})$

**Direct**

$m_{SUSY} = m_{\chi_1^\pm}$

- $\chi_1^+ \chi_1^-$
- $\chi_1^\pm / \chi_2^0$
- $\chi_1^\pm / \chi_2^0 (light \ \tilde{t})$
- $\chi_1^\pm / \chi_2^0 (heavy \ \tilde{t})$

95% CLs limits

- RP conserved

- BR=100%

All limits are observed nominal
What does this imply for Linear Collider?

Kinematic area covered by a 1 TeV linear collider:

$$e^+ e^- \rightarrow \chi^{SUSY} \chi^{SUSY}$$
There remain kinematic regions that are currently beyond the reach of the LHC while still being accessible with a 1 TeV linear collider.

However, the LHC might fill these gaps rather soon!

\[ \chi_1^+ \chi_1^- \]
Characterizing Dark Matter Searches

**complete theory vs. simple interpretations**

**SUSY**

**Example:**
Effective Field Theory
Simplified models
Mono-Mania (at the LHC)

- Mono-Z
- Mono-photon
- Mono-jet
- Mono-Higgs
- Mono-W
- Mono-top
Mono-Mania (at the LHC)

- Mono-Z
- Mono-photon
- Mono-jet
- Mono-Higgs
- Mono-W
- Mono-top
Mono-X searches at colliders

**ET^{miss} trigger**

**Example Monojet**
(8 TeV, 20.3 fb⁻¹)

- \( {E_T}^{miss} \), \( p_T(j) > 150 - 900 \) GeV
- 1 or 2 jets (anti-\( k_T \), \( R=0.4, p_T>30 \) GeV)
- \(|\Delta\phi( {E_T}^{miss},j_2)| > 0.5\)

**Example Monophoton**
(8 TeV, 19.6 fb⁻¹):

- \( {E_T}^{miss} \), \( p_T(\gamma) > 140 \) GeV,
- \( N_{jet} < 2 \) (anti-\( k_T \), \( R=0.5, p_T>30 \) GeV)
- \( \Delta\phi (\gamma, {E_T}^{miss}) > 2\),
- \( (X^2, \Delta\phi (jet, {E_T}^{miss}) > 0.4)\)
ATLAS Mono-Jet: Comparison with Direct Detection

90% CL
\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

WIMP-nucleon cross section \([\text{cm}^2]\)

WIMP mass \(m_\chi\) [GeV]
ATLAS Mono-Jet: Comparison with Direct Detection

ATLAS

90% CL
\( \sqrt{s}=8 \text{ TeV}, \) 20.3 fb\(^{-1} \)

EFT operators

<table>
<thead>
<tr>
<th>Initial state</th>
<th>Type</th>
<th>Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>(qq)</td>
<td>scalar</td>
<td>( \frac{m_1}{m_2} \bar{\chi} \chi q \bar{q} )</td>
</tr>
<tr>
<td>(qq)</td>
<td>vector</td>
<td>( \frac{1}{M_2} \bar{\chi} \gamma^\mu \chi q \bar{q} \gamma_\mu q )</td>
</tr>
<tr>
<td>(qq)</td>
<td>axial-vector</td>
<td>( \frac{1}{M_2} \bar{\chi} \gamma^\mu \gamma^5 \chi q \bar{q} \gamma^5 q )</td>
</tr>
<tr>
<td>(qq)</td>
<td>tensor</td>
<td>( \frac{1}{M_2} \bar{\chi} \sigma^{\mu \nu} \chi q \bar{q} \sigma_{\mu \nu} q )</td>
</tr>
<tr>
<td>(gg)</td>
<td>scalar</td>
<td>( \frac{1}{4M_2^2} \bar{\chi} \chi s(G_{\mu \nu}^a)^2 )</td>
</tr>
</tbody>
</table>

WIMP-nucleon cross section [cm\(^2\)]

WIMP mass \( m_\chi \) [GeV]

spin-independent

DAMA/LIBRA, 3\( \sigma \)
CRESST II, 2\( \sigma \)
CoGeNT, 99% CL
CDMS, 1\( \sigma \)
CDMS, 2\( \sigma \)
CDMS, low mass
LUX 2013 90% CL
Xenon100 90% CL
CMS 8TeV D5
CMS 8TeV D11
ATLAS Mono-Jet: Comparison with Direct Detection
Claim [often made]:
For low mass and the entire spin-dependent case monojet limits are stronger than direct detection limits!
Effective Field Theory (EFT) Interpretation

