1. Previous SUSY analyses

2. Introduction to non-SUSY analyses

3. Set-up and validation

4. General Results

5. Towards UV completions

6. Conclusions
1. Previous SUSY analyses

GUT based models:

1.) CMSSM: \( m_0, m_{1/2}, A_0, \tan \beta, \text{sign} \mu \)

2.) NUHM1: CMSSM + 1 scalar mass parameter
\( m_0, m_{1/2}, A_0, \tan \beta, \text{sign} \mu \) and \( M_A \)

3.) NUHM2: CMSSM + 2 scalar mass parameters
\( m_0, m_{1/2}, A_0, \tan \beta, \mu \) and \( M_A \)

4.) SU(5): CMSSM + 3 scalar mass parameters
\( m_5, m_{10}, m_{1/2}, A_0, \tan \beta, m_{H_u}, m_{H_d} \)

5.) mAMSB: different mechanism for SUSY breaking
\( m_{3/2}, m_0, \tan \beta, \text{sign}(\mu) \)

6.) sub-GUT: CMSSM, but unification at lower scale
\( m_0, m_{1/2}, A_0, \tan \beta, \text{sign} \mu \) and \( M_{\text{in}} \)

7.) . . .

\( \Rightarrow \) wide variety of models covered!
Problem: We cannot be sure about the SUSY-breaking mechanism

⇒ it is possible that with the CMSSM, NUHM, SU(5), mAMSB, sub-GUT we missed the “correct” mechanism

⇒ hint: strong connection between colored and uncolored sector
tension between low-energy EW effects and (colored) LHC searches
Problem: We cannot be sure about the SUSY-breaking mechanism

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⇒ hint: strong connection between colored and uncolored sector
  tension between low-energy EW effects and (colored) LHC searches

Solution: investigate also the “general MSSM”

⇒ 11 parameters are manageable ⇒ pMSSM11

– squark mass parameters: $m_{\tilde{q}_{1,2}} = m_{\tilde{q}}, m_{\tilde{q}_3}$
– slepton mass parameter(s): $m_{\tilde{l}}, m_{\tilde{\tau}}$
– gaugino masses: $M_1, M_2, M_3$
– trilinear coupling: $A$
– Higgs sector parameters: $M_A, \tan \beta$
– Higgs mixing parameter: $\mu$
What if we still did not get it right?

– low-energy model different?
– richer SUSY structure?
– no SUSY model? ⇒ not really realistic! ;-)
What if we still did not get it right?

- low-energy model different?
- richer SUSY structure?
- no SUSY model? ⇒ not really realistic! ;-)

Lagrangian according to LHC-DM-WG recommendation:

\[ \mathcal{L}_{X_D} = X_D \gamma_\mu \left( g_{X_D}^Y + g_{X_D}^A \gamma_5 \right) X_D Y_1^\mu. \]

\[ \mathcal{L}_{Y_1} = \sum_{i,j} \left[ \bar{d}_{i} \gamma_\mu \left( g_{d_{i,j}}^Y + g_{d_{i,j}}^A \gamma_5 \right) d_{j} + \bar{u}_{i} \gamma_\mu \left( g_{u_{i,j}}^Y + g_{u_{i,j}}^A \gamma_5 \right) u_{j} \right] Y_1^\mu. \]

\[ \mathcal{L}_{Y_1} = \sum_{i,j} \left[ \bar{l}_{i} \gamma_\mu \left( g_{l_{i,j}}^Y + g_{l_{i,j}}^A \gamma_5 \right) l_{j} \right] Y_1^\mu. \]

[taken from E. Bagnaschi]
Our tool: **Mastercode**

⇒ collaborative effort of theorists and experimentalists

[Bagnaschi, Borsato, Buchmüller, Chobanova, Citron, Costa, De Roeck, Dolan, Ellis, Flächer, Hahn, SH, Isidori, Lucio, Martinez Santos, Olive, Trifa, Sakurai, Weiglein]

**Über-code for the combination of different tools:**

– Über-code original in Fortran, now re-written in C++
– tools are included as subroutines
– **compatibility** ensured by collaboration of authors of “MasterCode” and authors of “sub tools” /SLHA(2)
– sub-codes in Fortran or C++

⇒ evaluate observables of one parameter point consistently with various tools

[link to cern.ch/mastercode]
MSSM Direct Detection prediction

Direct detection: past-present-future

Red circle is meant to represent predictions from SUSY. Let’s see what our models say.
MSSM Direct Detection prediction: CMSSM

Future searches would significantly probe the CMSSM

Sven Heinemeyer, DSU Workshop – Buenos Aires, 16.07.2019
MSSM Direct Detection prediction: NUHM1

Some of the parameter of the NUHM1 space lies beyond the intrinsic background from atmospheric neutrinos.
MSSM Direct detection prediction: NUHM2

