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

Highlights on Supersymmetry, direct and indirect constraints

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Oje vita, oje vita mia Inno ...

Staje luntana da stu core
e a te volo cu' 'o penziero:
niente voglio e niente spero
ca 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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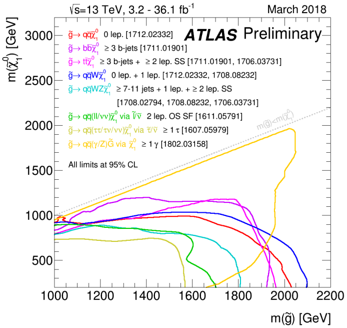
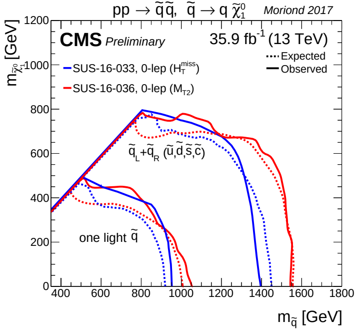
SUSY? Is she dead? Or too heavy?

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





$$M_{\tilde{g}} \gtrsim 2 \text{ TeV}, \qquad M_{\tilde{q}} \gtrsim 1.5 \text{ TeV}$$

Squarks and gluinos are getting heavier and heavier...

But these limits are valid only in very simple MSSM scenarios...

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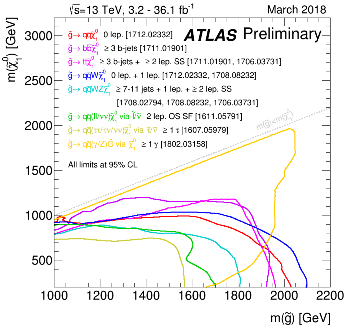

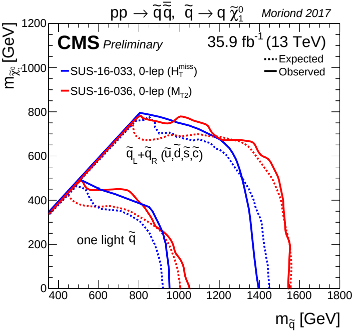

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Phenomenological MSSM

Phenomenological MSSM (pMSSM)

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

$\rightarrow$ 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

$\rightarrow$ Study of the pMSSM parameter space requires large scans and many constraints

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pMSSM scans

Random scans of the 19 pMSSM parameters with neutralino dark matter

Parameter	Range (in GeV)
M_A	[50, 2000]
M_1	[-3000, 3000]
M_2	[-3000, 3000]
M_3	[50, 5000]
$A_d = A_s = A_b$	[-15000, 15000]
$A_u = A_c = A_t$	[-15000, 15000]
$A_e = A_\mu = A_\tau$	[-15000, 15000]
μ	[-3000, 3000]
$M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$	[0, 5000]
$M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$	[0, 5000]
$M_{\tilde{\tau}_L}$	[0, 5000]
$M_{\tilde{\tau}_R}$	[0, 5000]
$M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$	[0, 5000]
$M_{\tilde{q}_{3L}}$	[0, 5000]
$M_{\tilde{u}_R} = M_{\tilde{c}_R}$	[0, 5000]
$M_{\tilde{t}_R}$	[0, 5000]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[0, 5000]
$M_{\tilde{b}_R}$	[0, 5000]
$\tan\beta$	[1, 60]

- 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)

Dark Matter Searches

Different ways of searching for dark matter:

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

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

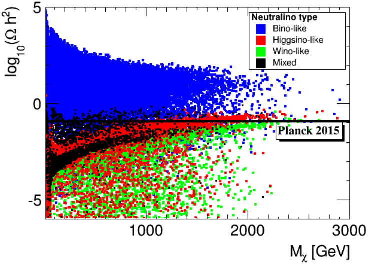
  Annihilation cross-sections can be enhanced through Higgs resonances

- **DM scattering** with matter: DM + matter $\rightarrow$ DM + matter
  $\rightarrow$ direct detection experiments

  Neutralino scattering cross-section sensitive to neutral Higgs bosons

- **Invisible Higgs decays** to LSPs
  $\rightarrow$ very much dependent on the nature of the LSP

Neutralino relic density

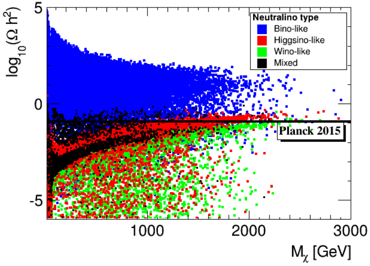


A. Arbey, M. Boudaud, FM, G. Robbins, JHEP 1711 (2017) 132

Relic density “naturally” obtained for a Higgsino of 1.3 TeV or a Wino of 2.7 TeV

Neutralino relic density

imposing $0.077 < \Omega_\chi h^2 < 0.160$



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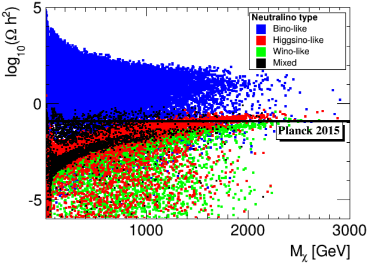

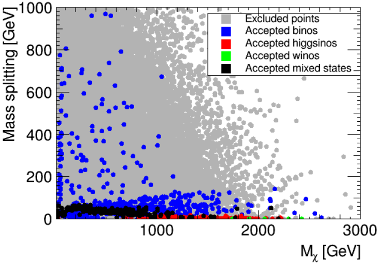

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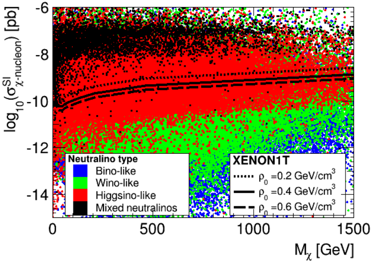
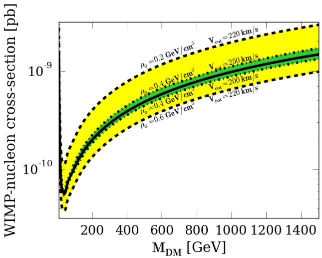
In the following, we will use only the upper limit: $\Omega_\chi h^2 < 0.160$

Neutralino direct detection





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Upper limits on the WIMP-nucleon scattering cross sections