Example of considered operators:

\[ O_V = \frac{(\bar{\chi} \gamma_\mu \chi)(\bar{q} \gamma_\mu q)}{\Lambda^2} \quad \text{Vector operator, s-channel} \]

\[ O_{AV} = \frac{(\bar{\chi} \gamma_\mu \gamma_5 \chi)(\bar{q} \gamma_\mu \gamma_5 q)}{\Lambda^2} \quad \text{Axial vector operator, s-channel} \]

Assumption of EFT

If the operator (e.g. V or AV) mediator is suitably(!) heavy it can be integrated out to obtain the effective V or AV contact operator. In this case (and only this case), the contact interaction scale \( \Lambda \) is related to the parameters entering the Lagrangian:

\[ \Lambda = \frac{M_{\text{mediator}}}{\sqrt{g_q g_\chi}} \quad \text{(relation in the full theory)} \]
Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan, C.McCabe: arXiv:1308.6799
➢ Compare Effective Field Theory (EFT) with Full Theory (FT)

Use vector and axial-vector mediators (e.g. Z') as example - scalar are similar in conclusion!

Three regions become visible:

Region I: EFT and FT agree better than 20%
➢ EFT is valid!

Region II: EFT yields significant weaker limits than FT
➢ EFT limits are too conservative!

Region III: EFT yields significant stronger limits than FT
➢ EFT limits are too aggressive!
Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan, C.McCabe: arXiv:1308.6799

- Compare Effective Field Theory (EFT) with Full Theory (FT)

Use vector and axial-vector mediators (e.g. Z') as example - scalar are similar in conclusion!

Three Regions as function of mediator mass:

- **Region I**: Heavy $m_{med}$
  - EFT is valid!
- **Region II**: Medium $m_{med}$ – Resonant enhancement
  - EFT limits are too conservative!
- **Region III**: Low $m_{med}$
  - EFT limits are too aggressive!
Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan, C.McCabe: arXiv:1308.6799
- Compare Effective Field Theory (EFT) with Full Theory (FT)

EFT approach

FT one diagram

“simplified model”

Three Regions as function of mediator mass:

Region I: Heavy $m_{med}$
- EFT is valid!

Region II: Medium $m_{med}$ – Resonant enhancement
- EFT limits are too conservative!

Region III: Low $m_{med}$
- EFT limits are too aggressive!

Conclusion:
- The EFT is not an appropriate framework for a comprehensive Interpretation of DM searches at colliders and especially must taken with very (as in VERY) special care when comparing with other experiments such as Direct Detection!
Minimal Simplified Dark Matter Model

Define simplified model with (minimum) 4 parameters

<table>
<thead>
<tr>
<th>Mediator mass ($M_{med}$)</th>
<th>DM mass ($M_{DM}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_q$</td>
<td>$g_{DM}$</td>
</tr>
</tbody>
</table>

DM

<table>
<thead>
<tr>
<th>Dirac fermion</th>
<th>Scalar - real</th>
</tr>
</thead>
<tbody>
<tr>
<td>Majorana fermion</td>
<td>Scalar - complex</td>
</tr>
</tbody>
</table>

Consider comprehensive set of diagrams for mediator

<table>
<thead>
<tr>
<th>Vector</th>
<th>Axial-vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar</td>
<td>Pseudoscalar</td>
</tr>
</tbody>
</table>

Based on work from: OB, S. Malik, M.Dolan, C. McCabe
arXiv:1407.8257

($\Gamma_{med}$ can also be free as long as $\Gamma_{med} < M_{med}$)
Collider vs Direct Detection

<table>
<thead>
<tr>
<th>M_{DM}</th>
<th>M_{med}</th>
</tr>
</thead>
<tbody>
<tr>
<td>g_q</td>
<td>g_{DM}</td>
</tr>
</tbody>
</table>

Vector

Axial vector

**Vector: 90% CL limits**
- LHC8 19.5 fb^{-1}
- LUX 2013
- \( g_q = g_{DM} = 1 \)
- \( g_q = 0.3, g_{DM} = 1 \)
- \( g_q = g_{DM} = 0.5 \)

**Axial vector: 90% CL limits**
- LHC8 19.5 fb^{-1}
- LUX 2013
- \( g_q = g_{DM} = 1 \)
- \( g_q = 0.3, g_{DM} = 1 \)
- \( g_q = g_{DM} = 0.5 \)

arXiv:1407.8257
Collider vs Direct Detection

Vector

- 90% CL limits
- LHC8 19.5 fb^{-1}
- LUX 2013
- \(m_{DM}=100 \text{ GeV}, M_{med}=1000 \text{ GeV}\)
- \(m_{DM}=200 \text{ GeV}, M_{med}=500 \text{ GeV}\)
- \(m_{DM}=200 \text{ GeV}, M_{med}=800 \text{ GeV}\)

