DM Predictions from the LHC

Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

Corpus Cristi, 05/2019

1. Introduction & Models
2. Results in SUSY GUT models
3. Results in the pMSSM11
4. Results in non-SUSY models
5. Conclusions
1. Introduction & Models

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

⇒ 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

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?
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- no SUSY model? ⇒ not really realistic!

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

### Scenarios

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

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

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

[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 Mastercode website](https://cern.ch/mastercode)
Data we have:

- Higgs boson mass/couplings/... (LHC) $\Rightarrow$ FeynHiggs
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- Higgs boson signal strengths (LHC) ⇒ HiggsSignals
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- SUSY / di-jet /mono-jet searches (LHC) ⇒ own re-cast
Data we have:

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- SUSY / di-jet /mono-jet searches (LHC) ⇒ own re-cast
- electroweak precision data ⇒ FeynWZ, FeynHiggs
- flavor data ⇒ SuperIso, SuFla
- astrophysical data (DM properties) ⇒ MicrOMEGAs, SSARD
The $\chi^2$ evaluation:

\[ \chi^2 = \sum_i^{N_{\text{meas}}} \left( \frac{P_i - \mu_i}{\sigma_i} \right) \]
2. Results in SUSY GUT models

Results in the CMSSM, NUHM1, NUHM2

$\Rightarrow$ only very large values are favored

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$\sigma_p^{\text{SI}}$ incl. 20/fb of LHC data

$\sigma_p^{\text{SI}}$ \[2014\]

⇒ only very small values are favored

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MSSM DM prediction

Direct detection: past-present-future

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

Future searches would significantly probe the CMSSM

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Some of the parameter space of the NUHM1 is beyond the intrinsic background from atmospheric neutrinos.

MSSM DM prediction
All these GUT-models are indeed within the red blob. So what about the pMSSM10?
Results in the SU(5)

Dark Matter annihilation mechanism:

\[ 2016 \Rightarrow \tilde{\nu}_R/\tilde{c}_R/\tilde{\tau} \text{ co-annihilation possible} \]
Dark Matter Direct Detection prospects:

\[ \sigma_{p}^{SI} \left[ \text{cm}^2 \right] \]

\[ m_{\tilde{\chi}_1^0} \left[ \text{GeV} \right] \]

- $\tilde{\tau}$ coann.
- $\tilde{\tau}_1$ coann. + $H/A$
- $\tilde{\chi}_1^{\pm}$ coann.
- $A/H$ funnel
- $\tilde{\nu}_\tau$ coann.
- $\tilde{\nu}_R/\tilde{c}_R$ coann.

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Results in the mAMSB

Known fact: Dark Matter requirement restricts $m_{3/2}$:

$\Rightarrow$ no Sommerfeld enhancement

[2016]
Results in the mAMSB

Known fact: **Dark Matter requirement restricts** $m_{3/2}$:

$\Rightarrow$ with Sommerfeld enhancement $\Rightarrow$ shift to higher $m_{3/2}$
Dark Matter composition:

$\Rightarrow m_{\tilde{\chi}^0_1} \sim 2.9 \pm 0.1 \text{ TeV (wino), } \sim 1.1 \pm 0.02 \text{ TeV (higgsino)}$
Dark Matter Direct Detection prospects:

\[ \sigma_p^{SI} \left[ \text{cm}^2 \right] \]

- mAMSB: \( \tilde{W} \) best fit, \( \tilde{H} \) best fit, 1\( \sigma \), 2\( \sigma \)
- LSP composition: \( \tilde{W} \), Mixed, \( \tilde{H} \)

\( \mu > 0, \Omega_{\chi_1^0} = \Omega_{\text{CDM}} \)

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

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Results in sub-GUT

\[ \Rightarrow \text{many DM mechanisms possible} \]
\[ \Rightarrow \text{low } M_{\text{in}} \text{ possible/favored} \]
Dark Matter Direct Detection prospects:

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

$\sigma_{SD}^p$: unclear prospects, best-fit regions below the neutrino floor

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3. Results in the pMSSM11

DM mass: pMSSM10 vs. GUT based models prediction:

⇒ pMSSM10 predicts much lower DM mass than GUT-based models
3. Results in the pMSSM11

DM mass: similar in the pMSSM11:

⇒ pMSSM11 predicts much lower DM mass than GUT-based models
pMSSM prediction: \( m_{\tilde{\chi}_1^0} \) vs. \( \sigma_{p}^{SI} \):

⇒ best-fit point covered by future experiments
⇒ but very low cross sections possible at 1σ, below neutrino floor
pMSSM prediction: $m_{\tilde{\chi}_1^0}$ vs. $\sigma_p^{SD}$:

$\Rightarrow$ slim prospects for future experiments

$\Rightarrow$ large regions allowed at $1\sigma$, below neutrino floor
4. Results in non-SUSY models

\[ \Rightarrow \text{SM + Dirac DM + Leptophobic spin-1 mediator} \]

Lagrangian according to LHC-DM-WG recommendation:

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

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1. \( g_{X_D}^V \equiv g_{DM} \quad g_{X_D}^V = 0 \)
   \( g_{u/d}^V \equiv g_{SM} \quad g_{u/d}^V = 0 \),
   pure vector.

2. \( g_{X_D}^V = 0 \quad g_{X_D}^V \equiv g_{DM} \)
   \( g_{u/d}^V = 0 \quad g_{u/d}^A \equiv g_{SM} \),
   pure axial-vector.

[taken from E. Bagnaschi]

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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) \text{ TeV})</td>
<td>10</td>
</tr>
<tr>
<td>( m_\chi ) (DM)</td>
<td>((0, 2.5) \text{ 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>
Constraints:

- **DM constraints: relic abundance**
  ⇒ full agreement with ATLAS/CMS results/implementations

- **DM constraints: direct detection**
  ⇒ LUX, Xenon1T, PANDAX, PICO60

- **Mono-jet constraints**
  ⇒ MC5 aMC(N)NLO, Fastlim approach

- **di-jet constraints**
  ⇒ MC5 aMC(N)NLO, Fastlim approach

→ details in the back-up
General Results

- Results for vector mediator model

- Results for axial-vector mediator model → back-up

- 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
Towards UV completions

So far no UV completion considered!
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!

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

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

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

⇒ 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

$\Rightarrow t$-channel can fully be probed, $s$-channel only partially
5. Conclusinos

- **SUSY** constrained: CMSSM, NUHM, SU(5), mAMSB, sub-GUT
  - **SUSY** general: pMSSM11, …

- Our tool: MasterCode: combination of all relevant data!

- **CMSSM, NUHM1, NUHM2**: $m_{\tilde{\chi}^0_1} \gtrsim 400$ GeV, neutrino floor
  - best-fit regions (mostly) above/at/below

- **SU(5)**: stau co-ann., but also $\tilde{u}_R/\tilde{c}_R/\tilde{\nu}_\tau$ co-ann. possible
  - $m_{\tilde{\chi}^0_1}$ as in CMSSM, NUHM1, NUHM2

- **mAMSB**: $m_{\tilde{\chi}^0_1} \sim 2.9 \pm 0.1$ TeV (wino), $\sim 1.1 \pm 0.02$ TeV (higgsino)
  - DD: wino at neutrino floor, higgsino tested by next round

- **pMSSM11**: $m_{\tilde{\chi}^0_1} \lesssim 500$ GeV; important: chargino co-annihilation
  - $\sigma_p^{SI}$ partially cov. at future exp., $\sigma_p^{SD}$ below neutrino floor

- **SM + Dirac DM + Leptophobic spin-1 mediator**
  \Rightarrow MasterCode approach: full fit of the model (no simplifying ass.)

