Higgs, Supersymmetry and Dark Matter: Relations and Perspectives

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Work in collaboration with A. Arbey and M. Battaglia

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Introduction

Discovery of a light **Higgs boson**

$\rightarrow$ new chapter in the search for new physics and its connection to cosmology

The properties of the Higgs boson may be sensitive to **new physics**:

- the observed particle could be part of an extended Higgs sector
- new particles may modify its couplings and decay rates compared to the SM

Also important connection with the **dark matter** sector

- If dark matter is a WIMP, the Higgs boson most likely couples to it
- it may have a major role in mediating the WIMP interactions
- strong implications for the relic density
- and for dark matter interactions in underground experiments

Supersymmetry: the best motivated and most thoroughly formulated and investigated model of BSM physics

$\rightarrow$ predicts the Higgs boson to be light and naturally incorporates dark matter

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MSSM scenarios

The most economical implementation of supersymmetry: MSSM

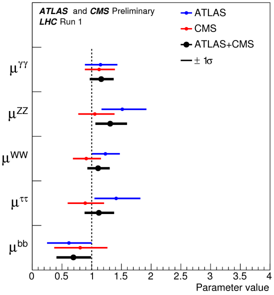
An adequate framework to study the relations between the Higgs sector, new physics and dark matter in the MSSM: **phenomenological MSSM (pMSSM)**

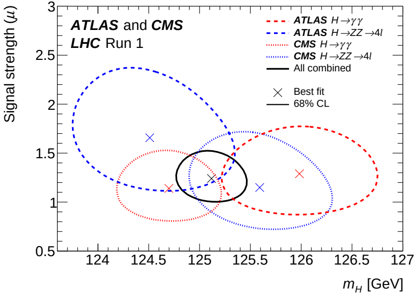
- 19-parameter implementation of the MSSM
- no universality assumptions at the GUT scale
- offers the freedom and generality of a model where the SUSY particle masses are independent
- keeps the number of parameters manageable for extensive scans

The lightest neutralino (and gravitino) are taken to be the LSP
Flat scans by varying all SUSY particle masses, independently, up to 5 TeV,
the SUSY trilinear couplings in the range -15 to 15 TeV and $2 < \tan\beta < 60$

Higgs searches

ATLAS and CMS measurements:





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

Signal strength defined as:

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

→ The results are compatible with the SM Higgs

Implications of the Higgs mass determination

- In the SM, the Higgs mass is essentially a free parameter
- In the MSSM, the lightest CP-even Higgs particle is bounded from above: $M_h^{max} \approx M_Z |\cos 2\beta| +$ radiative corrections $\lesssim 110 - 135$ GeV
- Imposing M_h places very strong constraints on the MSSM parameters through their contributions to the radiative corrections

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

- Important parameters for MSSM Higgs mass:
  - $\tan\beta$ and M_A
  - the SUSY breaking scale $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$
  - the mixing parameter in the stop sector $X_t = A_t - \mu/\tan\beta$

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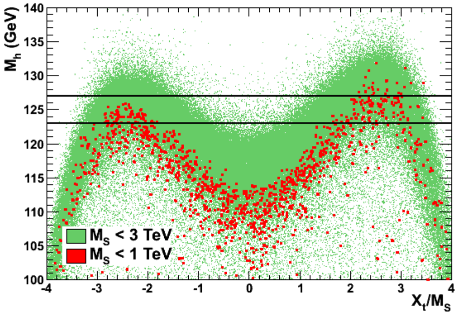
Implications of the Higgs mass determination

Implications in pMSSM:



A. Arbey, M. Battaglia, A. Djouadi, FM, J. Quevillon, Phys. Lett. B708 (2012) 162

$M_h \sim 125$ GeV is easily satisfied in pMSSM

No mixing case ($X_t \approx 0$) excluded for small M_S

Higgs couplings

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

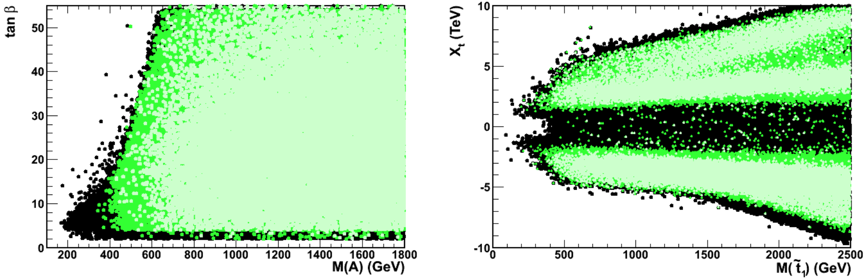
ϕ	$g_{\phi u\bar{u}}$	$g_{\phi d\bar{d}} = g_{\phi \ell\bar{\ell}}$	$g_{\Phi VV}$
h	$\cos\alpha / \sin\beta \rightarrow 1$	$-\sin\alpha / \cos\beta \rightarrow 1$	$\sin(\beta-\alpha) \rightarrow 1$
H	$\sin\alpha / \sin\beta \rightarrow \cot\beta$	$\cos\alpha / \cos\beta \rightarrow \tan\beta$	$\cos(\beta-\alpha)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

where:

$$\alpha = \frac{1}{2}\arctan\left(\tan(2\beta)\,\frac{M_A^2+M_Z^2}{M_A^2-M_Z^2}\right)$$

Higher order corrections to the tree level couplings can be large for light SUSY particles

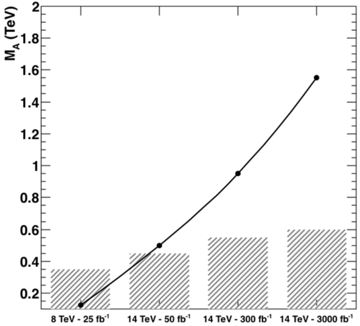
Consequences of the Higgs rate measurements in pMSSM



Black: all accepted points
Dark green: points compatible at 90% CL with the Higgs rates
Light green: points compatible at 68% CL with the Higgs rates

$\rightarrow$ $M_A < 350$ GeV disfavoured by the Higgs signal strengths ($\rightarrow$ decoupling regime)
$\rightarrow$ Still possible to have $M_{\tilde{t}} < 500$ GeV!
$\rightarrow$ $|X_t| < 1.5$ TeV strongly disfavoured

Sensitivity to the mass of the CP-odd A boson



A. Arbey, M. Battaglia, FM, Ann. Phys. (2015)

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

Direct SUSY and monojet searches at the LHC

Direct SUSY searches:

- squark and gluino direct searches (jets + $\not{E}_T$)
- stop and sbottom direct searches (b-jets + $\not{E}_T$)
- chargino and neutralino direct searches (2 or 3 leptons + $\not{E}_T$)

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

Usually interpretation in terms of effective operators (WIMP-WIMP-q-$\bar{q}$ or -g-g)

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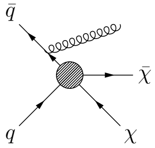

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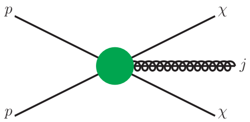
Monojets in the MSSM

Generic monojets in "simple" DM scenarios:



Monojets in the MSSM:

LHC very sensitive to the strongly interacting particles

→ many SUSY events with monojet signature!

→ particularly relevant for small mass splitting between squark/gluino and neutralino

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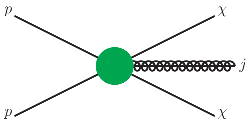

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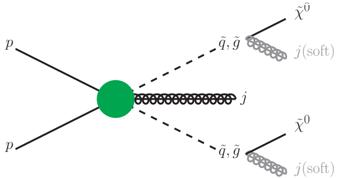

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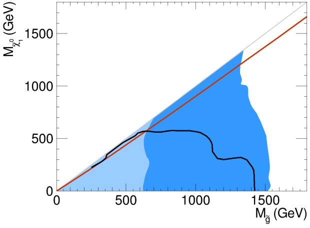
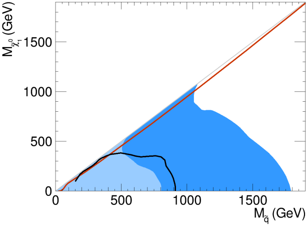
Monojets in simplified MSSM scenarios