Axial vector

- 90% CL limits
- LHC8 19.5 fb^{-1}
- LUX 2013
- \(m_{DM}=100 \text{ GeV}, M_{med}=1000 \text{ GeV}\)
- \(m_{DM}=200 \text{ GeV}, M_{med}=500 \text{ GeV}\)
- \(m_{DM}=200 \text{ GeV}, M_{med}=800 \text{ GeV}\)

arXiv:1407.8257
Scalar and Pseudoscalar

Philip Harris, Valentin V. Khoze,
Michael Spannowsky, Ciaran Williams

arXiv:1411.0535

See also Buckley et al
arXiv:1410.6497
Projections for Future Experiments: $M_{\text{med}}$ vs $M_{\text{DM}}$

Based on work from: S. Malik, OB, M. Dolan, C. McCabe et al
arXiv:1409.4075

Limits from 8 TeV monojet search and projected limits for 3 LHC scenarios:
- 13 TeV 30 fb$^{-1}$
- 14 TeV, 300 fb$^{-1}$
- 14 TeV, 3000 fb$^{-1}$

LUX 2013 limits and projected limits for LZ assuming 10 tonne-year exposure

Discovery reach accounting for coherent neutrino scattering
Projections for Future Experiments: \( \sigma \) vs \( M_{\text{DM}} \)

Can be also shown in the \( \sigma \) vs \( M_{\text{DM}} \) plane …

Direct Detection experiments and collider are complementary! They are probing different regions of the relevant parameter space!
### Summary for most basic Mediator Interactions

... in a nutshell!

<table>
<thead>
<tr>
<th>Basic Mediators</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vector</strong></td>
</tr>
<tr>
<td>EWK like coupling (assumed equal to all leptons).</td>
</tr>
<tr>
<td>Besides very low DM masses</td>
</tr>
<tr>
<td>DD wins clearly over collider!</td>
</tr>
<tr>
<td><strong>Axial-vector</strong></td>
</tr>
<tr>
<td>EWK like coupling (assumed equal to all leptons).</td>
</tr>
<tr>
<td>DD and collider are equal in overall sensitivity but probe different regions of parameter space!</td>
</tr>
<tr>
<td><strong>Scalar</strong></td>
</tr>
<tr>
<td>Yukawa like coupling on SM side (mass based on SM side)</td>
</tr>
<tr>
<td>DD and collider are equal in overall sensitivity but probe different regions of parameter space!</td>
</tr>
<tr>
<td><strong>Pseudoscalar</strong></td>
</tr>
<tr>
<td>Yukawa like coupling on SM side (mass based on SM side)</td>
</tr>
<tr>
<td>No limits from DD (only from indirect detection). Collider provides limits similar in sensitivity to scalar limits</td>
</tr>
</tbody>
</table>
Outlook: 8 TeV vs 14 TeV

Use parton luminosities to illustrate the gain of 14 vs 8 TeV

**Higgs:**

\[ pp \to H, \ H \to WW, \ ZZ \text{ and } \gamma\gamma \]

mainly \( gg \): factor \( \sim 2 \)

**SUSY – 3\textsuperscript{rd} Generation:**

Mass scale \( \sim 500 \text{ GeV} \)

\( qq \) and \( gg \): factor \( \sim 3 \text{ to } 6 \)

**Scalar/Pseudoscalar Mediator**

Mass scale \( \sim 2.0 \text{ TeV} \)

\( gg \): factor \( \sim 20 \)

**SUSY – Squarks/Gluino:**

Mass scale \( \sim 1.5 \text{ TeV} \)

\( qq, gg, qg \): factor \( \sim 40 \text{ to } 80 \)

**Vector/Axialvector a la Z':**

Mass scale \( \sim 5 \text{ TeV} \)

\( qq \): factor \( \sim 1000 \)

*Increase in energy will help a lot!*
Summary

➢ So far New Physics has not revealed itself!
  ➢ Even by 2010 the LHC has enter new territory for New Physics searches and since pushed e.g. the (coloured) SUSY mass scale to the ~1 TeV scale
  ➢ We were well prepared for an early discovery but we also knew that it could take more time and ingenuity before we can claim a discovery (if NP exist)

➢ The LHC experiments have established an impressive variety of very powerful direct searches for many different final states!
  ➢ Based on these results we need to establish the “big picture” in order to understand find out if/where our search strategy might have weak spots or even holes!
  ➢ This requires appropriate interpretations of the searches and a MEANIGFUL comparison with other experiments – important example DM searches!