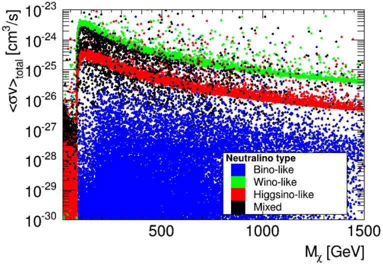
Limits affected by the local dark matter density and velocity

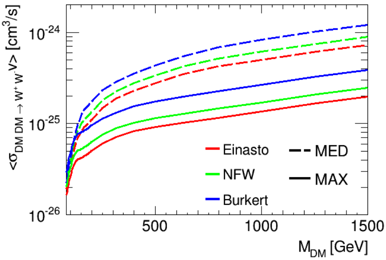
Higgsino-like neutralinos more strongly probed

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

Complementary to $H/A \to \tau^+\tau^-$ and $B_s \to \mu^+\mu^-$ searches

Neutralino indirect detection





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Upper limits on annihilation cross sections

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

Fermi-LAT: gamma rays from dwarf spheroidal galaxies
$\rightarrow$ affected by galaxy profile

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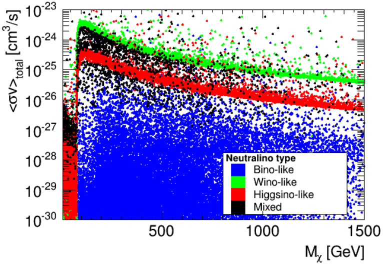

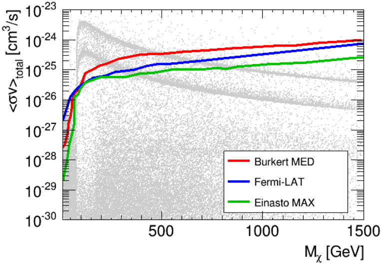

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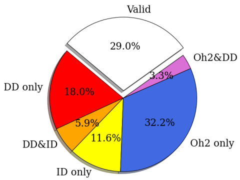
Wino-like neutralinos more strongly probed
→ complementary to direct detection!

Dependence on the choice of astrophysical assumptions

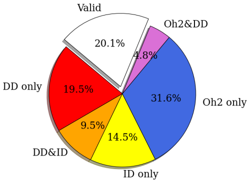
Three Dark Matter benchmark cases

- CONSERVATIVE: AMS-02 antiprotons with Burkert profile and MED propagation model + local density of 0.2 GeV/cm^3
- STANDARD: Fermi-LAT gamma rays with NFW profile + local density of 0.4 GeV/cm^3
- STRINGENT: AMS-02 antiprotons with NFW profile and MAX propagation model + local density of 0.6 GeV/cm^3

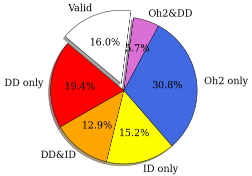
Exclusion by dark matter observables



CONSERVATIVE



STANDARD



STRINGENT

Direct SUSY and monojet searches at the LHC

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

  squark and gluino direct searches (jets + $\not{E}_T$)

  stop and sbottom direct searches (t, b-jets (+ leptons) + $\not{E}_T$)

  chargino and neutralino direct searches (leptons (+ b-jets) + $\not{E}_T$)

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

- **Monojet searches**: search for 1 hard jet + $\not{E}_T$

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

$\rightarrow$ Mono-X search results need to be reinterpreted in the MSSM!

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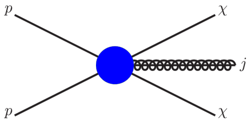
Mono-X searches

Generic monojets in "simple" DM scenarios:



Monojets in the MSSM:

A. Arbey, M. Battaglia, FM, Phys. Rev. D94 (2016) 055015

LHC very sensitive to the strongly interacting particles

$\to$ larger monojet cross sections in the MSSM

$\to$ particularly relevant when small mass splitting between squark/gluino and neutralino

$\to$ monojet searches in the MSSM are more sensitive to squarks and gluinos than to neutralinos!

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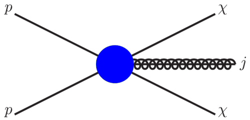

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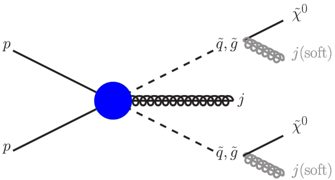

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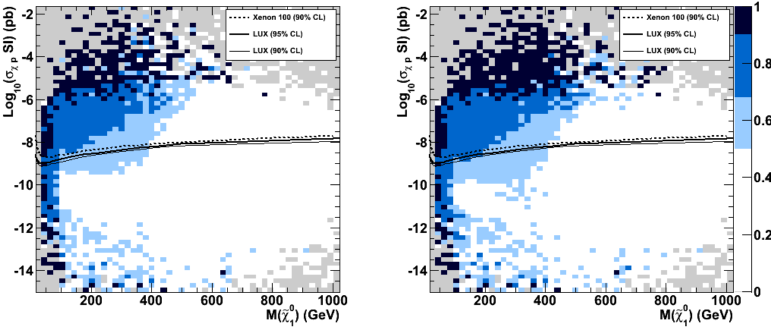
LHC and direct detection

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

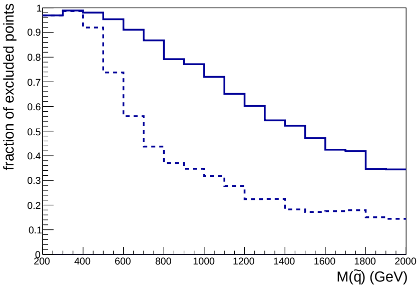
In contrast with simplified models, in the MSSM monojet searches probe different regions than direct detection

DM direct detection and LHC searches are complementary!