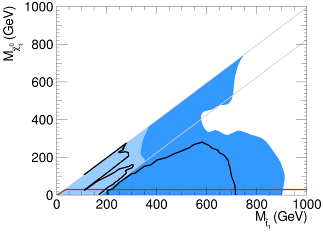
gluino + 1 bino



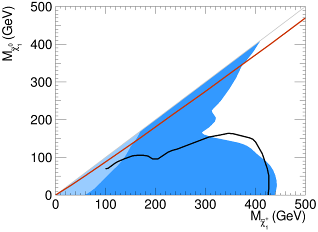
8 degenerate squarks + 1 bino



1 stop + 1 wino neutralino + 1 chargino



2 wino-bino neutralinos + 1 chargino



A. Arbey, M. Battaglia, FM, arXiv:1506.02148

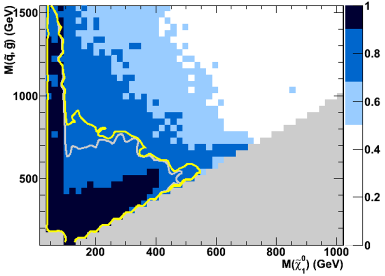
light blue: monojets 8 TeV run, dark blue: monojets 14 TeV, 300 fb^{-1}, black lines: ATLAS SUSY searches, red: DM relic density

Interesting complementarity between SUSY and monojet searches!

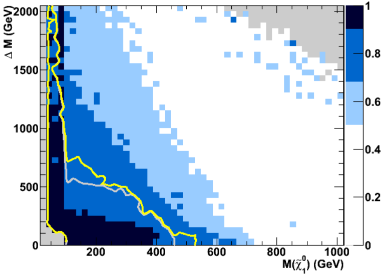
Complementarity between monojets and direct SUSY searches in the pMSSM

Neutralino mass:

lightest squark/gluino mass



mass splitting with lightest squark/gluino



A. Arbey, M. Battaglia, FM, Phys. Rev. D89 (2014) 077701

Color scale: fraction of excluded points

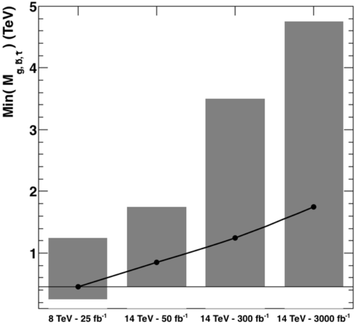
Grey line: 68% C.L. exclusion by jets/leptons+MET searches

Yellow line: + monojet analyses

Squarks and gluino masses below 1 TeV are still allowed!

Monojet searches improve sensitivity by more than 100 GeV in the small mass splitting region!

Sensitivity to SUSY mass scales



A. Arbey, M. Battaglia, FM, Ann. Phys. (2015)

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 sector

Dark Matter Searches

Different types of dark matter searches:

- direct production of LSP's at the LHC
- DM annihilations: DM + DM $\rightarrow$ SM + SM + ...
  - indirect detection: protons, gammas, anti-protons, positrons, ...
  - dark matter relic density

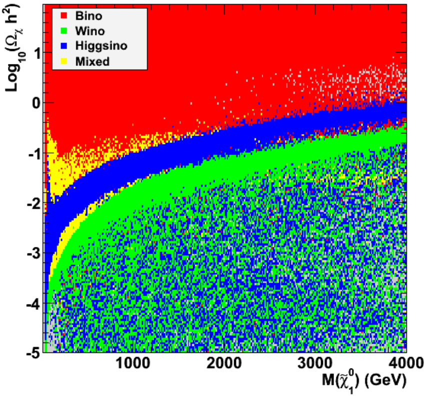
  Possible enhancements of the annihilation cross-sections through Higgs resonances
- DM scattering with matter: DM + matter $\rightarrow$ DM + matter

  $\rightarrow$ direct detection experiments

  Neutralino scattering cross-section sensitive to neutral Higgs bosons

Dark matter direct detection experiments probe the Higgs sector of the MSSM!

Neutralino states & neutralino relic density

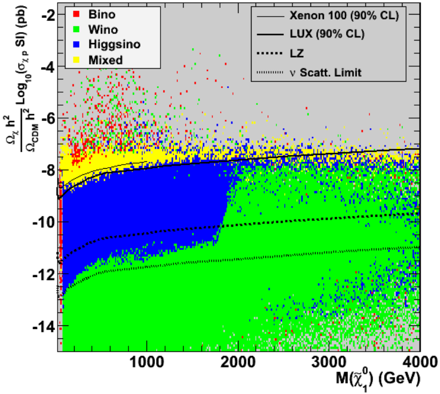


The colours give the nature of the neutralino with the largest fraction in each bin

A. Arbey, M. Battaglia, FM, Ann. Phys. (2015)

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

Neutralino states & neutralino DM direct detection



The colours give the nature of the neutralino with the largest fraction in each bin

