Higgs Properties and Supersymmetry:
Constraints and Sensitivity from the LHC to an e^+e^- Collider

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IP2I (theory)

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1st IP2I Particle Physics Intra-axis meeting

Going beyond constrained scenarios is a necessity

- CMSSM is a useful "exercise" but we need to go beyond!
- Some signatures can be overlooked and conclusions can be very different!
- Important to know how the results change when moving to general MSSM

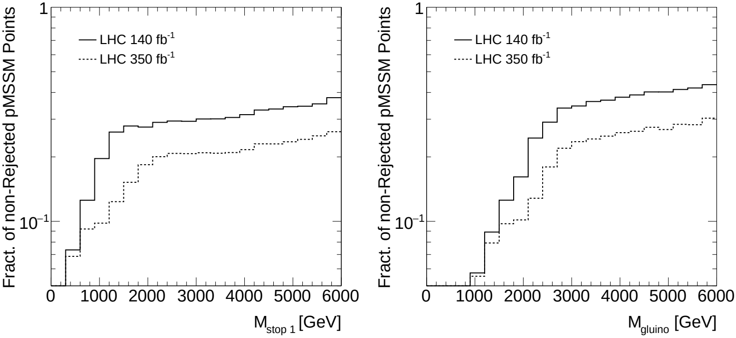
Phenomenological MSSM (pMSSM)

- 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

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: $M_{\mathbf{1}}$, $M_{\mathbf{2}}$, $M_{\mathbf{3}}$
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

Fraction of accepted pMSSM points not excluded at 95% C.L. by the present jet/ℓ+MET searches and the expected sensitivity of Run 3:



Higgs part of the supersymmetric potential:

$$
\begin{aligned}
V_H \quad &= \quad (|\mu|^2 + m_1^2)|\Phi_1|^2 + (|\mu|^2 + m_2^2)|\Phi_2|^2 - B\mu\epsilon_{ij}(\Phi_1^i\Phi_2^j + \mathrm{h.c.}) \\
&+ \frac{g_1^2 + g_2^2}{8}(|\Phi_1|^2 - |\Phi_2|^2) + \frac{g_1^2}{2}|\Phi_1^\dagger\Phi_2|^2
\end{aligned}
$$

μ parameter: Higgsino mass term

B: SUSY breaking term parameter

$\tan\beta \equiv \frac{v_1}{v_2}$

All Higgs tree level masses can be re-expressed in terms of M_A and $\tan\beta$:

$$
M_{H,h}^2 = \frac{1}{2}\left(M_A^2 + M_Z^2 \pm \sqrt{(M_A^2 + M_Z^2)^2 - 4M_Z^2 M_A^2 \cos^2 2\beta}\right)
$$

$$
M_{H^\pm}^2 = M_A^2 + M_W^2
$$

- At leading order:

$$M_h^2 = M_Z^2 \cos^2 2\beta \left[1 - \frac{M_Z^2}{M_A^2} \sin^2 2\beta\right]$$

- Large one-loop correction from top/stop loops:

$$(\Delta M_h^2)_{\tilde{t}} \approx \frac{3\sqrt{2}G_F}{2\pi^2}\, m_t^4 \left[-\log\left(\frac{m_t^2}{M_S^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right]$$

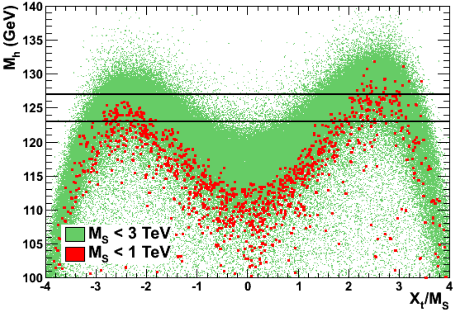
with $X_t = A_t - \mu/\tan\beta$ and $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$

- Contributions from sbottoms and staus in the large $\tan\beta$ limit

$$(\Delta M_h^2)_{\tilde{f}} \approx -\frac{N_c^{\tilde{f}}}{\sqrt{2}G_F}\, \frac{y_f^4}{96\pi^2}\, \frac{\mu^4}{m_{\tilde{f}}^4}$$

where $N_c^{\tilde{b}} = 3$, $N_c^{\tilde{\tau}} = 1$, $m_{\tilde{f}}^2 = m_{\tilde{f}_1} m_{\tilde{f}_2}$