Direct detection: NUHM2

All these GUT-models are indeed within the red blob. So what about the pMSSM10?
MSSM Direct Detection prediction: SU(5)

- $\tilde{\tau}$ coann.
- $\tilde{\tau}_1$ coann. + $H/A$
- $\tilde{\chi}^\pm_1$ coann.
- $\tilde{u}_R/\tilde{c}_R$ coann.
- $\tilde{A}/H$ funnel
- $\tilde{\nu}_\tau$ coann.
MSSM Direct Detection prediction: mAMSB:

\[
\sigma_p^{SI} \text{[cm}^2\text{]} \quad \mu > 0, \ \Omega_{\chi_1^0} = \Omega_{\text{CDM}}
\]

\[
m_{\chi_1^0} \text{[GeV]}\]

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MSSM Direct Detection prediction: sub-GUT

$\sigma_{SI}^p$: good prospects, all above the neutrino floor

$\sigma_{SD}^p$: unclear prospects, best-fit regions below the neutrino floor
MSSM Direct detection prediction: pMSSM11: $m_{\tilde{\chi}_1^0}$ vs. $\sigma_p^{\text{SI}}$: [2017]

⇒ best-fit point covered by future experiments
⇒ but very low cross sections possible at 1σ, below neutrino floor

Sven Heinemeyer, DSU Workshop – Buenos Aires, 16.07.2019
MSSM Direct detection prediction: pMSSM11: $m_{\tilde{\chi}_1^0}$ vs. $\sigma_p^{SD}$: [2017]

$\Rightarrow$ slim prospects for future experiments

$\Rightarrow$ large regions allowed at 1$\sigma$, below neutrino floor
2. Introduction to non-SUSY analyses

We infer the existence of Dark Matter (DM) from indirect observations (cosmological, astrophysical).

Can we probe DM at the LHC? Yes, if we assume that it couple sufficiently strongly to the SM (freeze-out points to that). Unknown: the mass.

DM searches at the LHC fully underway.

How to predict the signals and interpret the results? Different possibilities have been studied:

1. EFT approach.
2. Dark Matter Simplified Models
3. Complete models (e.g. SUSY).

[taken from E. Bagnaschi]
Approach at the LHC for DMSMs: example for spin-1 mediator

- Simplifying assumptions on the Lagrangian (more soon)
- Results for fixed values of $m_{\text{med}}, m_{\text{DM}}, g_{\text{SM}}, g_{\text{DM}}$
- Overlay results from mono-jet search
- Overlay results from di-jet searches
- …
**MasterCode approach**

Fit to the full Lagrangian (some simplifying assumptions)

Included into the fit:
- DM relic density
- DM direct detection limits
- LHC mono-jet searches
- LHC di-jet searches

⇒ global picture of status and prospects
3. Set-up and validation

Lagrangian according to LHC-DM-WG recommendation:

- We consider DMSMs with a spin-1 ($Y_1$) s-channel mediator.
- The dark matter candidate is a Dirac fermion ($X_D$).
- We use the model files provided by the DMSIMP package for our implementation.

**Spin-1 mediator**

- Interaction Lagrangian mediator-DM
  \[
  \mathcal{L}_{X_D}^{Y_1} = X_D \gamma_{\mu} \left( g_{X_D}^V + g_{X_D}^A \gamma_5 \right) X_D Y_1^\mu.
  \]

- Interaction Lagrangian mediator-quarks
  \[
  \mathcal{L}_{\text{quarks}}^{Y_1} = \sum_{i,j} \left[ \bar{d}_i \gamma_{\mu} \left( g_{d_{i,j}}^V + g_{d_{i,j}}^A \gamma_5 \right) d_j + \bar{u}_i \gamma_{\mu} \left( g_{u_{i,j}}^V + g_{u_{i,j}}^A \gamma_5 \right) u_j \right] Y_1^\mu
  \]

- Interaction Lagrangian mediator-leptons
  \[
  \mathcal{L}_{\text{leptons}}^{Y_1} = \sum_{i,j} \left[ \bar{l}_i \gamma_{\mu} \left( g_{l_{i,j}}^V + g_{l_{i,j}}^A \gamma_5 \right) l_j \right] Y_1^\mu
  \]

**Scenarios**

- Leptophobic, $g_{l_{i,j}}^V = g_{l_{i,j}}^A = 0$ (no constraints from dilepton searches).
- Flavor diagonal, $g_{u_{i,j}}^V/A = 0$ if $i \neq j$.
- Flavor blind, $g_{u_{i,j}}^V/A = g_{u_{i,j}}^V/A$.

1. $g_{X_D}^V \equiv g_{DM}$
   \[ g_{X_D}^V = 0 \]
   \[ g_{u/d}^V \equiv g_{SM} \]
   \[ g_{u/d}^A = 0, \]
   pure vector.