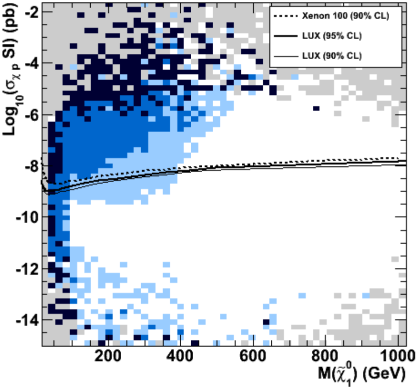
A. Arbey, M. Battaglia, FM, arXiv:1504.05091

Direct detection is mainly probing the mixed state neutralinos and will probe the Higgsino and wino states

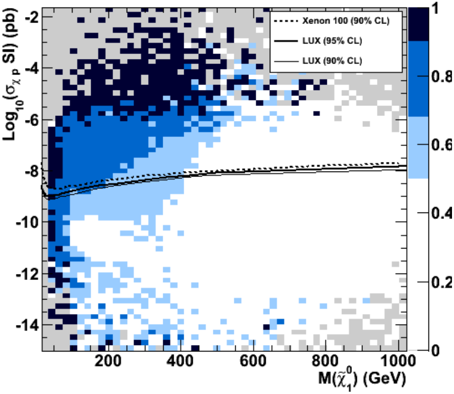
DM direct detection constraints combined with LHC results

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

jets/leptons+MET only



jets/leptons+MET searches and monojet



A. Arbey, M. Battaglia, FM, Phys. Rev. D89 (2014) 077701

Colour scale: fraction of excluded points

Nice complementarity between LHC and DM direct detection results!

DM direct detection constraints combined with LHC results

Fractions of pMSSM points excluded by the combination of LHC MET searches, LHC and ILC Higgs data and LZ DM direct detection

	LHC 8	**LHC**	**LHC**	**HL-LHC**
	8 TeV	14 TeV	14 TeV	14 TeV
	25 fb^{-1}	50 fb^{-1}	300 fb^{-1}	3 ab^{-1}
js+ℓs+MET	0.145	0.570	0.698	0.820
+h^0 μs	0.317	0.622	0.793	0.920
+ILC h^0 BRs	0.588	0.830	0.890	0.945
+LZ		0.914	0.940	0.964

Gravitino Dark Matter

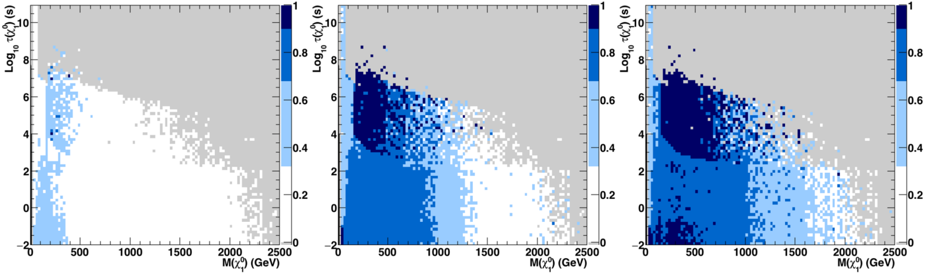
Study restricted to neutralino NLSP case for comparison with neutralino LSP scenario

- Gravitino LSP, single component of dark matter
- Neutralino NLSP short-lived with respect to cosmology
  → Gravitino produced either through NLSP decay or reheating after inflation
  → Neutralino lifetime constrained by Big-Bang Nucleosynthesis
- Neutralino NLSP long-lived with respect to collider physics
  → Same collider constraints as for neutralino LSP scenario
- DM composed exclusively of gravitinos
  → Constraints from direct and indirect detection relaxed
  (gravitino very elusive!)
  → Constraints from relic density strongly relaxed
  (in particular because of gravitino production during reheating)

Gravitino LSP scenario much less constrained than the neutralino LSP scenario!

Gravitino dark matter at the LHC

Fraction of points excluded by the LHC SUSY and monojet searches



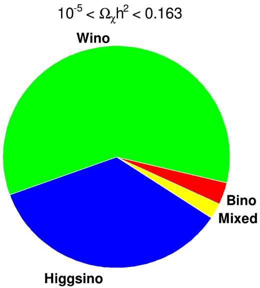
8 TeV, 25 fb^{-1} 14 TeV, 300 fb^{-1} 14 TeV, 3000 fb^{-1}

A. Arbey, M. Battaglia, L. Covi, J. Hasenkamp, FM, arXiv:1505.04595

In the gravitino LSP scenario, LHC will probe neutralino masses up to ∼1.5 TeV

Neutralino LSP vs. Gravitino LSP

Fraction of neutralino states after dark matter constraints



Dark matter constraints strongly affect the neutralino composition

Gravitino LSP with neutralino NLSP opens up different scenarios lifting the DM constraints and establishing an almost equal share of bino, wino and higgsino NLSP