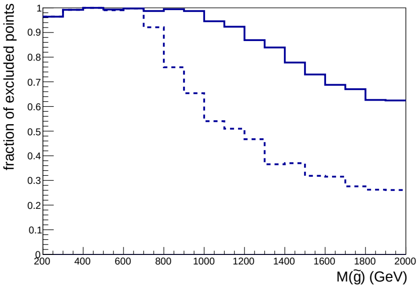
LHC and SUSY

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 ~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: $M_h^{max} \lesssim 110 - 135$ GeV

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

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):

ϕ	$g_{\phi u\bar{u}}$	$g_{\phi d\bar{d}} = g_{\phi \ell\bar{\ell}}$	$g_{\Phi VV}$
h	$\cos\alpha / \sin\beta \rightarrow 1$	$-\sin\alpha / \cos\beta \rightarrow 1$	$\sin(\beta-\alpha) \rightarrow 1$
H	$\sin\alpha / \sin\beta \rightarrow \cot\beta$	$\cos\alpha / \cos\beta \rightarrow \tan\beta$	$\cos(\beta-\alpha) \rightarrow 0$
A	$\cot\beta$	$\tan\beta$	0

ATLAS and CMS measurements:

Signal strength:

$$\mu_{XX} = \frac{\sigma(pp \to h)\,\mathrm{BR}(h \to XX)}{\sigma(pp \to h)_{\rm SM}\,\mathrm{BR}(h \to XX)_{\rm SM}}$$

ATLAS, CMS Collaborations, Phys. Rev. Lett. 114, 191803 (2015)

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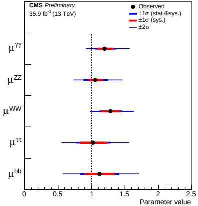

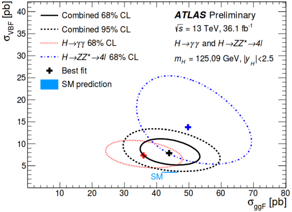

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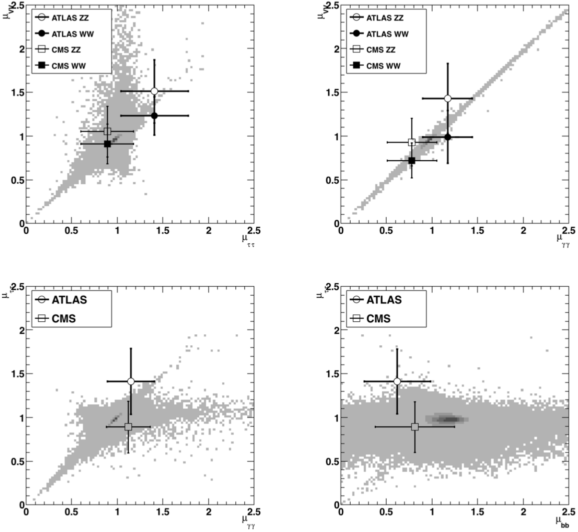
$$\mu_{XX} = \frac{\sigma(pp \rightarrow h)\, \mathrm{BR}(h \rightarrow XX)}{\sigma(pp \rightarrow h)_{\mathrm{SM}}\, \mathrm{BR}(h \rightarrow XX)_{\mathrm{SM}}}$$

ATLAS, CMS Collaborations, Phys. Rev. Lett. 114, 191803 (2015)

$\rightarrow$ The results are compatible with the SM Higgs

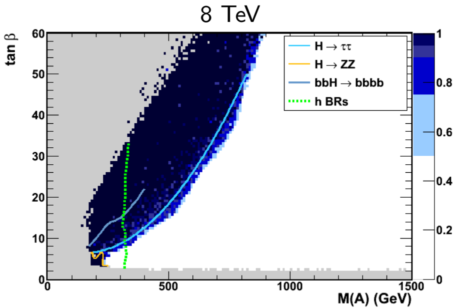
Higgs constraints in pMSSM

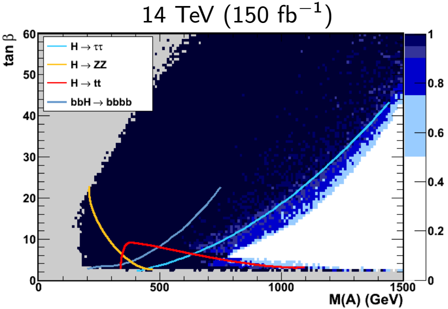


A. Arbey, M. Battaglia, A. Djouadi, FM, M. Spira, in preparation

Heavy Higgs search constraints in pMSSM

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



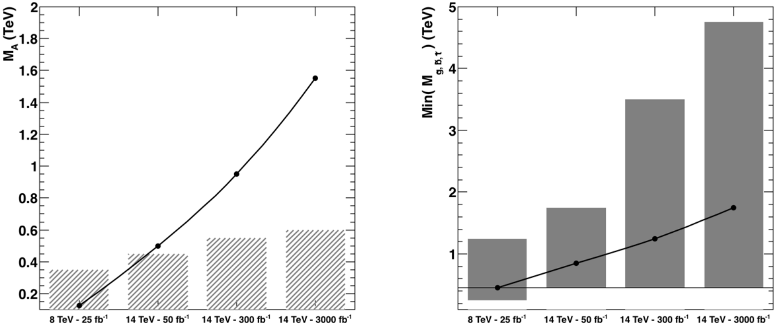


lines: limits corresponding to an exclusion of 99.9% of the points
Grey points: excluded by dark matter, flavour physics and Higgs mass constraints
Colour scale: fraction of excluded points

→ Some points inside the $H \to \tau\tau$ excluded region still survive

→ Other channels ($H \to ZZ$, $H \to t\bar{t}$, ...) will help probing the small $\tan\beta$ region

Sensitivity to the mass of the CP-odd A boson



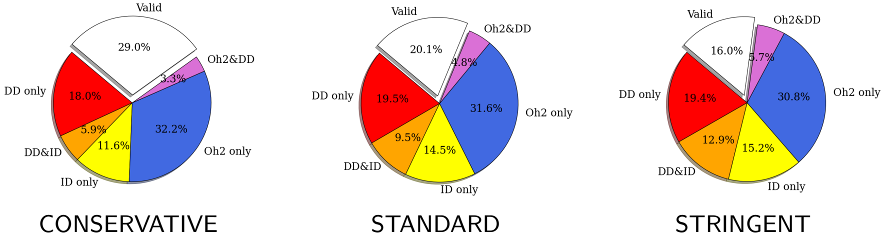
A. Arbey, M. Battaglia, FM, Ann. Phys. 528 (2016) 179

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)



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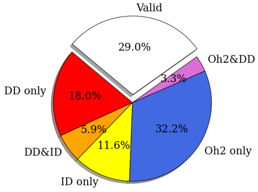
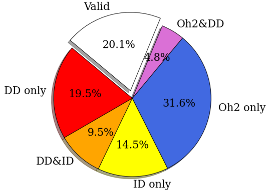
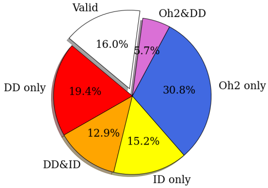
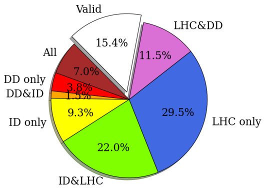


