Supersymmetry, direct and indirect constraints

Nazila Mahmoudi
Lyon University & CERN

Thanks to A. Arbey, M. Battaglia, A. Djouadi, G. Robbins and M. Spira

“Seventh Workshop on Theory, Phenomenology and Experiments in Flavour Physics
FPCapri2018 – 8-10 June 2018
Oje vita, oje vita mia Inno ...

Staje luntana da stu core
e a te volo cu’ ‘o penziero:
niente voglio e niente spero
car tenerte sempe a ffianco a me!
Si’ sicura ’e chist’ammore
comm’i’ so’ sicuro ’e te...

Oje vita, oje vita mia,
oje core ’e chistu core,
si’ stata ’o primmâ ammore,
e ’o primmo e ll’ultimo sarra pe’ me!

Quanta notte nun te veco,
nun te sento in fra sti bracia,
nun te vaso chesta faccia,
nun t’astrengo forte ’mbraccio a me?
Ma, scetanomi’a sti suonne,
mme faj chiagner per te.

Oje vita....
Where to look for Supersymmetry?

**At high energy collider**
- SUSY and exotic searches
- Higgs boson searches and measurements
- flavour physics

**At low energy experiments**
- $B$-factories
- Electric dipole moments
- ...

**In space**
- Relic density
- Direct detection
- Indirect detection
- ...
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Capri – June 9th, 2018
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N. Mahmoudi
Capri – June 9th, 2018
**SUSY? Is she dead? Or too heavy?**

ATLAS and CMS set very strong constraints on the MSSM strongly interacting sector

\[ M_{\tilde{g}} \gtrsim 2 \text{ TeV}, \quad M_{\tilde{q}} \gtrsim 1.5 \text{ TeV} \]

Squarks and gluinos are getting heavier and heavier...

But these limits are valid only in very simple MSSM scenarios...
ATLAS and CMS set very strong constraints on the MSSM strongly interacting sector

\[ \tilde{q} \rightarrow q \tilde{\chi}_i^\pm, \tilde{q} \rightarrow q \tilde{\chi}_i^0 \]

\[ M_{\tilde{g}} \gtrsim 2 \text{ TeV}, \quad M_{\tilde{q}} \gtrsim 1.5 \text{ TeV} \]

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But these limits are valid only in very simple MSSM scenarios...
Phenomenological MSSM (pMSSM)

The most general MSSM scenario with $R$-parity and minimal flavour violation

→ 19 independent parameters with CP conservation

In the following, we consider the lightest neutralino as dark matter

The neutralino can be

- bino-like ($|M_1| \ll |M_2|, |\mu|$)
- wino-like ($|M_2| \ll |M_1|, |\mu|$)
- higgsino-like ($|\mu| \ll |M_1|, |M_2|$)
- or a mixed state