- **Vector mediator**: $s$- and $t$-channel separated, mixed prospects for DD

- **Axialvector**: $s$- and $t$-channel continous, 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?
The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

Problem in the MSSM: more than 100 free parameters

Nobody(?) believes that a model describing nature has so many free parameters!
A. Unconstrained models (MSSM):
agnostic about how SUSY breaking is achieved
no particular SUSY breaking mechanism assumed, parameterization of possible soft SUSY-breaking terms
most general case:
⇒ 105 new parameters: masses, mixing angles, phases
⇒ no model missed (within the MSSM)
⇒ $\mathcal{O}(100)$ parameters difficult to handle

B. Constrained models:
CMSSM, NUHM1, NUHM2, SU(5), mAMSB, sub-GUT, . . . :
assumption on the scenario that achieves spontaneous SUSY breaking
⇒ prediction for soft SUSY-breaking terms
  in terms of small set of parameters
⇒ easy to handle
GUT based models: 1.) CMSSM (sometimes wrongly called mSUGRA):

⇒ Scenario characterized by

\[ m_0, m_{1/2}, A_0, \tan \beta, \text{sign } \mu \]

\[ m_0 : \text{universal scalar mass parameter} \]
\[ m_{1/2} : \text{universal gaugino mass parameter} \]
\[ A_0 : \text{universal trilinear coupling} \]
\[ \tan \beta : \text{ratio of Higgs vacuum expectation values} \]
\[ \text{sign}(\mu) : \text{sign of supersymmetric Higgs parameter} \]

⇒ particle spectra from renormalization group running to weak scale

⇒ Lightest SUSY particle (LSP) is the lightest neutralino ⇒ DM!
“Typical” CMSSM scenario (SPS 1a benchmark scenario):

Strong connection between all the sectors
GUT based models: 2.) NUHM1: (Non-universal Higgs mass model)

Assumption: no unification of scalar fermion and scalar Higgs parameter at the GUT scale

⇒ effectively $M_A$ as free parameters at the EW scale

⇒ Scenario characterized by

$m_0, m_{1/2}, A_0, \tan \beta, \text{sign } \mu \text{ and } M_A$

GUT based models: 3.) NUHM2: (Non-universal Higgs mass model 2)

Assumption: no unification of scalar Higgs parameter at the GUT scale

⇒ effectively $M_A$ and $\mu$ as free parameters at the EW scale

⇒ Scenario characterized by

$m_0, m_{1/2}, A_0, \tan \beta, \mu \text{ and } M_A$
GUT based models: 4.) SU(5) GUT:

Assumption I:
no unification of scalar Higgs parameter at the GUT scale
(⇒ effectively $M_A$ and $\mu$ as free parameters at the EW scale)

Assumption II:

$$(q_L, u^c_L, e^c_L)_i \in 10_i, \ (\ell_L, d^c_L)_i \in \bar{5}_i$$

⇒ Scenario characterized by

$m_5, m_{10}, m_{1/2}, A_0, \tan \beta, m_{H_u}, m_{H_d}$
GUT based models: 5.) mAMSB:

mAMSB scenario characterized by

\[ m_{3/2}, m_0, \tan \beta, \text{sign}(\mu) \]

\[ m_{3/2} = \langle F \rangle/M_{\text{Planck}} \] overall scale of SUSY particle masses

\[ m_0 \] phenomenological parameter: universal scalar mass term introduced in order to keep squares of slepton masses positive

typical feature: very small neutralino–chargino mass difference

\[ \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + \pi^\pm \] with very soft pions
GUT based models: 6.) sub-GUT:

Based on CMSSM with unification at $M_{\text{GUT}} \sim 2 \cdot 10^{16}$ GeV:

\[
\Rightarrow \text{Scenario characterized by}
\]

\[
m_0, m_{1/2}, A_0, \tan \beta, \text{sign } \mu
\]

Unification is assumed at $M_{\text{in}} \leq M_{\text{GUT}}$:

\[
\Rightarrow \text{Scenario characterized by}
\]

\[
M_{\text{in}}, m_0, m_{1/2}, A_0, \tan \beta, \text{sign } \mu
\]

Possible realization in “mirage unification”

warped extra dimensions

\[
\ldots
\]
Mechanisms for relic dark matter density fulfillment in the CMSSM

- CMSSM: best fit, 1σ, 2σ
- CMSSM (4 parameters)

- stau coann.
- H/A-funnel
- chargino coann.
- stop coann.

