Higgs properties: constraints and sensitivity on Supersymmetry?

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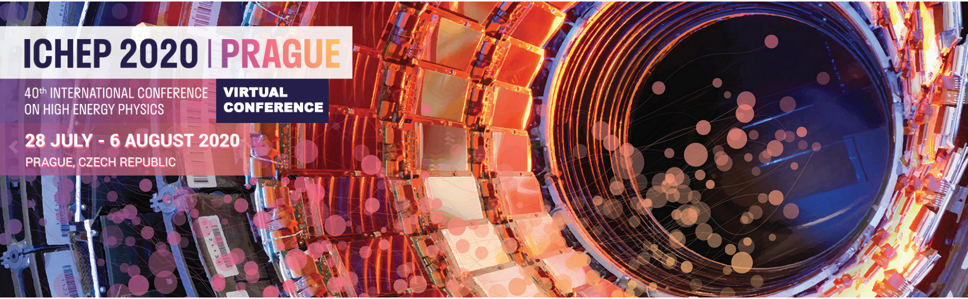
In collaboration with A. Arbey, M. Battaglia, A. Djouadi, M. Mühlleitner & M. Spira



The Higgs boson discovery $\rightarrow$ a vast program of studies of its properties as new tests of the SM and of models of NP!

In the SM: the properties of the Higgs particle are fixed once its mass is determined

In SUSY: the Higgs couplings and its decay branching fractions can be shifted

In this talk:

We discuss the MSSM effects on the light Higgs branching ratios (BRs) and couplings:

- The dependence of the Higgs BRs on M_A and $\tan\beta$
- The effects of Δ_b corrections on the BRs
- Invisible decays into neutralino pairs and DM direct detection constraints
- The sensitivity of Higgs factories on the BRs to the MSSM

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Tree-level couplings, normalized to SM (in the decoupling limit when $M_A \gg M_Z$):

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

$$\text{with } \alpha = -\arctan\left(\frac{(M_Z^2 + M_A^2)\cos\beta\sin\beta}{M_Z^2\cos^2\beta + M_A^2\sin^2\beta - M_h^2}\right)$$

The couplings can be modified by QCD and EW corrections:

$$g^{\text{eff}}_{hf\bar{f}} = \frac{g_{hf\bar{f}}}{1 + \Delta_f}\left[1 - \frac{\Delta_f}{\tan\alpha\tan\beta}\right]$$

$$g^{\text{eff}}_{Hf\bar{f}} = \frac{g_{Hf\bar{f}}}{1 + \Delta_f}\left[1 + \Delta_f\frac{\tan\alpha}{\tan\beta}\right]$$

$$g^{\text{eff}}_{Af\bar{f}} = \frac{g_{Af\bar{f}}}{1 + \Delta_f}\left[1 - \frac{\Delta_f}{\tan^2\beta}\right]$$

where the Δ_f incorporates the QCD and EW corrections, and the SUSY-QCD corrections can make $|\Delta_f| \sim 1$.

Best fit values for the Higgs coupling modifiers $k_X = g_{hXX}^{\mathrm{MSSM}}/g_{hXX}^{\mathrm{SM}}$ from the combination of the **ATLAS** measurements, and projections for different stages of the LHC, and for the ILC and FCC-ee colliders

Coupling modifier	ATLAS 13 TeV 25-79.8 fb^{-1} *	ATLAS 14 TeV 3 ab^{-1} †	ILC 250 GeV 2 ab^{-1}	ILC 1 TeV 8 ab^{-1}	FCC-ee 365 GeV 1.5 ab^{-1}
k_W	1.05 ± 0.09	± 0.022	± 0.0180	± 0.0024	± 0.0043
k_Z	1.11 ± 0.08	± 0.018	± 0.0029	± 0.0022	± 0.0017
k_t	$1.03^{+0.15}_{-0.14}$	$^{+0.043}_{-0.040}$	–	± 0.016	–
k_b	$1.09^{+0.19}_{-0.17}$	$^{+0.044}_{-0.028}$	± 0.0180	± 0.0048	± 0.067
k_τ	$1.05^{+0.16}_{-0.15}$	$^{+0.028}_{-0.027}$	± 0.0190	± 0.0057	± 0.0073
k_g	1.05 ± 0.09	$^{+0.032}_{-0.030}$	± 0.0230	± 0.0066	± 0.0100
k_γ	$0.99^{+0.11}_{-0.10}$	$^{+0.028}_{-0.023}$	± 0.0670	± 0.019	± 0.0390

* ATLAS, PRD 101 (2020) 012002

† ATL-PHYS-PUB-2018-054

Higgs factory projections from de Blas et al., JHEP 01 (2020) 2139

Current determination with precisions of the order of 10%, uncertainties will decrease by a factor 10 in the future