→ Study of the pMSSM parameter space requires large scans and many constraints
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Random scans of the 19 pMSSM parameters with neutralino dark matter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range (in GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_A$</td>
<td>[50, 2000]</td>
</tr>
<tr>
<td>$M_1$</td>
<td>[-3000, 3000]</td>
</tr>
<tr>
<td>$M_2$</td>
<td>[-3000, 3000]</td>
</tr>
<tr>
<td>$M_3$</td>
<td>[50, 5000]</td>
</tr>
<tr>
<td>$A_d = A_s = A_b$</td>
<td>[-15000, 15000]</td>
</tr>
<tr>
<td>$A_u = A_c = A_t$</td>
<td>[-15000, 15000]</td>
</tr>
<tr>
<td>$A_e = A_\mu = A_\tau$</td>
<td>[-15000, 15000]</td>
</tr>
<tr>
<td>$\mu$</td>
<td>[-3000, 3000]</td>
</tr>
<tr>
<td>$M_{\tilde{e}<em>L} = M</em>{\tilde{\mu}_L}$</td>
<td>[0, 5000]</td>
</tr>
<tr>
<td>$M_{\tilde{e}<em>R} = M</em>{\tilde{\mu}_R}$</td>
<td>[0, 5000]</td>
</tr>
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<td>[0, 5000]</td>
</tr>
<tr>
<td>$M_{\tilde{q}<em>1L} = M</em>{\tilde{q}_2L}$</td>
<td>[0, 5000]</td>
</tr>
<tr>
<td>$M_{\tilde{q}_3L}$</td>
<td>[0, 5000]</td>
</tr>
<tr>
<td>$M_{\tilde{u}<em>R} = M</em>{\tilde{\ell}_R}$</td>
<td>[0, 5000]</td>
</tr>
<tr>
<td>$M_{\tilde{t}_R}$</td>
<td>[0, 5000]</td>
</tr>
<tr>
<td>$M_{\tilde{d}<em>R} = M</em>{\tilde{s}_R}$</td>
<td>[0, 5000]</td>
</tr>
<tr>
<td>$M_{\tilde{b}_R}$</td>
<td>[0, 5000]</td>
</tr>
<tr>
<td>$\tan\beta$</td>
<td>[1, 60]</td>
</tr>
</tbody>
</table>

- Calculation of masses, mixings and couplings (SoftSusy, Suspect)
- Computation of low energy observables and $Z$ widths (SuperIso)
- Computation of dark matter observables (SuperIso Relic, Micromegas)
- Determination of SUSY and Higgs mass limits (SuperIso, HiggsBounds)
- Calculation of Higgs cross-sections and decay rates (HDECAY, Higlu, FeynHiggs, SusHi)
- Calculation of SUSY decay rates (SDECAY)
- Event generation and evaluation of cross-sections (PYTHIA, Prospino, MadGraph)
- Implementation of ATLAS and/or CMS SUSY and monoX search results
- Determination of detectability with fast detector simulation (Delphes)
Different ways of searching for dark matter:

- **Direct production** of LSPs at the LHC
  → neutralinos present in most of the SUSY search channels
  → monojet searches specifically designed for invisible particle searches

- **DM annihilations**: $\text{DM} + \text{DM} \rightarrow \text{SM} + \text{SM} + \ldots$
  - indirect detection: protons, gammas, anti-protons, positrons, ...
  - dark matter relic density: also dependent on co-annihilations

  Annihilation cross-sections can be enhanced through Higgs resonances

- **DM scattering** with matter: $\text{DM} + \text{matter} \rightarrow \text{DM} + \text{matter}$
  → direct detection experiments

  Neutralino scattering cross-section sensitive to neutral Higgs bosons

- **Invisible Higgs decays** to LSPs
  → very much dependent on the nature of the LSP
Relic density “naturally” obtained for a Higgsino of 1.3 TeV or a Wino of 2.7 TeV

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The relic density tends to select more compressed scenarios with co-annihilations
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In the following, we will use only the upper limit: $\Omega \chi h^2 < 0.160$
Neutralino direct detection

Upper limits on the WIMP-nucleon scattering cross sections

Limits affected by the local dark matter density and velocity

**Higgsino**-like neutralinos more strongly probed

Strong constraints on the \((M_A, \tan \beta)\) parameter plane

Complementary to \(H/A \rightarrow \tau^+ \tau^-\) and \(B_s \rightarrow \mu^+ \mu^-\) searches
Neutralino indirect detection

Upper limits on annihilation cross sections

AMS-02: anti-proton fluxes
→ largely affected by propagation model (factor $\sim 10$) and galaxy profile (factor $\sim 2$)

Fermi-LAT: gamma rays from dwarf spheroidal galaxies
→ affected by galaxy profile
Neutralino indirect detection

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Wino-like neutralinos more strongly probed
→ complementary to direct detection!
Dependence on the choice of astrophysical assumptions