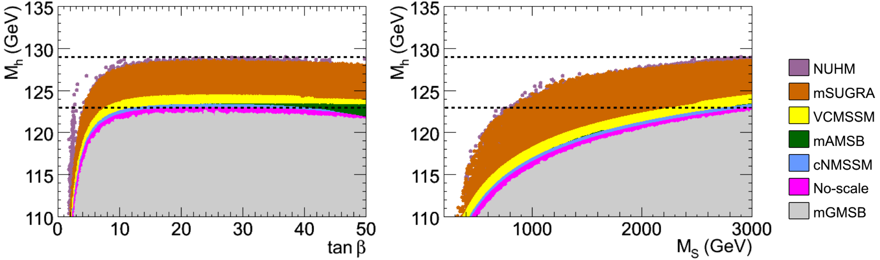
- M_h^{max} is obtained for:
  - a decoupling regime with a heavy pseudoscalar Higgs boson, $M_A \sim \mathcal{O}(\text{TeV})$
  - large $\tan\beta$, *i.e.* $\tan\beta \gtrsim 10$
  - heavy stops, *i.e.* large M_S
  - maximal mixing scenario, *i.e.* $X_t = \sqrt{6}M_S$



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

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

Maximal Higgs mass in constrained MSSM scenarios



Several constrained models are excluded or about to be!
But CMSSM is still surviving!

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 $|\Delta_f| \sim 1$.

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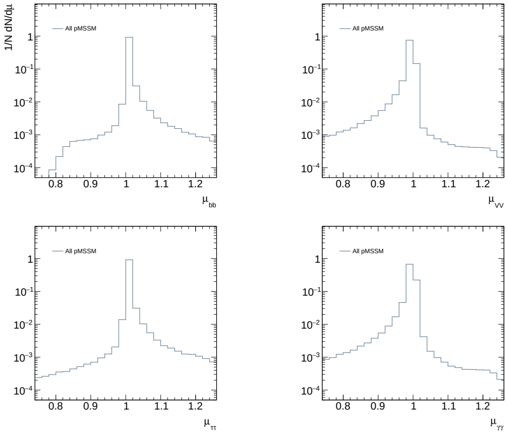
Distributions of *h* decay branching fractions normalised to their SM prediction:

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



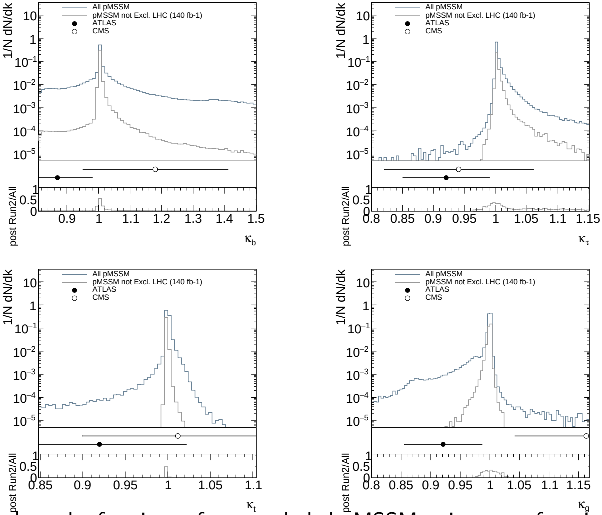
Best fit values for the Higgs coupling modifiers $\kappa_X = g_{hXX}^{\text{MSSM}}/g_{hXX}^{\text{SM}}$ from the combination of the **ATLAS** measurements, and projections for different stages of the LHC, and for the ILC and FCC-ee colliders:

Coupling modifier	ATLAS 13 TeV up to 140 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}
κ_W	1.05 ± 0.09	± 0.022	± 0.0180	± 0.0024	± 0.0043
κ_Z	1.11 ± 0.08	± 0.018	± 0.0029	± 0.0022	± 0.0017
κ_t	$1.03^{+0.15}_{-0.14}$	$^{+0.043}_{-0.040}$	–	± 0.016	–
κ_b	$1.09^{+0.19}_{-0.17}$	$^{+0.044}_{-0.028}$	± 0.0180	± 0.0048	± 0.067
κ_τ	$1.05^{+0.16}_{-0.15}$	$^{+0.028}_{-0.027}$	± 0.0190	± 0.0057	± 0.0073
κ_g	1.05 ± 0.09	$^{+0.032}_{-0.030}$	± 0.0230	± 0.0066	± 0.0100
κ_γ	$0.99^{+0.11}_{-0.10}$	$^{+0.028}_{-0.023}$	± 0.0670	± 0.019	± 0.0390

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

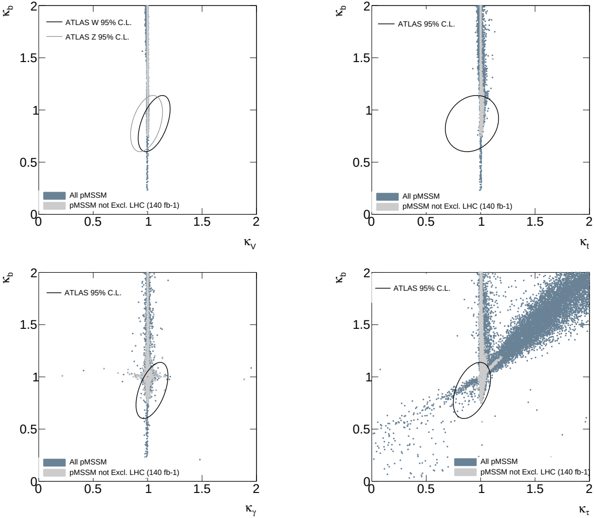
Higgs boson coupling modifiers

h coupling modifiers, κ_X, for all valid pMSSM points and those not excluded by the LHC Run 2 searches compared to the present measurements by the ATLAS and CMS.