The most general CP/R parity-conserving MSSM, assuming Minimal Flavour Violation at the TeV scale and suppresed FCNC's at tree level, with 19 free parameters:

10 sfermion masses, 3 gaugino masses, 3 trilinear couplings, 3 Higgs/Higgsino parameters

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

Flat scans over the pMSSM 19 parameters

Parameter	Range (in GeV)
M_A	[50, 6000]
M_1	[-6000, 6000]
M_2	[-6000, 6000]
M_3	[50, 6000]
$A_d = A_s = A_b$	[-15000, 15000]
$A_u = A_c = A_t$	[-15000, 15000]
$A_e = A_\mu = A_\tau$	[-15000, 15000]
μ	[-6000, 6000]
$M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$	[0, 6000]
$M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$	[0, 6000]
$M_{\tilde{\tau}_L}$	[0, 6000]
$M_{\tilde{\tau}_R}$	[0, 6000]
$M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$	[0, 6000]
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$M_{\tilde{t}_R}$	[0, 6000]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[0, 6000]
$M_{\tilde{b}_R}$	[0, 6000]
$\tan\beta$	[1, 60]

- Calculation of masses, mixings and couplings (SoftSusy)
- Computation of low energy observables and Z widths (SuperIso)
- Computation of dark matter observables (SuperIso Relic)
- Calculation of Higgs cross-sections and decay rates (HDECAY, Higlu, 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)

We assume that the neutralino is the lightest SUSY particle and the light Higgs mass is between 123 and 127 GeV.

phenomenological MSSM (pMSSM)

The most general CP/R parity-conserving MSSM, assuming Minimal Flavour Violation at the TeV scale and suppresed FCNC's at tree level, with 19 free parameters:

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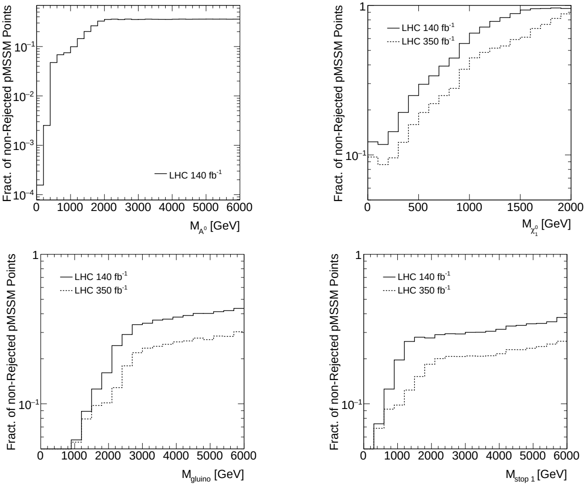
LHC constraints on MSSM masses

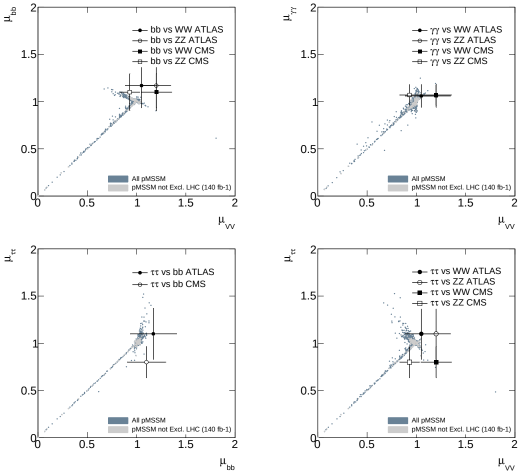
Fraction of pMSSM points consistent with LHC direct searches



Gluino masses below 1 TeV and stops below 400 GeV are globably excluded
Light pseudoscalar Higgs and charginos can still escape LHC

Correlations of μ_{XX} for all valid pMSSM points and those not excluded by the LHC Run 2 searches, compared to the ATLAS and CMS measurements

Preliminary

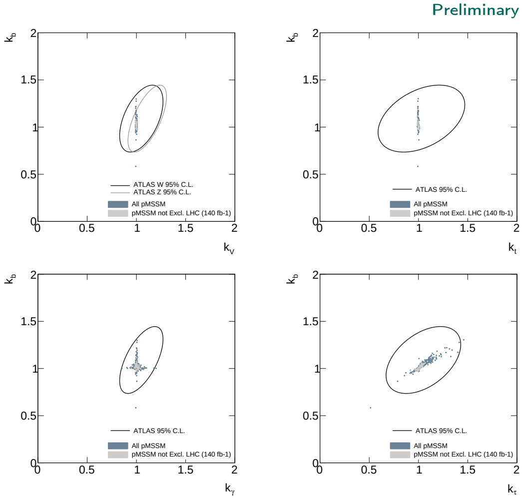


$$\mu_{XX} = \frac{\mathrm{BR}(h^0 \to X\bar{X})}{\mathrm{BR}(H_{\mathrm{SM}} \to X\bar{X})}$$

Higgs measurements exclude points with too small BRs, corresponding to large invisible decays.