Three Dark Matter benchmark cases

- **CONSERVATIVE**: AMS-02 antiprotons with Burkert profile and MED propagation model + local density of 0.2 GeV/cm³
- **STANDARD**: Fermi-LAT gamma rays with NFW profile + local density of 0.4 GeV/cm³
- **STRINGENT**: AMS-02 antiprotons with NFW profile and MAX propagation model + local density of 0.6 GeV/cm³

Exclusion by dark matter observables

CONSERVATIVE

STANDARD

STRINGENT
Direct SUSY and monojet searches at the LHC

**Direct SUSY searches (8 and 13 TeV):**

- Squark and gluino direct searches (jets + $E_T$)
- Stop and sbottom direct searches ($t$, $b$-jets (+ leptons) + $E_T$)
- Chargino and neutralino direct searches (leptons (+ $b$-jets) + $E_T$)

generate events with MadGraph/Pythia and simulate the detector with Delphes

**Monojet searches:** search for 1 hard jet + $E_T$

**Other Mono-X searches:** mono-W/Z/γ, mono-top, mono-Higgs, ... searches

→ Mono-X search results need to be reinterpreted in the MSSM!
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Mono-X searches

Generic monojets in “simple” DM scenarios:

Monojets in the MSSM:

LHC very sensitive to the strongly interacting particles
→ larger monojet cross sections in the MSSM
→ particularly relevant when small mass splitting between squark/gluino and neutralino
→ monojet searches in the MSSM are more sensitive to squarks and gluinos than to neutralinos!

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LHC and direct detection

In the dark matter direct detection scattering cross section vs. neutralino mass plane:

- jets/leptons+MET only
- jets/leptons+MET searches and monojet

Colour scale: fraction of excluded points

In contrast with simplified models, in the MSSM monojet searches probe different regions than direct detection

DM direct detection and LHC searches are complementary!
Fraction of excluded points as a function of the

lightest squark mass

gluino mass

Dotted: 8 TeV only
Solid: 8+13 TeV

Squark masses below \( \sim 1 \) TeV are still allowed in pMSSM!
Implications of the Higgs mass measurement for the MSSM

In the MSSM light CP-even Higgs is bounded from above:  $M_h^{\text{max}} \lesssim 110 - 135$ GeV

\[
M_h^2 \approx M_Z^2 \cos^2 2\beta \left[ 1 - \frac{M_Z^2}{M_A^2} \sin^2 2\beta \right] + \frac{3m_t^4}{2\pi^2 v^2} \left[ \log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} \left( 1 - \frac{X_t^2}{12M_S^2} \right) \right]
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$M_S$: averaged stop mass and $X_t$ the stop mixing parameter

\rightarrow Imposing $M_h$ places very strong constraints on the MSSM parameters

- Modified couplings with respect to the SM Higgs boson (\rightarrow decoupling limit):

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ATLAS and CMS measurements:

Signal strength:

\[
\mu_{XX} = \frac{\sigma(pp \to h) \text{BR}(h \to XX)}{\sigma(pp \to h)_{\text{SM}} \text{BR}(h \to XX)_{\text{SM}}}
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\rightarrow The results are compatible with the SM Higgs
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Higgs constraints in pMSSM

A. Arbey, M. Battaglia, A. Djouadi, FM, M. Spira, in preparation
Heavy Higgs search constraints in pMSSM

Complementary channels: $H \rightarrow \tau\tau, ZZ, bb, tt, hZ, hh$

8 TeV

14 TeV (150 fb$^{-1}$)

lines: limits corresponding to an exclusion of 99.9% of the points
Grey points: excluded by dark matter, flavour physics and Higgs mass constraints
Colour scale: fraction of excluded points

→ Some points inside the $H \rightarrow \tau\tau$ excluded region still survive
→ Other channels ($H \rightarrow ZZ, H \rightarrow t\bar{t}, ...$) will help probing the small $\tan\beta$ region
Sensitivity to the mass of the CP-odd A boson

continuous line: 95% C.L. exclusion bounds by the LHC direct searches
gray bars: indirect constraints from the Higgs signal strength measurements

Higgs searches complementary to the direct searches!