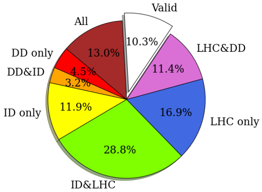


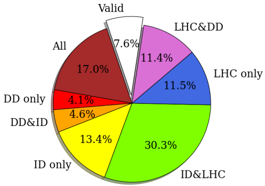


CONSERVATIVE | STANDARD | STRINGENT

Exclusion by dark matter observables and LHC searches



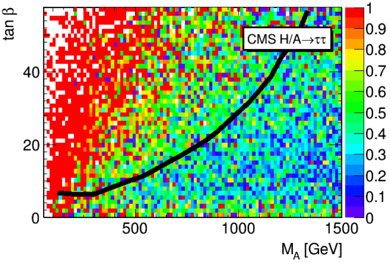




Interesting complementary between DM searches and LHC!

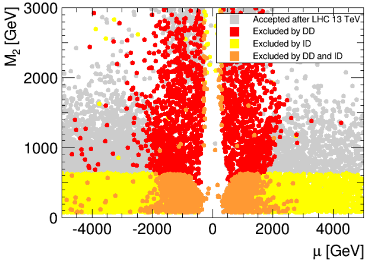
Complementary of LHC and dark matter searches

Direct detection and Heavy Higgs searches



Fraction of points excluded by DD

Direct and indirect detection and LHC

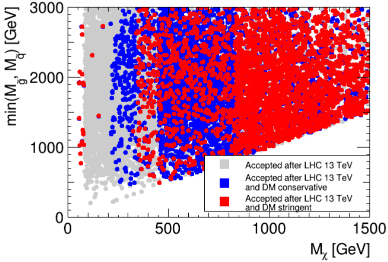


A. Arbey, M. Boudaud, FM, G. Robbins, JHEP 1711 (2017) 132

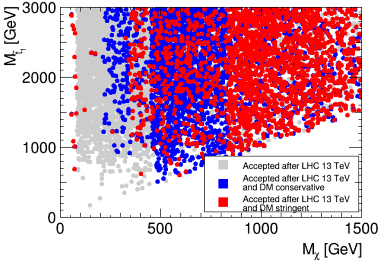
Interesting interplay in the Higgs and Higgsino sectors!

Complementary of LHC and dark matter searches

Gluino/squark mass vs. Neutralino mass



Stop 1 mass vs. Neutralino mass

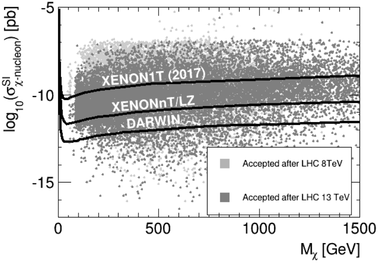


A. Arbey, M. Boudaud, FM, G. Robbins, JHEP 1711 (2017) 132

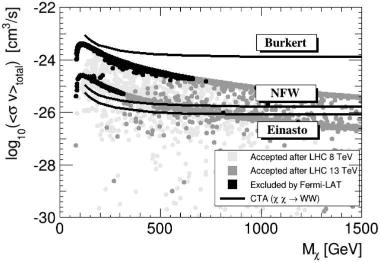
Interplay also interesting in the squark and gluino sectors!

Perspectives

Future of direct detection



Future of indirect detection



A. Arbey, M. Boudaud, FM, G. Robbins, JHEP 1711 (2017) 132

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

CP violating pMSSM

CP violating pMSSM

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

CP violating phenomenological MSSM (CPV-pMSSM)

$\rightarrow$ 19 pMSSM parameters + 6 phases = 25 parameters

A. Arbey, J. Ellis, R. Godbole, FM, Eur. Phys. J. C75 (2015), 85

$$M_\alpha = |M_\alpha| e^{i\phi_\alpha} \qquad A_\beta = |A_\beta| e^{i\phi_\beta}$$

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:

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

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.

EDM	Upper limit (e.cm)	Equivalent limit (e.cm)	Reference
Thallium	1.3×10^{-24}	$d_e : 2.1 \times 10^{-27}$	PRL 88 (2002) 071805
Thorium monoxide	-	$d_e : 1.1 \times 10^{-28}$	Science 343 (2014) 269
Muon	1.9×10^{-19}	$d_\mu : 1.9 \times 10^{-19}$	PRD 80 (2009) 052008
Mercury	7.4×10^{-30}	$d_n : 1.6 \times 10^{-26}$ $d_p : 2.0 \times 10^{-25}$	PRL 116 (2016) 161601
Neutron	4.2×10^{-26}	$d_n : 4.2 \times 10^{-26}$	PRL 97 (2006) 131801

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

$$d_l^{\tilde{\chi}^\pm} = -\frac{e}{16\pi^2}\sum_i \frac{m_{\tilde{\chi}_i^\pm}}{m^2_{\tilde{\nu}_l}} \mathrm{Im}\left(g_{Ri}^{\tilde{\chi}^\pm l\tilde{\nu}*} g_{Li}^{\tilde{\chi}^\pm l\tilde{\nu}}\right) f(m^2_{\tilde{\chi}_i^\pm}/m^2_{\tilde{\nu}_l})$$

$$d_u^{\tilde{\chi}^\pm} = \frac{e}{16\pi^2}\sum_{i,j} \frac{m_{\tilde{\chi}_i^\pm}}{m^2_{\tilde{d}_j}} \mathrm{Im}\left(g_{Rij}^{\tilde{\chi}^\pm u\tilde{d}*} g_{Lij}^{\tilde{\chi}^\pm u\tilde{d}}\right) \left[f(m^2_{\tilde{\chi}_i^\pm}/m^2_{\tilde{d}_j}) - \frac{1}{3}g(m^2_{\tilde{\chi}_i^\pm}/m^2_{\tilde{d}_j})\right]$$

$$d_d^{\tilde{\chi}^\pm} = \frac{e}{16\pi^2}\sum_{i,j} \frac{m_{\tilde{\chi}_i^\pm}}{m^2_{\tilde{u}_j}} \mathrm{Im}\left(g_{Rij}^{\tilde{\chi}^\pm d\tilde{u}*} g_{Lij}^{\tilde{\chi}^\pm d\tilde{u}}\right) \left[-f(m^2_{\tilde{\chi}_i^\pm}/m^2_{\tilde{u}_j}) + \frac{2}{3}g(m^2_{\tilde{\chi}_i^\pm}/m^2_{\tilde{u}_j})\right]$$