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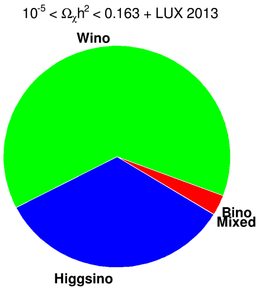

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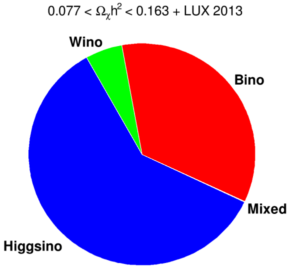

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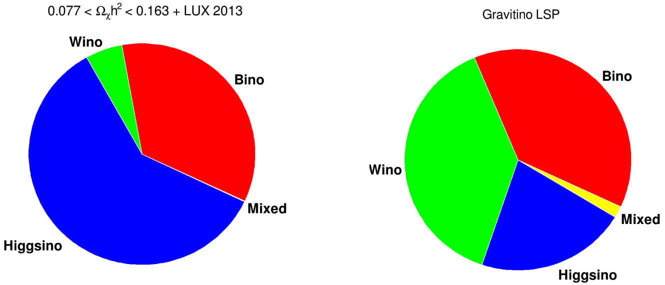

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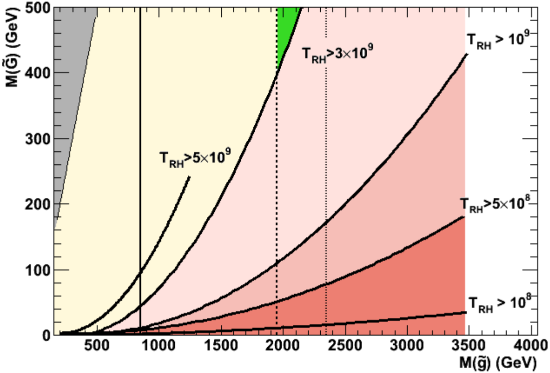
Constraining the reheating temperature with LHC in the MSSM with gravitino DM

Production of gravitino after inflation related to reheat temperature and gaugino masses

→ LHC gluino searches and DM density measurements probe the reheating temperature



Interesting interplay between cosmology and collider physics!

Conclusions

- MSSM still provides many solutions in agreement with all the current data
  - Below 1 TeV mass scale is still possible
  - It's important to go beyond the lamp-post (constrained MSSM...) scenarios
  - pMSSM provides an adequate set-up
  - Monojet searches are complementary to the usual SUSY searches
- Important interconnection with the Higgs and DM searches
- Gravitino DM represents a compelling scenario in SUSY
  - Relation between gravitino mass, gluino mass and reheating temperature
  - Offers a unique opportunity to place stringent bounds on cosmological models from the LHC results

The study of the Higgs boson properties, the search for BSM physics at colliders and the direct searches for dark matter at dedicated experiments will likely shape a new picture of particle physics and cosmology,

Backup

Beyond constrained scenarios

Phenomenological MSSM (pMSSM)

- The most general CP/R parity-conserving MSSM
- Minimal Flavour Violation at the TeV scale
- The first two sfermion generations are degenerate
- The three trilinear couplings are general for the 3 generations

$\rightarrow$ 19 free parameters (20 with gravitino mass)

10 sfermion masses: $M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$, $M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$, $M_{\tilde{\tau}_L}$, $M_{\tilde{\tau}_R}$, $M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$, $M_{\tilde{q}_{3L}}$, $M_{\tilde{u}_R} = M_{\tilde{c}_R}$, $M_{\tilde{t}_R}$, $M_{\tilde{d}_R} = M_{\tilde{s}_R}$, $M_{\tilde{b}_R}$

3 gaugino masses: M_1, M_2, M_3

3 trilinear couplings: $A_d = A_s = A_b$, $A_u = A_c = A_t$, $A_e = A_\mu = A_\tau$

3 Higgs/Higgsino parameters: M_A, $\tan\beta$, μ

A. Djouadi et al., hep-ph/9901246

In the following, neutralino LSP (and gravitino LSP in the last part)

The lightest 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

pMSSM analysis set-up

Complete analysis in pMSSM:

- Calculation of masses, mixings and couplings (SoftSusy, Suspect)
- Computation of low energy observables (**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, ...)
- Calculation of SUSY decay rates (SDECAY)
- Event generation and evaluation of cross-sections (PYTHIA, MadGraph, Prospino)
- Determination of detectability with fast detector simulation (Delphes)

Parameter	Range (in GeV)
$\tan\beta$	[1, 60]
M_A	[50, 5000]
M_1	[-5000, 5000]
M_2	[-5000, 5000]
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	[-5000, 5000]
$M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$	[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]

pMSSM scans

Constraints from:

- LEP and Tevatron direct search limits
- Flavour precision limits, in particular from BR($B \to X_s \gamma$), BR($B_s \to \mu^+\mu^-$), BR($B \to \tau\nu$)
- Muon anomalous magnetic moment, $(g-2)_\mu$
- Higgs mass limits
- Dark matter relic density

} "**accepted**" points

- Dark matter direct search limits
- Higgs production and decay rates
- LHC SUSY direct searches
- LHC monojet searches

Statistics:

- more than 300M model points in general analyses
- more than 1B model points for dedicated analyses

Largest statistics in the MSSM so far.

pMSSM scans

Constraints from:

- LEP and Tevatron direct search limits
- Flavour precision limits, in particular from BR($B \to X_s\gamma$), BR($B_s \to \mu^+\mu^-$), BR($B \to \tau\nu$)
- Muon anomalous magnetic moment, $(g-2)_\mu$
- Higgs mass limits
- Dark matter relic density

} "**accepted**" points

- Dark matter direct search limits
- Higgs production and decay rates
- LHC SUSY direct searches
- LHC monojet searches

Statistics:

- more than 300M model points in general analyses
- more than 1B model points for dedicated analyses

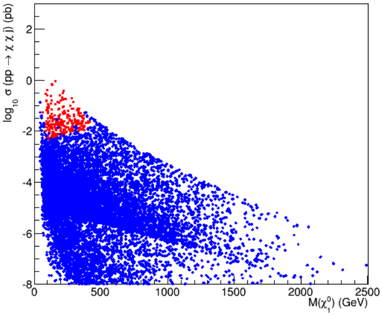
Largest statistics in the MSSM so far.

Monojets in the pMSSM

Analysis in the pMSSM for the 14 TeV run with 300 fb^{-1}

Production cross-section vs. neutralino mass for

Monojets with neutralinos only:



Red: excluded points
Blue: surviving points

Monojets particularly constraining if all signatures considered!

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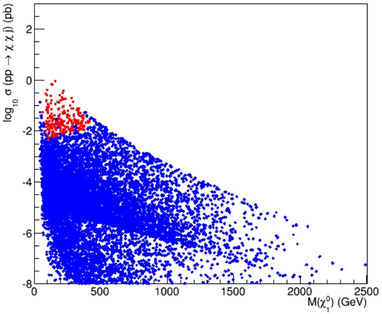
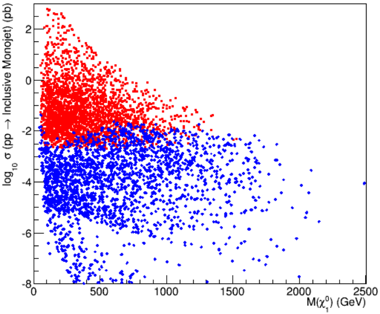


Other monojet signatures:



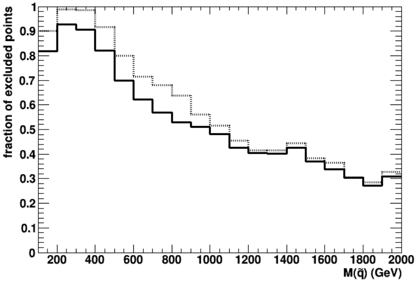
Red: excluded points
Blue: surviving points

Monojets particularly constraining if all signatures considered!

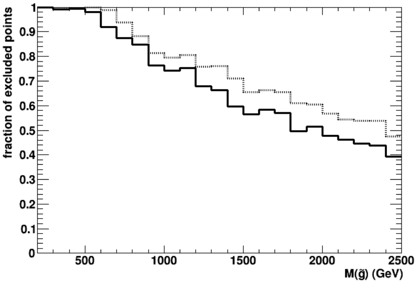
Consequences for SUSY particle masses in the pMSSM

Limits on sparticle masses:

Lightest squark mass



Gluino mass



Solid: jets/leptons+MET searches
Dotted: + monojet analyses

squark and gluino masses well below 1 TeV are still allowed!