Dark matter detection and LHC in the pMSSM

Exclusion by dark matter observables only (Higgs mass pre-imposed)

CONSERVATIVE

STANDARD

STRINGENT
Exclusion by dark matter observables only (Higgs mass pre-imposed)

CONSERVATIVE

STANDARD

STRINGENT

Exclusion by dark matter observables and LHC searches

Interesting complementary between DM searches and LHC!
Complementary of LHC and dark matter searches

Direct detection and Heavy Higgs searches

Fraction of points excluded by DD

Direct and indirect detection and LHC

Interesting interplay in the Higgs and Higgsino sectors!

Complementary of LHC and dark matter searches

Gluino/squark mass vs. Neutralino mass

Stop 1 mass vs. Neutralino mass

Interplay also interesting in the squark and gluino sectors!

Perspectives

Future of direct detection

![Plot of direct detection sensitivity vs mass](image1)

- XENON1T (2017)
- XENONnT/LZ
- DARWIN

- Accepted after LHC 8 TeV
- Accepted after LHC 13 TeV

Future of indirect detection

![Plot of indirect detection sensitivity vs mass](image2)

- Burkert
- NFW
- Einasto

- Accepted after LHC 8 TeV
- Accepted after LHC 13 TeV
- Excluded by Fermi-LAT
- CTA ($\chi\chi \to WW$)


**Strong improvements expected!**

Direct detection will be limited after DARWIN by the neutrino background.

Indirect detection will be limited by our knowledge of the dark matter profile.
<table>
<thead>
<tr>
<th>Introduction</th>
<th>DM constraints</th>
<th>Direct searches</th>
<th>Higgs constraints</th>
<th>Combined constraints</th>
<th>CPV MSSM</th>
<th>Future</th>
</tr>
</thead>
</table>

**CP violating pMSSM**
New physics could well be hidden in CP violating observables...

**CP violating phenomenological MSSM (CPV-pMSSM)**

→ 19 pMSSM parameters + 6 phases = 25 parameters


\[
M_\alpha = |M_\alpha|e^{i\phi_\alpha} \quad A_\beta = |A_\beta|e^{i\phi_\beta}
\]

The CP phases can take values between -180 and 180 degrees, and modify the mixing matrices and couplings

3 neutral Higgs bosons \(h_1, h_2, h_3\) with scalar and pseudoscalar components
Electric dipole moment (EDM) constraints

Convention used thereafter:

\[ \mathcal{L}_{\text{EDM}} = -\frac{i}{2} d_f F^{\mu\nu} \bar{f} \sigma_{\mu\nu} \gamma_5 f \]

Nucleon EDMs: \((\eta^E, |\Delta| \sim 1)\)

\[ d_N = \eta^E (\Delta_d^N d_d + \Delta_u^N d_u + \Delta_s^N d_s) \]

Current limits at 95% C.L.

<table>
<thead>
<tr>
<th>EDM</th>
<th>Upper limit (e.cm)</th>
<th>Equivalent limit (e.cm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thallium</td>
<td>(1.3 \times 10^{-24})</td>
<td>(d_e : 2.1 \times 10^{-27})</td>
<td>PRL 88 (2002) 071805</td>
</tr>
<tr>
<td>Thorium monoxide</td>
<td>-</td>
<td>(d_e : 1.1 \times 10^{-28})</td>
<td>Science 343 (2014) 269</td>
</tr>
<tr>
<td>Muon</td>
<td>(1.9 \times 10^{-19})</td>
<td>(d_\mu : 1.9 \times 10^{-19})</td>
<td>PRD 80 (2009) 052008</td>
</tr>
<tr>
<td>Mercury</td>
<td>(7.4 \times 10^{-30})</td>
<td>(d_n : 1.6 \times 10^{-26}) (d_p : 2.0 \times 10^{-25})</td>
<td>PRL 116 (2016) 161601</td>
</tr>
<tr>
<td>Neutron</td>
<td>(4.2 \times 10^{-26})</td>
<td>(d_n : 4.2 \times 10^{-26})</td>
<td>PRL 97 (2006) 131801</td>
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Prospective values for proton EDM (CPEDM Collaboration, CERN proton ring, 2021+):