Neutralino-mediated one-loop EDMs

$$d_f^{\tilde{\chi}^0} = \frac{e}{16\pi^2}\sum_{i,j} \frac{m_{\tilde{\chi}_i^0}}{m^2_{\tilde{f}_j}} \mathrm{Im}\left(g_{Rij}^{\tilde{\chi}^0 f\tilde{f}*} g_{Lij}^{\tilde{\chi}^0 f\tilde{f}}\right) Q_{\tilde{f}}\, g(m^2_{\tilde{\chi}_i^0}/m^2_{\tilde{f}_j})$$

Gluino-mediated one-loop EDMs

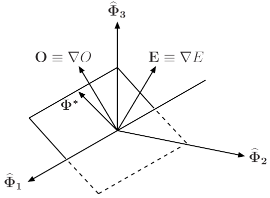
$$d_q^{\tilde{g}} = \frac{e}{3\pi^2}\sum_i \frac{m_{\tilde{g}}}{m^2_{\tilde{q}_i}} \mathrm{Im}\left(g_{Ri}^{\tilde{g}q\tilde{q}*} g_{Li}^{\tilde{g}q\tilde{q}}\right) Q_{\tilde{f}}\, g(m^2_{\tilde{g}}/m^2_{\tilde{q}_i})$$

The $g^{\tilde{G}ff'}$ contains the gaugino/neutralino/squark mixing matrices, $Q_{\tilde{f}}$ is the charge of $\tilde{f}$.

Geometric approach

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 $O_\alpha \equiv \partial O/\partial\phi_\alpha$

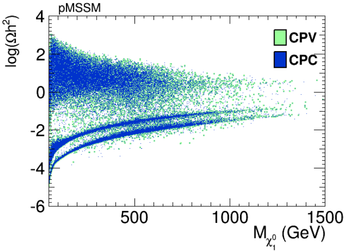
Works well in the limit of small phases... then an iterative approach is necessary:

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.

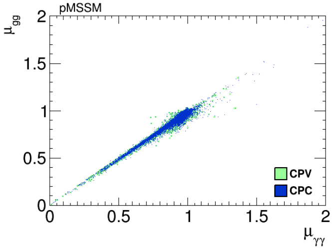
Sectors weakly affected by CP violation

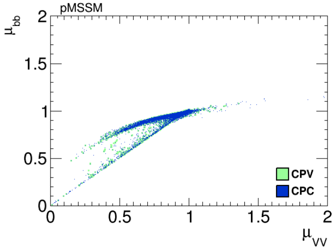
Relic density

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



Higgs signal strengths ($M_{h_1} \in [122, 128]$ GeV)

