Low energy SUSY and H boson studies

Nazila Mahmoudi

IP2I - Lyon University

In collaboration with A. Arbey, M. Battaglia, A. Djouadi, M. Mühlleitner and M. Spira
[Based on PRD106, 055002 (2022)]

The H boson turns 11 this year!

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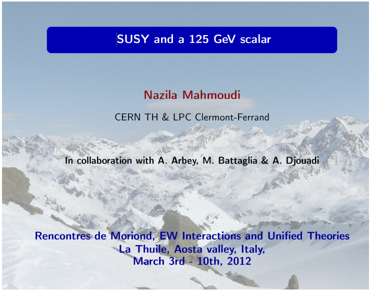

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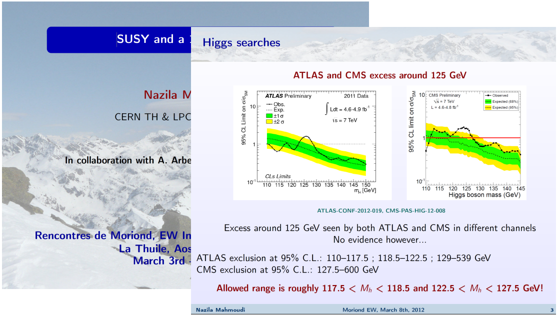

Discovery of a new scalar announced on July 4th, 2012!

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"New results indicate that particle discovered at CERN is a Higgs boson"
– Rolf Heuer

Introduction

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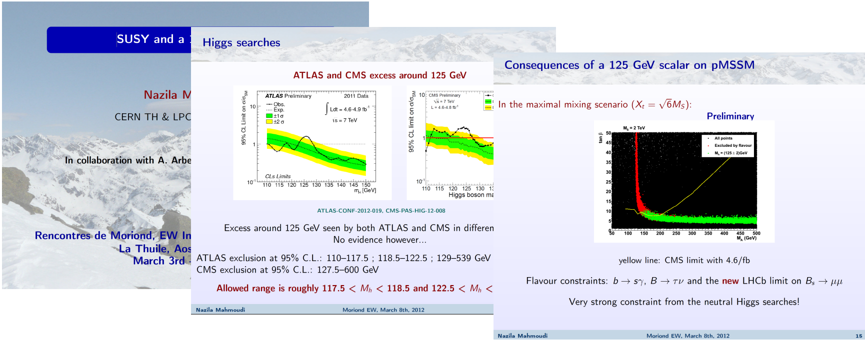

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The Higgs boson discovery → a vast program of studies of its properties as new tests of the SM and of models of NP!

In the **Standard Model**:
Higgs mass = free parameter related to the Higgs potential parameters:

$$M_H = \sqrt{-2\mu^2} = \sqrt{\frac{1}{2}\lambda v^2}$$

M_H measured $\Rightarrow$ all parameters of the Higgs theory fixed

Yukawa couplings determined by the measurement of all the fermion masses

In **extended Higgs scenarios**:
The Higgs couplings and its decay branching fractions can be shifted!

Precision study of the mass and the production and decay rates:

- essential for establishing the mechanism of EWSB and mass generation
- exploring the contributions of new physics models to the Higgs sector
  $\rightarrow$ setting constraints on their parameter spaces

MSSM: excellent benchmark for an extended Higgs sector
→ the MSSM effects on the light Higgs BRs and couplings

- Results for most of the Higgs decay and production channels of interest now in hand
- Mass bounds set by a broad variety of SUSY searches

⇒ Detailed assessment of the interplay between Higgs physics and SUSY at the LHC and beyond

In this talk:

- Brief introduction to the methodology
- Dependence of the Higgs BRs on M_A and $\tan\beta$ and Δ_b corrections
- Relation between the coupling modifiers and SUSY parameters
- Invisible decays into neutralino pairs and DM direct detection constraints
- From a given accuracy in the Higgs measurements to the reconstruction of the NP model parameters

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Minimal Supersymmetric extension of the Standard Model

The Higgs sector is extended (2HDM type II):

2 Higgs doublets → five Higgs states:

two CP–even h and H, one CP–odd A, and two charged Higgs bosons $H^\pm$

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

→ 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_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

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Random scans of the 19 pMSSM parameters with neutralino dark matter