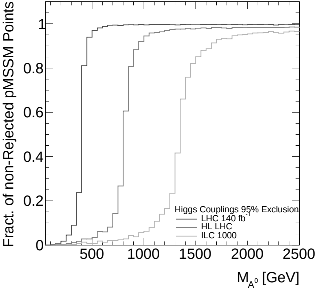


The lower panels show the fractions of non-excluded pMSSM points as a function κ_X.

Correlations of h coupling modifiers comparing the valid pMSSM points, those not excluded by the LHC Run 2 searches and the 95% C.L. contours of the current measurements by the ATLAS experiment:

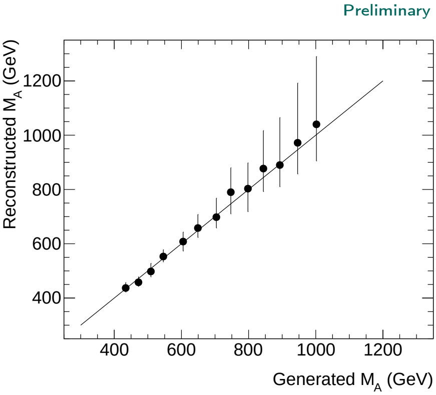


Fraction of accepted pMSSM points not excluded at the 95% of C.L. by the Higgs couplings as a function of the M_A mass:



dark grey: present Run 2 ATLAS results
medium grey: expected HL-LHC
light grey: ILC-1000 accuracies

Reconstruction of M_A at ILC 1 TeV from Higgs decay measurements

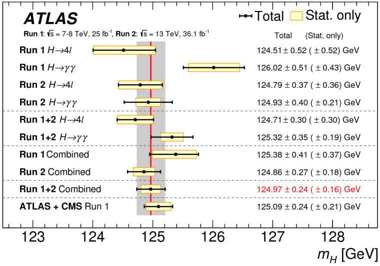


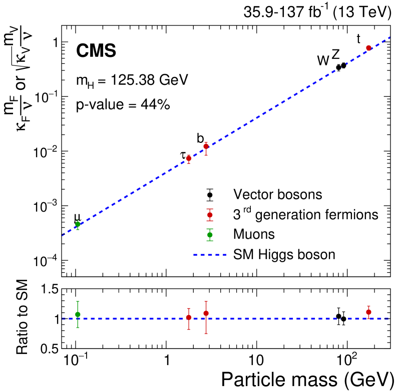
M_A (GeV)	$\tan\beta$	μ	$M_{\chi_1^0}$
434.4	5.58	-549.3	562.1
472.4	6.62	1993.7	314.8
509.8	5.48	-181.9	184.7
546.9	5.55	-50.5	49.9
605.7	6.31	369.1	380.1
649.5	3.15	1722.6	108.3
704.4	5.24	480.5	170.6
747.0	4.51	-3596.1	1072.0
798.4	5.75	-3301.7	1329.4
844.3	9.11	-1679.5	1695.1
893.2	7.14	-367.9	379.5
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 $\tan\beta$

Extra slides

Higgs mass


ATLAS
Total
Stat. only
Run 1: √s = 7-8 TeV, 25 fb⁻¹, Run 2: √s = 13 TeV, 36.1 fb⁻¹
Total (Stat. only)
Run 1 H→4l 124.51 ± 0.52 (± 0.52) GeV
Run 1 H→γγ 126.02 ± 0.51 (± 0.43) GeV
Run 2 H→4l 124.79 ± 0.37 (± 0.36) GeV
Run 2 H→γγ 124.93 ± 0.40 (± 0.21) GeV
Run 1+2 H→4l 124.71 ± 0.30 (± 0.30) GeV
Run 1+2 H→γγ 125.32 ± 0.35 (± 0.19) GeV
Run 1 Combined 125.38 ± 0.41 (± 0.37) GeV
Run 2 Combined 124.86 ± 0.27 (± 0.18) GeV
Run 1+2 Combined 124.97 ± 0.24 (± 0.16) GeV
ATLAS + CMS Run 1 125.09 ± 0.24 (± 0.21) GeV
123 124 125 126 127 128
m_H [GeV]


35.9-137 fb⁻¹ (13 TeV)
CMS
m_H = 125.38 GeV
p-value = 44%
t
W Z
b
τ
μ
Vector bosons
3rd generation fermions
Muons
SM Higgs boson
Ratio to SM
Particle mass (GeV)

Cross sections and partial decay widths