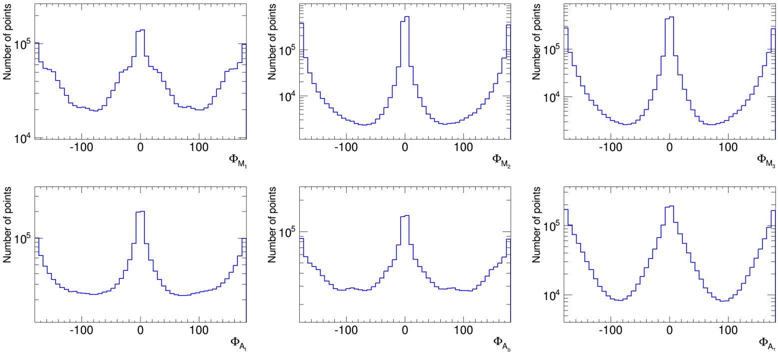




Effects of the EDMs on the CP-violating phases

Preliminary

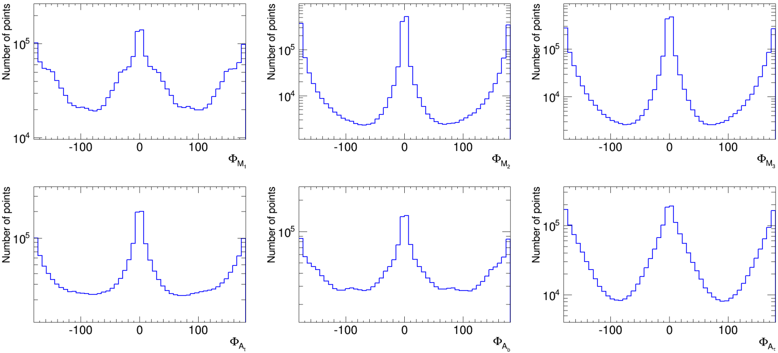
Original sample with no EDM constraints



Effects of the EDMs on the CP-violating phases

Preliminary

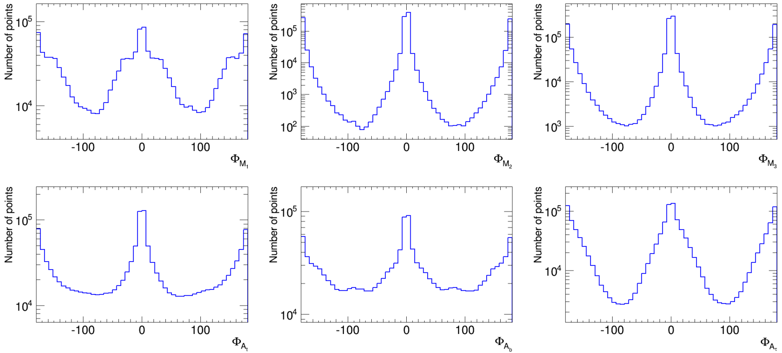
Adding EDM constraints: Muon



Effects of the EDMs on the CP-violating phases

Preliminary

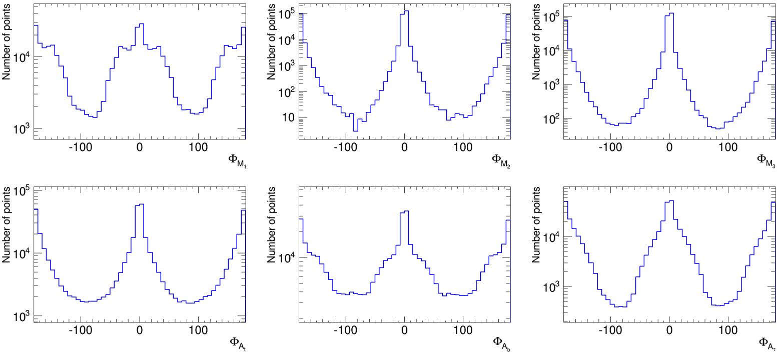
Adding EDM constraints: Muon, Thallium



Effects of the EDMs on the CP-violating phases

Preliminary

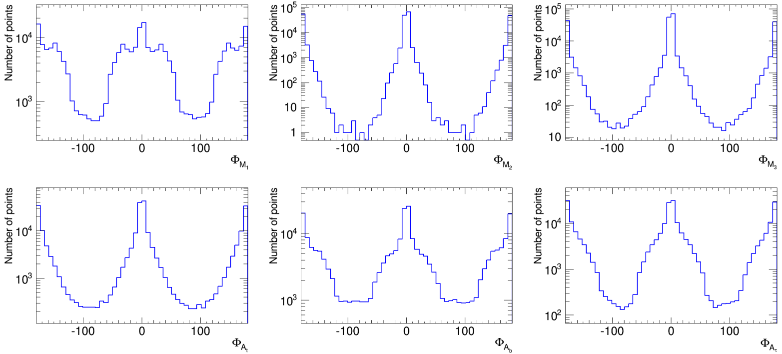
Adding EDM constraints: Muon, Thallium, Mercury



Effects of the EDMs on the CP-violating phases

Preliminary

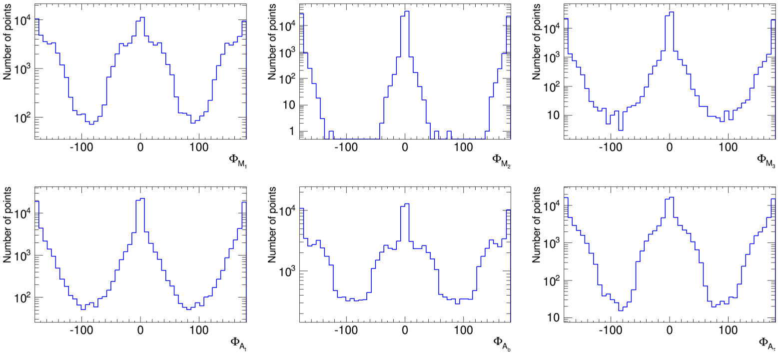
Adding EDM constraints: Muon, Thallium, Mercury, Neutron



Effects of the EDMs on the CP-violating phases

Preliminary

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

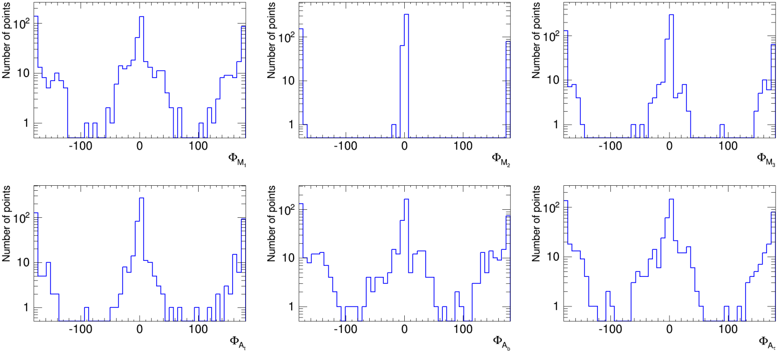


Φ_{M_2} already very severely constrained

Effects of the EDMs on the CP-violating phases

Preliminary

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

$$\tan \phi_\tau^{h_i} \equiv \frac{g_P^{h_i \tau\tau}}{g_S^{h_i \tau\tau}} , \quad \tan \phi_t^{h_i} \equiv \frac{g_P^{h_i \bar{t} t}}{g_S^{h_i \bar{t} t}}$$

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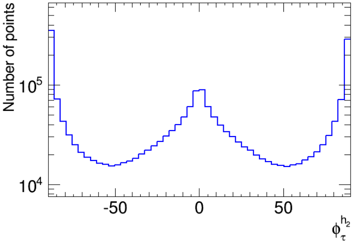

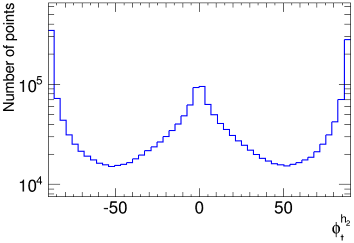

Similar plots for h_3

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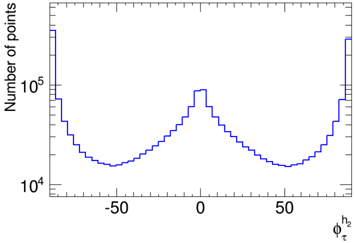
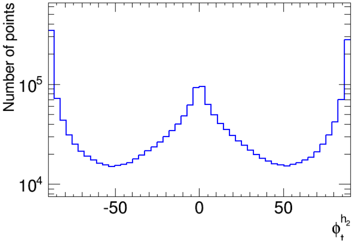
Adding EDM constraints: Muon





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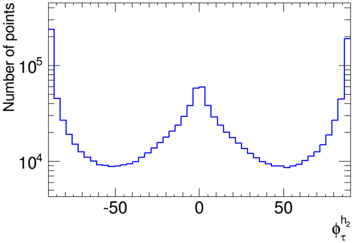
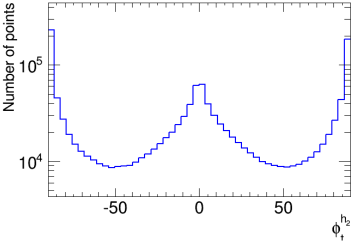
Adding EDM constraints: Muon, Thallium





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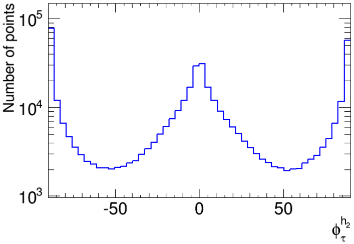
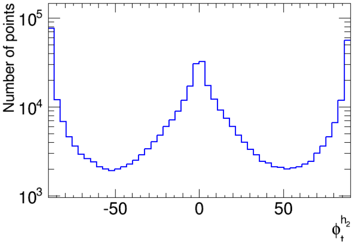
Adding EDM constraints: Muon, Thallium, Mercury