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]
$M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$	[50, 6000]
$M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$	[50, 6000]
$M_{\tilde{\tau}_L}$	[50, 6000]
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$M_{\tilde{q}_{3L}}$	[50, 6000]
$M_{\tilde{u}_R} = M_{\tilde{c}_R}$	[50, 6000]
$M_{\tilde{t}_R}$	[50, 6000]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[50, 6000]
$M_{\tilde{b}_R}$	[50, 6000]
$\tan\beta$	[1, 60]

- Calculation of masses, mixings and couplings (**SoftSusy**)
- Computation of flavour 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**)

- **Direct SUSY searches**:

  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) + $\not{E}_T$)

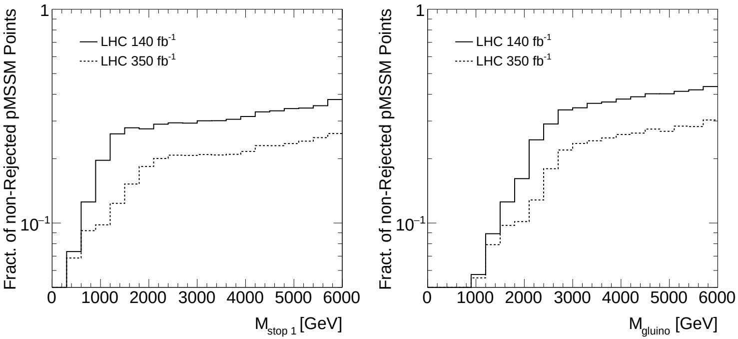
- **Monojet searches**:

  search for 1 hard jet + $\not{E}_T$ and other Mono-X searches: mono-W/Z/γ

Here we used ATLAS searches listed below:

Channel	Int. lum. fb^{-1}	Sensitivity
$H/A \to \tau\tau$	36	H, A
$H/A \to ZZ$	36	H, A
$H/A \to t\bar{t}$	20	H, A
jets + MET	139	$\tilde{g}$, $\tilde{q}$
jets + MET	36	$\tilde{g}$, $\tilde{q}$
1 ℓ + jets + MET	36	$\tilde{g}$, $\tilde{q}$
$\ell^+\ell^+$, $\ell^-\ell^-$ + MET	139	$\tilde{g}$, $\tilde{q}$
b-jets + MET	36	$\tilde{t}$
multiple b-jets + MET	80	$\tilde{t}$, b
2 ℓ + MET	139	$\tilde{\chi}^0$, $\tilde{\chi}^\pm$, $\tilde{\ell}$
3 ℓ + MET	36	$\tilde{\chi}^0$ $\tilde{\chi}^\pm$, $\tilde{\ell}$
mono-jet + MET	36	$\tilde{\chi}\tilde{\chi}$, $\tilde{q}\tilde{q}$
mono-W/Z + MET	3.2	$\tilde{\chi}\tilde{\chi}$, $\tilde{q}\tilde{q}$

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:



gluinos as light as 1 TeV or stops as light as 500 GeV can still escape the direct searches

- 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:

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

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

The maximal value can be reached for $X_t = \sqrt{6} M_S$ (maximal mixing)

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

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

- 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 $X_t = A_t - \mu \cot\beta$
- 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.* $X_t = \sqrt{6} M_S$
- In contrast, much smaller M_h^{max} values for the no-mixing scenario, *i.e.* $X_t \approx 0$

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:

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

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

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

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

Higgs couplings and SUSY corrections

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

ϕ	$g_{\phi u\bar{u}}$	$g_{\phi d\bar{d}} = g_{\phi \ell\bar{\ell}}$	$g_{\Phi VV}$
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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

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

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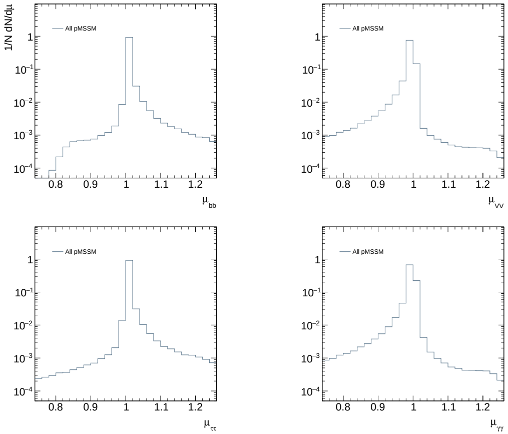
$$g^{\text{eff}}_{Hf\bar{f}} = \frac{g_{Hf\bar{f}}}{1+\Delta_f}\left[1 + \Delta_f\frac{\tan\alpha}{\tan\beta}\right]$$