\[ |d_p| < 2 \times 10^{-29} \]
EDMs in the MSSM

\[ d_f = d_f^{\tilde{\chi}^\pm} + d_f^{\tilde{\chi}^0} + d_f^{\tilde{g}} \text{ (+higher order } d_f^H \text{)} \] where \( f = e, \mu, u, d, s \).

Chargino-mediated one-loop EDMs

\[
\begin{align*}
    d_{\tilde{f}}^{\tilde{\chi}^\pm} &= -\frac{e}{16\pi^2} \sum_i \frac{m_{\tilde{\chi}^\pm}}{m_{\tilde{\nu}_l}^2} \text{Im} \left( g_{\tilde{R}_i}^{\tilde{\chi}^\pm \tilde{\nu}_l^*} g_{\tilde{L}_j}^{\tilde{\chi}^\pm \tilde{\nu}_l} \right) f(m_{\tilde{\chi}^\pm}^2/m_{\tilde{\nu}_l}^2) \\
    d_{\tilde{u}}^{\tilde{\chi}^\pm} &= \frac{e}{16\pi^2} \sum_{i,j} \frac{m_{\tilde{\chi}^\pm}}{m_{\tilde{d}_j}^2} \text{Im} \left( g_{\tilde{R}_{ij}}^{\tilde{\chi}^\pm \tilde{u}_j^*} g_{\tilde{L}_{ij}}^{\tilde{\chi}^\pm \tilde{u}_j} \right) \left[ f(m_{\tilde{\chi}^\pm}^2/m_{\tilde{d}_j}^2) - \frac{1}{3} g(m_{\tilde{\chi}^\pm}^2/m_{\tilde{d}_j}^2) \right] \\
    d_{\tilde{d}}^{\tilde{\chi}^\pm} &= \frac{e}{16\pi^2} \sum_{i,j} \frac{m_{\tilde{\chi}^\pm}}{m_{\tilde{u}_j}^2} \text{Im} \left( g_{\tilde{R}_{ij}}^{\tilde{\chi}^\pm \tilde{d}_j^*} g_{\tilde{L}_{ij}}^{\tilde{\chi}^\pm \tilde{d}_j} \right) \left[ -f(m_{\tilde{\chi}^\pm}^2/m_{\tilde{u}_j}^2) + \frac{2}{3} g(m_{\tilde{\chi}^\pm}^2/m_{\tilde{u}_j}^2) \right]
\]

Neutralino-mediated one-loop EDMs

\[
    d_{\tilde{f}}^{\tilde{\chi}^0} = \frac{e}{16\pi^2} \sum_{i,j} \frac{m_{\tilde{\chi}^0}}{m_{\tilde{f}_j}^2} \text{Im} \left( g_{\tilde{R}_{ij}}^{\tilde{\chi}^0 \tilde{f}_j^*} g_{\tilde{L}_{ij}}^{\tilde{\chi}^0 \tilde{f}_j} \right) Q_{\tilde{f}} g(m_{\tilde{\chi}^0}^2/m_{\tilde{f}_j}^2)
\]

Gluino-mediated one-loop EDMs

\[
    d_{\tilde{q}}^{\tilde{g}} = \frac{e}{3\pi^2} \sum_i \frac{m_{\tilde{g}}}{m_{\tilde{q}_i}^2} \text{Im} \left( g_{\tilde{R}_i}^{\tilde{g} \tilde{q}_i^*} g_{\tilde{L}_i}^{\tilde{g} \tilde{q}_i} \right) Q_{\tilde{f}} g(m_{\tilde{g}}^2/m_{\tilde{q}_i}^2)
\]

The \( g^{\tilde{G}ff'} \) contains the gaugino/neutralino/squark mixing matrices, \( Q_{\tilde{f}} \) is the charge of \( \tilde{f} \).
Problem: the EDMs impose so strong constraints that only zero phases are allowed, apart in some very restricted regions of the parameter space!