➢ The high energy running of the LHC starting 2015 will be our next very (as in VERY) real chance for discovery!

The story continues … stay tuned!
BACKUP
Early SUSY Search Strategy at the LHC

Search Signatures

- SUSY-like decay chains range from short to long and simple to very complicated.
- All physics objects, MET, jets, leptons, photons, b’s taus, tops, W, Z, etc are involved.
- Comprehensive coverage of all possible signature requires a topology oriented search strategy:

References Analyses

<table>
<thead>
<tr>
<th>0-leptons</th>
<th>1-lepton</th>
<th>OSDL</th>
<th>SSDL</th>
<th>≥3 leptons</th>
<th>2-photons</th>
<th>γ+lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jets + MET</td>
<td>Single lepton + Jets + MET</td>
<td>Opposite-sign di-lepton + jets + MET</td>
<td>Same-sign di-lepton + jets + MET</td>
<td>Multi-lepton</td>
<td>Di-photon + jet + MET</td>
<td>Photon + lepton + MET</td>
</tr>
</tbody>
</table>

Already in less then two years of operation ATLAS & CMS managed to carry out the full list of these core “SUSY References Analyses”!
The Large Hadron Collider at CERN
The Large Hadron Collider at CERN

LHC: 27 km long
100m underground
The Large Hadron Collider at CERN

LHC: 27 km long
100m underground

General Purpose,
pp, heavy ions
The Large Hadron Collider at CERN

LHC: 27 km long
100m underground

General Purpose, pp, heavy ions

Heavy ions, pp
The Large Hadron Collider at CERN

LHC: 27 km long
100m underground

General Purpose,
pp, heavy ions

Heavy ions, pp

pp, B-Physics,
CP Violation

CMS

ALICE

ATLAS

DM Searches @ LHC O. Buchmüller
**Direct squark**

\[ m_{SUSY} = m_{\tilde{q}} \]

\[ \tilde{t} \rightarrow t\chi_1^0 \]  
ATLAS-CONF-2013-037

---

**Direct slepton**

\[ \tilde{l}_R \rightarrow l^{\pm}\chi_1^0 \]  
ATLAS-CONF-2013-049

\[ \chi_1^{\pm} / \chi_2^0 \]

---

**Direct**

\[ m_{SUSY} = m_{\chi_1^\pm} = m_{\chi_2^0} \]

---

Example of “difficult” SUSY channels!

---

BR=100%

all limits are observed nominal
95% CLs limits
RP conserved
**Direct squark**

\[ m_{SUSY} = m_{\tilde{q}} \]

\[ \tilde{t} \rightarrow t\chi_1^0 \text{ ATLAS-CONF-2013-037} \]

**Direct slepton**

\[ \tilde{\ell}_R \rightarrow l^\pm \chi_1^0 \text{ ATLAS-CONF-2013-049} \]

**Direct** \[ \chi_1^\pm / \chi_2^0 \]

\[ m_{SUSY} = m_{\chi_1^\pm} = m_{\chi_2^0} \]

---

BR=100%

all limits are observed nominal 95% CLs limits

RP conserved

---

**LHC: 8 TeV 20 fb^{-1}**

---

**LHC: 14 TeV 300 fb^{-1}**

---

SUSY & DM Searches @ LHC O. Buchmüller

---
\( m_{\text{LSP}} \) [GeV]

**Direct squark**

\[ m_{\text{SUSY}} = m_{\tilde{q}} \]

\( \tilde{t} \to t\chi_1^0 \) ATLAS-CONF-2013-037

**Direct slepton**

\( \tilde{l}_R \to l^\pm \chi_1^0 \) ATLAS-CONF-2013-049

**Direct** \( \chi_1^\pm / \chi_2^0 \)

\( \chi_1^\pm \chi_2^0 (\text{heavy } \tilde{t}) \)

CMS-PAS-SUS-13-006

\[ m_{\text{SUSY}} = m_{\chi_1^\pm} = m_{\chi_2^0} \]

---

BR=100%

All limits are observed nominal 95% CLs limits RP conserved
**Direct squark**
\[ m_{SUSY} = m_{\tilde{q}} \]
\[ \tilde{t} \rightarrow t\chi_1^0 \text{ ATLAS-CONF-2013-037} \]