2. $g_{X_D}^V = 0$
   \[ g_{X_D}^V \equiv g_{DM} \]
   \[ g_{u/d}^V = 0 \]
   \[ g_{u/d}^A = g_{SM}, \]
   pure axial-vector.

[taken from E. Bagnaschi]
**MasterCode set-up:**

- **Frequentist fitting** framework written in Python/Cython and C++
- **Multinest** algorithm is used to sample the parameter space
- **udocker** used for deployment

**Scan ranges:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th># of Segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_Y$ (mediator)</td>
<td>$(0.1, 5)$ TeV</td>
<td>10</td>
</tr>
<tr>
<td>$m_\chi$ (DM)</td>
<td>$(0, 2.5)$ TeV</td>
<td>8</td>
</tr>
<tr>
<td>$g_{SM}$</td>
<td>$(10^{-6}, \sqrt{4\pi})$</td>
<td>2</td>
</tr>
<tr>
<td>$g_{DM}$</td>
<td>$(10^{-6}, \sqrt{4\pi})$</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total # of segments</strong></td>
<td></td>
<td><strong>320</strong></td>
</tr>
</tbody>
</table>
DM constraints:

⇒ micrOMEGAs for relic density and DD cross sections

⇒ full agreement with ATLAS/CMS results (here: vector model)
Non-LHC constraints

**Dark matter**

- Relic density constraints from Planck.
- Direct detection constraints on $\sigma_p^{SI}$ from LUX, XENON1T and PANDAX.
- Direct detection constraints on $\sigma_p^{SD}$ from PIC060.

[taken from E. Bagnaschi]

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Mono-jet constraints

⇒ MG5 aMC(N)LO, Fastlim approach

⇒ full agreement with ATLAS/CMS (red-dashed)
Di-jet constraints

⇒ MG5 aMC(N)LO, Fastlim approach

⇒ full agreement with ATLAS/CMS
4. General Results

- Results for vector mediator model

- Results for axial-vector mediator model

- No restrictions on couplings or masses

- Color coding:
  - green: annihilation via \( t \)-channel \( \chi \) exchange into pairs of mediator particles \( Y \) that subsequently decay into SM particles
  - yellow: rapid annihilation directly into SM particles via the \( s \)-channel \( Y \) resonance
Vector mediator (I):

⇒ clear separation between $s$- and $t$-channel
Vector mediator (II):

$\Rightarrow$ large ranges allowed, $t$-channel only for $g_{DM} \gg g_{SM}$
⇒ mixed prospects, both for $s$- and $t$-channel case
Axial-vector mediator (I):

⇒ Larger $s$-channel region, continuous with $t$-channel
Axial-vector mediator (II):

$\Rightarrow t- (s-)\text{channel for } g_{SM} \lesssim (\gtrsim) 10^{-2}$
Axial-vector mediator (III):

⇒ will not be easy for PICO!
Axial-vector mediator (III):

\[ \Rightarrow \text{neither for LZ!} \]
5. Towards UV completions  ⇒ So far no UV completion considered!
5. **Towards UV completions** ⇒ So far no UV completion considered!

In any **UV completion** the spin-one boson could be expected to have comparable couplings to SM and DM particles, modulo possible group-theoretical factors and mixing angles!

\[ g_{\text{DM}}/g_{\text{SM}} = \mathcal{O}(1) \]
5. Towards UV completions ⇒ So far no UV completion considered!

In any UV completion the spin-one boson could be expected to have comparable couplings to SM and DM particles, modulo possible group-theoretical factors and mixing angles!

\[ \frac{g_{\text{DM}}}{g_{\text{SM}}} = O(1) \]

\[ \frac{1}{3} < \frac{g_{\text{DM}}}{g_{\text{SM}}} < 3 \]

⇒ dark yellow regions ⇒ \( s \)-channel favored!
Vector mediator: towards UV completions

⇒ mixed prospects for discovery

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Axial-vector mediator: towards UV completions

⇒ $t$-channel can fully be probed, $s$-channel only partially

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6. Conclusions

- Many SUSY analyses performed, with mixed prospects for DD
- EFT vs. DMSM vs. full theories
- Lagrangian for vector or axial-vector mediator
- So far results presented for fixed values for some of $g_{SM}$, $g_{DM}$, $m_{med}$, $m_{DM}$ and other constraints (mono-jet, di-jet) overlaid
- MasterCode approach: full fit of the model, including
  - DM relic density
  - DM direct detection limits
  - LHC mono-jet searches
  - LHC di-jet searches
- **Vector mediator**: $s$- and $t$-channel separated, mixed prospects for DD
- **Axialvector**: $s$- and $t$-channel continuous, mixed prospects for DD
- **UV-completions**: $1/3 < g_{SM}/g_{DM} < 3 \Rightarrow s$-channel preferred

$\Rightarrow$ prospects for DD not improved
Further Questions?