How to determine the direction in the phase parameter space minimizing the EDMs $E^i$ and maximizing another CP violating observable $O$?

We showed that the optimal direction, computed for each choice of the 19 CP conserving pMSSM parameters, is given by: A. Arbey, J. Ellis, R. Godbole, FM, Eur. Phys. J. C75 (2015), 85

$$\phi^*_{\alpha} = \epsilon_{\alpha \beta \gamma \delta \mu \eta} \epsilon_{\eta \nu \lambda \rho \sigma \tau} E^a_{\beta} E^b_{\gamma} E^c_{\delta} E^d_{\mu} O_{\nu} E^a_{\lambda} E^b_{\rho} E^c_{\sigma} E^d_{\tau}$$

with $\phi_{\alpha} = \phi_{1,2,3,t,b,\tau}$, $E^i_{\alpha} \equiv \partial E^i / \partial \phi_{\alpha}$ and $O_{\alpha} \equiv \partial O / \partial \phi_{\alpha}$

Works well in the limit of small phases... then an iterative approach is necessary:

To go beyond the limit of small phases, we start with phases at 0, determine the optimal direction, move by at most 20 degrees, and iterate to determine the optimal direction at the new position.
Sectors weakly affected by CP violation

**Relic density**

Planck: $\Omega h^2 \sim 0.1$

**Higgs signal strengths** ($M_{h_1} \in [122, 128]$ GeV)
Effects of the EDMs on the CP-violating phases

Original sample with no EDM constraints

Preliminary
Adding EDM constraints: Muon

Effects of the EDMs on the CP-violating phases

Preliminary
Adding EDM constraints: Muon, Thallium
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Preliminary

Adding EDM constraints: Muon, Thallium, Mercury, Neutron, Thorium Monoxyde

$\Phi_{M_2}$ already very severely constrained
Adding EDM constraints: Muon, Thallium, Mercury, Neutron, Thorium Monoxyde + Proton

Φ_{M_2} already very severely constrained
CP violation in the Higgs sector

The Higgs bosons can be mixtures of scalar and pseudoscalar components. The LHC constraints impose the $h_1$ to be a scalar with negligible pseudoscalar component. We define $(g_{S,P}^{h_i \bar{f} f} : \text{scalar,pseudoscalar coupling of } h_i \text{ to } \bar{f} f)$:

$$\tan \phi_{\tau}^{h_i} \equiv \frac{g_{P}^{h_i \tau \tau}}{g_{S}^{h_i \tau \tau}} , \quad \tan \phi_{t}^{h_i} \equiv \frac{g_{P}^{h_i \bar{t} t}}{g_{S}^{h_i \bar{t} t}}$$

Original sample with no EDM constraints

Similar plots for $h_3$
The Higgs bosons can be mixtures of scalar and pseudoscalar components.

The LHC constraints impose the $h_1$ to be a scalar with negligible pseudoscalar component.