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CMSSM DM prediction

Mechanisms for relic dark matter density fulfillment in the CMSSM

CMSSM: best fit, 1σ, 2σ

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29/09/2014  Kees Jan de Vries; Mastercode; BSM fit workshop 2014
CMSSM DM prediction

Mechanisms for relic dark matter density fulfillment in the CMSSM

CMSSM (4 parameters)

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Mechanisms for relic dark matter density fulfillment in the NUHM1

\[ m_{H_u}^2 = m_{H_d}^2 \neq m_0^2 \]

NUHM1 (5 parameters)

- stau coann.
- H/A-funnel
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$M_{H_u}^2 = M_{H_d}^2 \neq M_0^2$

NUHM1: best fit, 1σ, 2σ

NUHM1 (5 parameters)

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Mechanisms for relic dark matter density fulfillment in the NUHM2

- $m_{H_u}^2 \neq m_{H_d}^2 \neq m_0^2$

NUHM2 (6 parameters)

- stau coann.
- H/A-funnel
- stop coann.
- chargino coann.

29/09/2014

Kees Jan de Vries; Mastercode; BSM H. Workshop 2014

Sven Heinemeyer, SUSY 19, Corpus Cristi, 21.05.2019
Mechanisms for relic dark matter light in the NUHM2

NUHM2: best fit, 1σ, 2σ

NUHM2 (6 parameters)
Mechanisms for relic dark matter density fulfillment in the NUHM2

29/09/2014
Kees Jan de Vries; Mastercode; BSM R. Workshop 2014

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5. Conclusions

- **SUSY** is (still) the best-motivated BSM scenario
  - constrained models: CMSSM, NUHM, SU(5), mAMSB, sub-GUT
  - general models: pMSSM11, ...

- Our tool: **MasterCode**: combination of LHC searches, Higgs measurements, EWPO, BPO, CDM \( \Rightarrow \chi^2 \) evaluation

- Results wrt. neutrino floors:

<table>
<thead>
<tr>
<th>Model</th>
<th>Min. ( \chi^2 )/dof</th>
<th>( \chi^2 )-prob. (p)</th>
<th>( \sigma_p^{SI} )</th>
<th>( \sigma_p^{SD} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMSSM</td>
<td>32.8/18</td>
<td>11%</td>
<td>2( \sigma )</td>
<td>–</td>
</tr>
<tr>
<td>NUHM1</td>
<td>31.1/23</td>
<td>12%</td>
<td>1( \sigma )</td>
<td>–</td>
</tr>
<tr>
<td>NUHM2</td>
<td>30.3/22</td>
<td>11%</td>
<td>1( \sigma )</td>
<td>–</td>
</tr>
<tr>
<td>SU(5)</td>
<td>32.4/23</td>
<td>9%</td>
<td>1( \sigma )</td>
<td>–</td>
</tr>
<tr>
<td>mAMSB</td>
<td>36.5/27</td>
<td>11%</td>
<td>2( \sigma )</td>
<td>–</td>
</tr>
<tr>
<td>sub-GUT</td>
<td>28.9/24</td>
<td>23%</td>
<td>3( \sigma )</td>
<td>1( \sigma ) part. below</td>
</tr>
<tr>
<td>pMSSM11</td>
<td>22.1/20</td>
<td>33%</td>
<td>3( \sigma )</td>
<td>1( \sigma ) part. below</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 PICO60.

[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
Axial-vector mediator (I):

\[ m_Y \text{ [GeV]} \quad m_\chi \text{ [GeV]} \]

\[ \Rightarrow \text{ Larger } s\text{-channel region, continuous with } t\text{-channel} \]
Axial-vector mediator (II):

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

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

⇒ neither for LZ!