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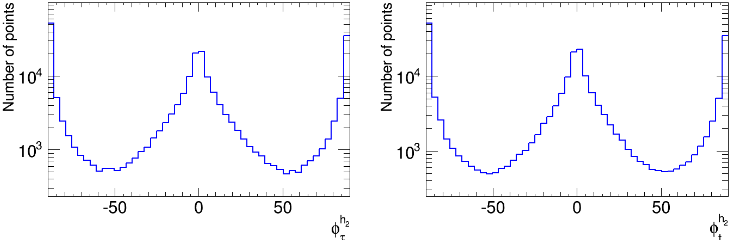
Adding EDM constraints: Muon, Thallium, Mercury, Neutron



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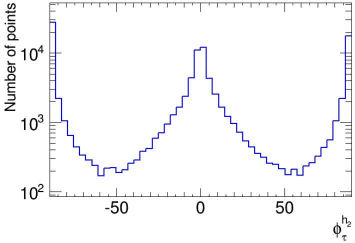
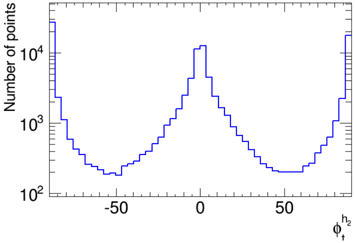
Adding EDM constraints: Muon, Thallium, Mercury, Neutron, Thorium Monoxyde





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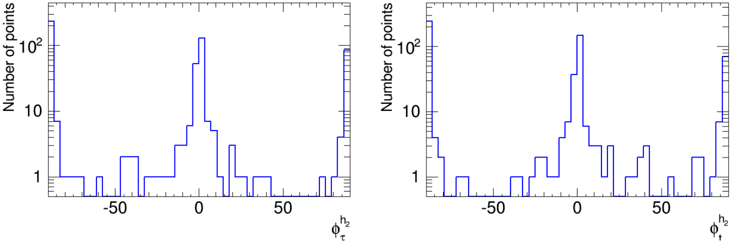
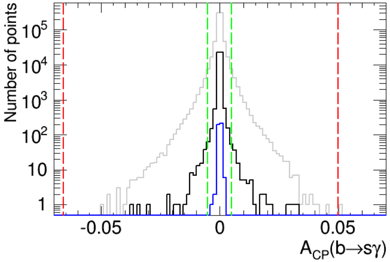
Adding EDM constraints: Muon, Thallium, Mercury, Neutron, Thorium Monoxyde + Proton



Similar plots for h_3

Flavour sector

CP asymmetry in $b \to s\gamma$



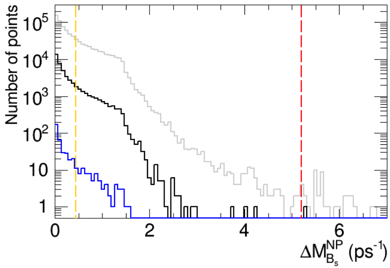
gray: without EDMs – black: with EDMs
blue: + prospective proton EDM

red: current limits – green: prospective Belle-II

Current experiment limits superseded by EDM constraints

Good perspectives for the future

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



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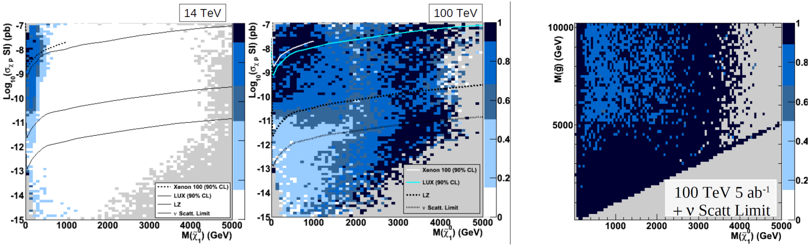
Constraints limited by the theoretical uncertainties

Good perpectives if order of magnitude improvement on theoretical uncertainties

pMSSM at 100 TeV

- 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:



	jets+MET+EWK+mono J,W,Z	+LUX	+LZ	+3rd gen. DM exp.
14 TeV (3 ab^{-1})	0.09	0.19	0.50	0.76
100 TeV (1 ab^{-1})	0.63	0.65	0.73	0.90
100 TeV (3 ab^{-1})	0.67	0.69	0.75	0.91
100 TeV (5 ab^{-1})	0.69	0.72	0.76	0.92

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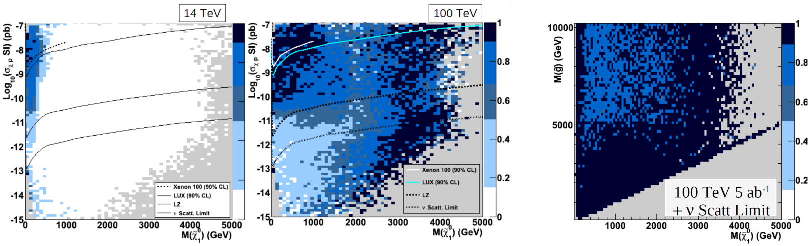

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Backup

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Dark matter relic density

In the Standard Model of Cosmology:

- before and at nucleosynthesis time, the expansion is dominated by radiation

$$H^2 = 8\pi G/3 \times \rho_{\mathrm{rad}}$$

- the evolution of the number density of supersymmetric particles follows the Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\mathrm{eff}} v \rangle (n^2 - n_{\mathrm{eq}}^2)$$

n: number density of relic particles
$\langle \sigma_{\mathrm{eff}} v \rangle$: 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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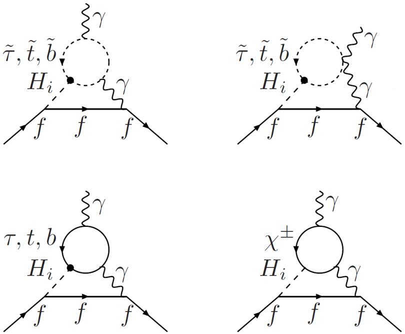
EDM in the MSSM