Light Higgs decays in the pMSSM

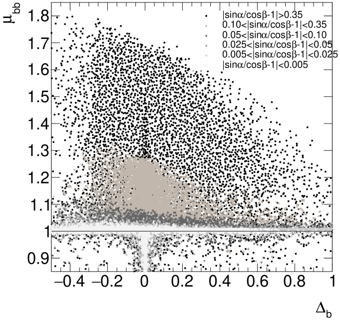
Coupling modifiers for all valid pMSSM points and those not excluded by the LHC Run 2 searches, compared to the ATLAS combined contours

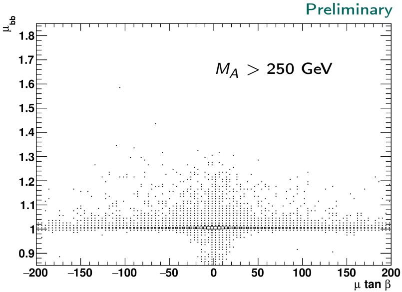


Most pMSSM points have coupling modifers in agreement with experimental results

Δ_b corrections to the hbb coupling:

$$g^{\rm eff}_{hb\bar{b}} = \frac{g_{hf\bar{b}}}{1+\Delta_b}\left[1 - \frac{\Delta_b}{\tan\alpha\tan\beta}\right] \ , \quad \Delta_b \approx \frac{2\alpha_s}{3\pi}\frac{m_{\tilde{g}}\,\mu\tan\beta}{\max(m^2_{\tilde{g}}, m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2})} + \frac{m_t^2}{8\pi^2 v^2\sin^2\beta}\frac{A_t\,\mu\tan\beta}{\max(\mu^2, m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2})}$$





In the limit of large M_A, the h^0 coupling to $b\bar{b}$ reaches the decoupling limit such that $-\sin\alpha/\cos\beta \to 1$

In this limit, small differences to the SM limit dominated by deviations of the mixing angle α from the SM limit
$\Rightarrow$ only mild correlation between $\mu\tan\beta$ and μ_{bb}

Invisible Higgs decays and DM direct detection

Invisible Higgs decay is related to dark matter when neutralino 1 mass below $M_h/2$

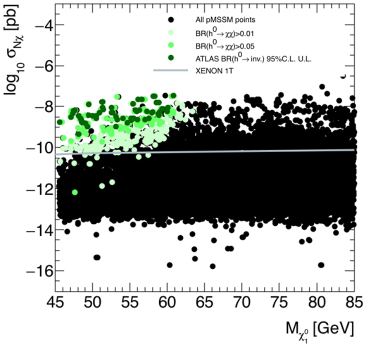
Decay width:

$$\Gamma(h \to \chi_1^0 \chi_1^0) = \frac{G_F M_W^2 M_h}{2\sqrt{2}\pi} g^2_{h\chi_1^0\chi_1^0} \beta_\chi^3 \quad \text{where} \quad \beta_\chi = (1 - 4m_\chi^2/M_h^2)^{1/2}$$

Light bino-like neutralinos can easily escape the LHC constraints

ATLAS limit on invisible decays: $\mathrm{BR}(h \to \mathrm{inv}) < 0.11$ (ATLAS-CONF-2020-008)

Spin-independent χ_1^0-nucleon scattering cross section driven by same coupling $g_{h\chi_1^0\chi_1^0}$



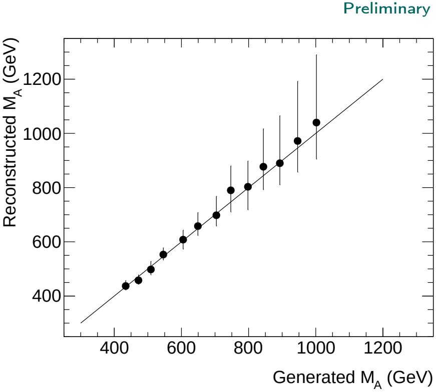
Black dots: all pMSSM points

Coloured dots: points with sizeable invisible BR

Dark green dots: points excluded by LHC Higgs invisible decay limit

Grey line: Xenon1T upper bound

Reconstruction of M_A at ILC 1 TeV from Higgs decay measurements



M_A (GeV)	$\tan\beta$	μ	$M_{\chi^0_1}$
434.4	5.58	-549.3	562.1
472.4	6.62	1993.7	314.8
509.8	5.48	-181.9	184.7
546.9	5.55	-50.5	49.9
605.7	6.31	369.1	380.1
649.5	3.15	1722.6	108.3
704.4	5.24	480.5	170.6
747.0	4.51	-3596.1	1072.0
798.4	5.75	-3301.7	1329.4
844.3	9.11	-1679.5	1695.1
893.2	7.14	-367.9	379.5
946.9	7.65	-4268.0	363.5
1001.9	5.39	715.9	732.0