**Direct slepton**
\[ \tilde{l}_R \rightarrow l^\pm \chi_1^0 \text{ ATLAS-CONF-2013-049} \]

**Direct**
\[ \chi_1^\pm / \chi_2^0 \]
\[ m_{SUSY} = m_{\chi_1^\pm} = m_{\chi_2^0} \]

All limits are observed nominal 95% CLs limits
RP conserved

BR = 100%

---

**LHC: 8 TeV 20 fb^{-1}**
**LHC: 14 TeV 300 fb^{-1}**
**HL-LHC: 14 TeV 3000 fb^{-1}**
**Direct squark**

\[ m_{SUSY} = m_{\tilde{q}} \]

\[ \tilde{t} \rightarrow t\chi_1^0 \] ATLAS-CONF-2013-037

**Direct slepton**

\[ \tilde{l}_R \rightarrow l^\pm \chi_1^0 \] ATLAS-CONF-2013-049

**Direct** \( \chi_1^\pm / \chi_2^0 \)

\[ m_{SUSY} = m_{\chi_1^\pm} = m_{\chi_2^0} \]

1 TeV linear collider

- - - LHC: 8 TeV 20 fb\(^{-1}\)
- - - LHC: 14 TeV 300 fb\(^{-1}\)
- - - HL-LHC: 14 TeV 3000 fb\(^{-1}\)

\( \chi_1^\pm \chi_2^0(heavy \tilde{t}) \)

CMS-PAS-SUS-13-006

all limits are observed nominal 95% CLs limits RP conserved

BR=100%
All results presented in this talk (and many more) can be accessed via the public page of the ATLAS and CMS experiments:

**ATLAS SUSY**: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

**CMS SUSY**: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
What those this imply on model-dependences of EFT limits?

Look at EFT validity in $m_{DM} -$ coupling* plane!

* Coupling chose such that CMS EFT limit on $\Lambda$ applies to FT
Model-dependences of EFT limits

Look at EFT validity in $m_{DM} -$ coupling* plane!

1. **Region in which EFT is valid**

For this we calculate the minimum coupling

$$\sqrt{g_q g_\chi} = \frac{m_{med}}{\Lambda_{CMS}}$$

that the simplified model must have for the EFT limits to apply. This is defined by region I (i.e. better than 20% agreement of FT and EFT).

* Coupling chose such that CMS EFT limit on $\Lambda$ applies to FT
Look at EFT validity in $m_{DM}$ – coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density

When exclude the region in which relic abundance is larger than the observed value of $\Omega\chi h^2 = 0.119$ only mediator masses above a few hundred GeV fulfill this.

* Coupling chose such that CMS EFT limit on $\Lambda$ applies to FT
Model-dependences of EFT limits

Look at EFT validity in $m_{\text{DM}} - \text{coupling}^*$ plane!

1. Must require $m_{\text{med}} < \Gamma_{\text{med}}$
2. Region in which EFT is valid (20%)
3. Require compatibility with relic density
4. Require theory to be perturbative ($< 4\pi$)

When we also require that the region/theory must be perturbative:

$$\sqrt{g_q g_\chi} < 4\pi$$

only a very small region is left!

EFT limits of monojet searches only apply to a very (as in VERY) small class of DM models!
Model-dependences of EFT limits

Look at EFT validity in $m_{DM} -$ coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density
3. Require theory to be perturbative ($<4\pi$)
4. $m_{med} < \Gamma_{med}$ ALWAYS!

We also find that for all DM models the EFT Is valid the mass of the mediator must be Smaller than its width!

In the remaining part of the plot:

$$\sqrt{g_q g_\chi} > 2$$

a particle-like interpretation of the mediator is doubtful because of $m_{med} < \Gamma_{med}$!

See discussion about equation 3.5 in arXiv:1308.6799 for further details.
What those this imply on model-dependences of EFT limits?

Look at EFT validity in $m_{\text{DM}}$ – coupling* plane!

1. Region in which EFT is valid (20%)
2. Require compatibility with relic density
3. Require theory to be perturbative ($< 4\pi$)
4. $m_{\text{med}} < \Gamma_{\text{med}}$ ALWAYS!

The observation that all DM theories for which the EFT is valid must have $m_{\text{med}} < \Gamma_{\text{med}}$ and the small class to models it applies in any case leads to the conclusion the EFT only applies to a very small class of DM models. EFT limits of monojet searches are therefore highly model-depended!