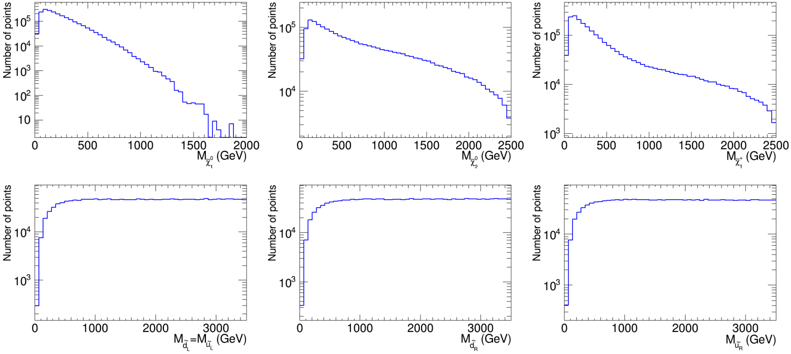
$$d_f = d_f^{\tilde{\chi}^\pm} + d_f^{\tilde{\chi}^0} + d_f^{\tilde{g}} + d_f^H \text{ where } f = e, \mu, u, d, s.$$

(Higher order) Higgs-mediated Barr-Zee diagrams:



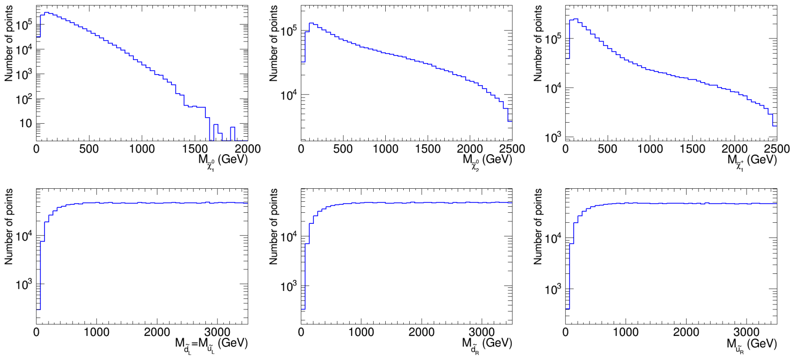
Effects of the EDMs on the SUSY masses

Original sample with no EDM constraints



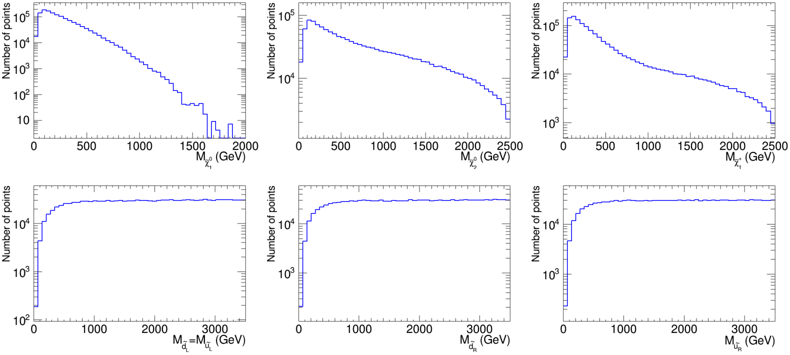
Effects of the EDMs on the SUSY masses

Adding EDM constraints: Muon



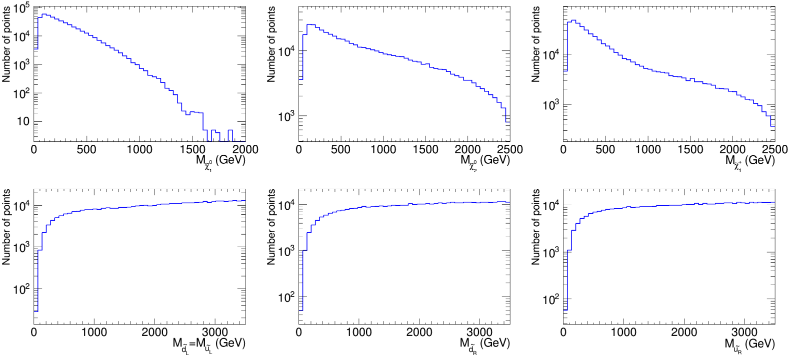
Effects of the EDMs on the SUSY masses

Adding EDM constraints: Muon, Thallium



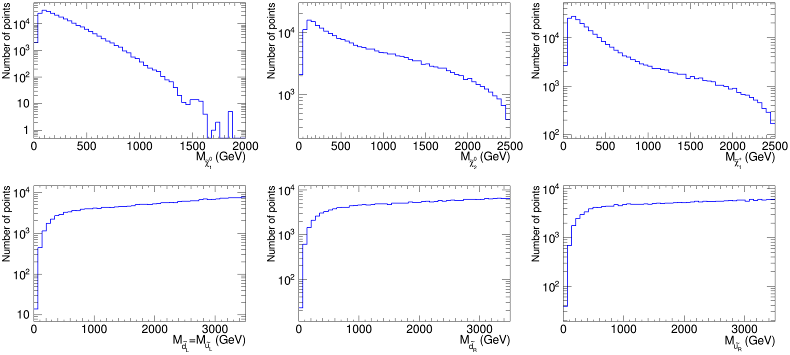
Effects of the EDMs on the SUSY masses

Adding EDM constraints: Muon, Thallium, Mercury



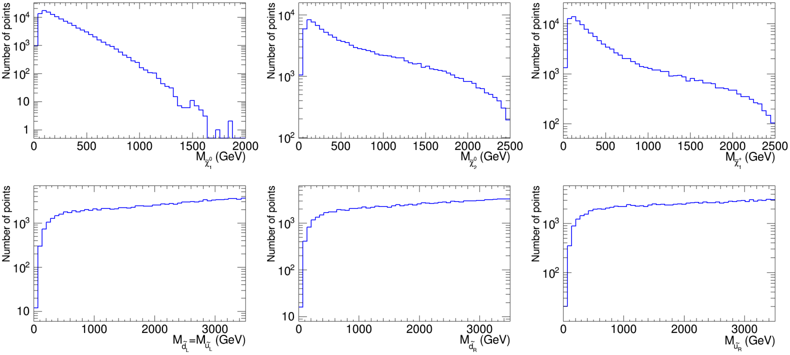
Effects of the EDMs on the SUSY masses

Adding EDM constraints: Muon, Thallium, Mercury, Neutron



Effects of the EDMs on the SUSY masses

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



Effects of the EDMs on the SUSY masses

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