ILC will be mainly sensitive to M_A and $\tan\beta$
because of the suppression of the Δ_b corrections

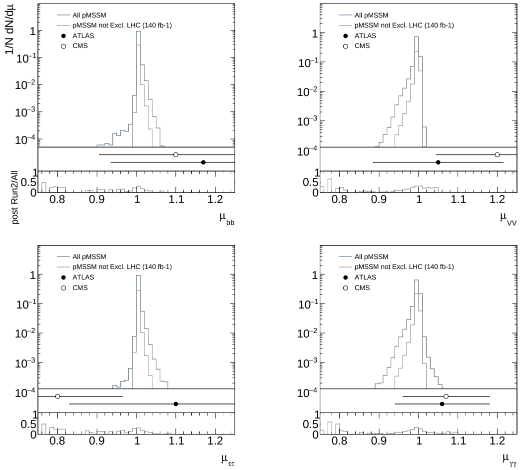
Conclusions

- Complementarity of direct searches, Higgs BRs and DM experiments essential to probe the MSSM
- The Higgs BRs and couplings are all severely constrained by the LHC searches
- The Δ_b corrections have negligible effects on the BRs at the allowed values of M_A
- Invisible decays into neutralino pairs can be ruled out by DM direct detection results even beyond the latest LHC limits
- Higgs factories can be potentially sensitive to the residual effects of M_A and $\tan\beta$ on the BRs

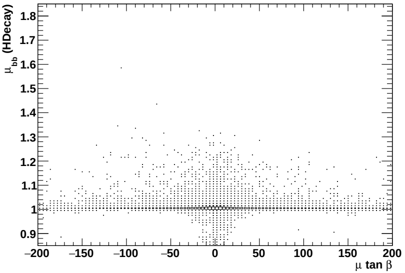
Backup

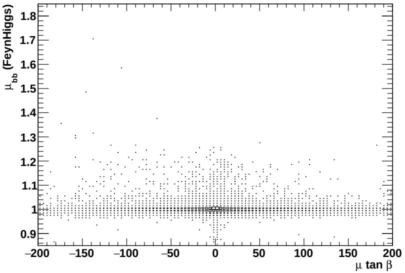
Light Higgs decays in the pMSSM

Distribution of h^0 BRs normalised to SM for all valid pMSSM points and those not excluded by the LHC Run 2 searches, compared to the ATLAS and CMS measurements



Light Higgs decays and Δ_b corrections: HDECAY vs. FeynHiggs





Summary of the analyses used to assess the observability of the pMSSM points by the LHC SUSY searches

Channel	Int. Lum. fb^{-1}	Sensitivity	Ref.
jets + MET	139	$\tilde{g}$, $\tilde{q}$	ATLAS-CONF-2019-040
jets + MET	36	$\tilde{g}$, $\tilde{q}$	ATLAS 1708.02794
1 ℓ + jets + MET	36	$\tilde{g}$, $\tilde{q}$	ATLAS 1708.08232
$\ell^+\ell^+$, $\ell^-\ell^-$ + MET	139	$\tilde{g}$, $\tilde{q}$	ATLAS 1909.08457
b-jets + MET	36	$\tilde{t}$	ATLAS 1709.04183
multiple b-jets + MET	80	$\tilde{t}$, b	ATLAS-CONF-2018-041
2 ℓ + MET	139	$\tilde{\chi}^0$, $\tilde{\chi}^\pm$, $\tilde{\ell}$	ATLAS 1908.08215
3 ℓ + MET	36	$\tilde{\chi}^0$ $\tilde{\chi}^\pm$, $\tilde{\ell}$	ATLAS 1803.02762
monojet + MET	36	$\tilde{\chi}\tilde{\chi}$, $\tilde{q}\tilde{q}$	ATLAS 1711.03301
monoW/Z + MET	3.2	$\tilde{\chi}\tilde{\chi}$, $\tilde{q}\tilde{q}$	ATLAS 1608.02372
$H/A \to \tau\tau$	36	H, A	ATLAS 1709.07242
$H/A \to Z^0 Z^0$	36	H, A	ATLAS 1712.06386
$H/A \to t\bar{t}$	20	H, A	ATLAS 1707.06025