We define $(g_{h_i \bar{f} f}^{\text{S}}, P):$ scalar, pseudoscalar coupling of $h_i$ to $\bar{f} f$:

$$\tan \phi_{\tau}^{h_i} \equiv \frac{g_{h_i \tau \tau}}{g_{h_i \tau \tau}^{\text{S}}}, \quad \tan \phi_t^{h_i} \equiv \frac{g_{h_i \bar{t} t}}{g_{h_i \bar{t} t}^{\text{S}}}$$

Adding EDM constraints: Muon

![Graphs showing number of points vs. $\phi_{\tau}^{h_i}$ and $\phi_t^{h_i}$](image)

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$$\tan \phi^h_i \tau \equiv \frac{g_P^{h_i \tau \tau}}{g^{h_i \tau \tau}_S}, \quad \tan \phi^h_i t \equiv \frac{g_P^{h_i \bar{t} t}}{g^{h_i \bar{t} t}_S}$$

Adding EDM constraints: Muon, Thallium

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Adding EDM constraints: Muon, Thallium, Mercury

![Diagram](image.png)

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Adding EDM constraints: Muon, Thallium, Mercury, Neutron.

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N. Mahmoudi Capri – June 9th, 2018
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Adding EDM constraints: Muon, Thallium, Mercury, Neutron, Thorium Monoxyde.
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Adding EDM constraints: Muon, Thallium, Mercury, Neutron, Thorium Monoxyde + Proton
Flavour sector

CP asymmetry in $b \rightarrow s\gamma$

$B_s$ meson mixing $\Delta M^{NP}_{B_s}$

Constraints limited by the theoretical uncertainties

Good perspectives if order of magnitude improvement on theoretical uncertainties

Current experiment limits superseded by EDM constraints

Good perspectives for the future

gray: without EDMs – black: with EDMs
blue: + prospective proton EDM
red: current limits – green: prospective Belle-II

N. Mahmoudi Capri – June 9th, 2018
- Full scan of the pMSSM 19 parameter space with SUSY masses up to 25 TeV
- Using projected constraints of HL-LHC and determination of scenarios where signals could be observed
- Assess whether data at a O(100 TeV) pp collider will enable to either discover a signal, or combined with DM data falsify the (p)MSSM

Fraction of points excluded by monojet and SUSY searches:

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<tr>
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<th>jets+MET+EWK+mono J,W,Z</th>
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pMSSM at 100 TeV

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Backup
Dark matter relic density

In the Standard Model of Cosmology:

- before and at nucleosynthesis time, the expansion is dominated by radiation
  \[ H^2 = \frac{8\pi G}{3} \times \rho_{\text{rad}} \]
- the evolution of the number density of supersymmetric particles follows the Boltzmann equation
  \[ \frac{dn}{dt} = -3Hn - \langle \sigma_{\text{eff}} v \rangle (n^2 - n_{\text{eq}}^2) \]

\( n \): number density of relic particles
\( \langle \sigma_{\text{eff}} v \rangle \): thermal average of effective (co-)annihilation cross sections to SM particles

Solving the system of equations leads to the relic density of the LSP

To be compared to the very constraining Planck interval:

\[ 0.077 < \Omega_{\chi} h^2 < 0.160 \]

Using this constraint has very strong consequences on the MSSM parameter space and only specific and small regions are selected!
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Dark matter relic density

Caveat about the relic density constraints:

The relic density constraint is strong and can rule out many models, but changing the underlying hypotheses can make them survive, e.g. if:

- the neutralino is not the only component of dark matter
- neutralinos are produced non-thermally (e.g. by the decay of an inflaton)
- dark energy accelerated the expansion of the Universe before the freeze-out
- additional entropy were generated in the early Universe
- ...

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In the following, we use only the upper bound:

$$\Omega_\chi h^2 < 0.160$$
$d_f = d_f^{\tilde{\chi}^\pm} + d_f^{\tilde{\chi}^0} + d_f^g + d_f^H$ where $f = e, \mu, u, d, s$. 

(Higher order) Higgs-mediated Barr-Zee diagrams:
Effects of the EDMs on the SUSY masses

Original sample with no EDM constraints
Effects of the EDMs on the SUSY masses

Adding EDM constraints: Muon

![Graphs showing the effects of EDM constraints on SUSY masses](image-url)
Adding EDM constraints: Muon, Thallium
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