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

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

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

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



Higgs measurement accuracy

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

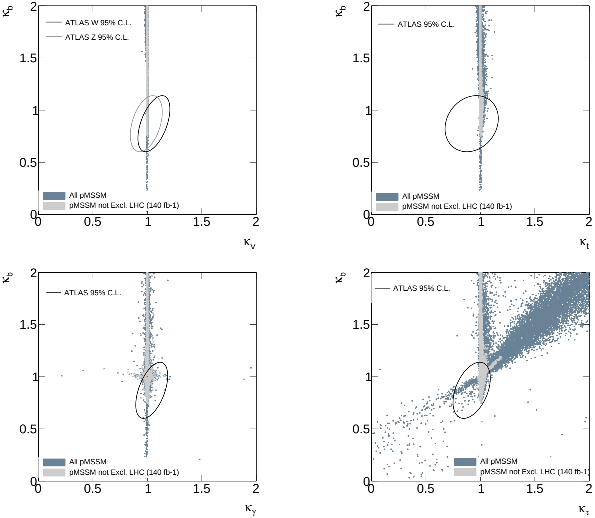
Coupling modifier	ATLAS 13 TeV up to 140 fb^{-1}	ATLAS 14 TeV 3 ab^{-1} †	ILC 250 GeV 2 ab^{-1}	ILC 1 TeV 8 ab^{-1}	FCC-ee 365 GeV 1.5 ab^{-1}
κ_W	1.05 ± 0.09	± 0.022	± 0.0180	± 0.0024	± 0.0043
κ_Z	1.11 ± 0.08	± 0.018	± 0.0029	± 0.0022	± 0.0017
κ_t	$1.03^{+0.15}_{-0.14}$	$^{+0.043}_{-0.040}$	–	± 0.016	–
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

[see JHEP 01 (2020) 2139]

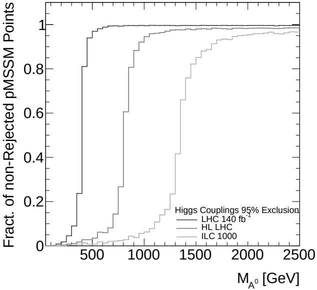
Current determination with precisions of the order of 10%, uncertainties will decrease by a factor 10 in the future.

Higgs boson coupling modifiers

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

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

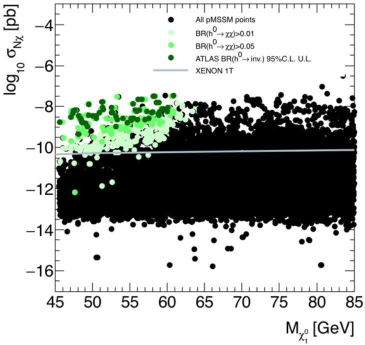
Decay width:

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

Light bino-like neutralinos can easily escape the LHC constraints

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

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



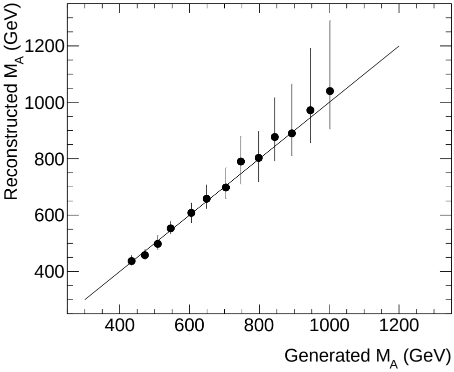
Black dots: all pMSSM points

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	$M_{\chi_1^0}$
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 $\tan\beta$
(suppression of the Δ_b corrections)

- Study of the Higgs boson properties
  $\rightarrow$ compelling perspectives for testing the effects of BSM physics at the LHC and at future colliders
- In the MSSM: The Higgs couplings to SM particles, both at tree level and through loops, are sensitive to new physics effects and can be used to discriminate the MSSM h from the SM H
- Higgs coupling measurements with the accuracies obtained on the LHC run 2 data and those expected for the HL-LHC and future e^+e^- colliders can exclude a significant fraction of the pMSSM points
- Future e^+e^- colliders of sufficient energy can indirectly determine M_A to a relative accuracy ranging from 8% to 40% for M_A values from 700 GeV to 1.1 TeV, from the deviations of the measured lightest h couplings with respect to their SM expectations

$\rightarrow$ Large parts of the MSSM parameters are still to be probed

$\rightarrow$ The properties of the observed Higgs boson are SM-like
they are also MSSM-like!

Conclusion

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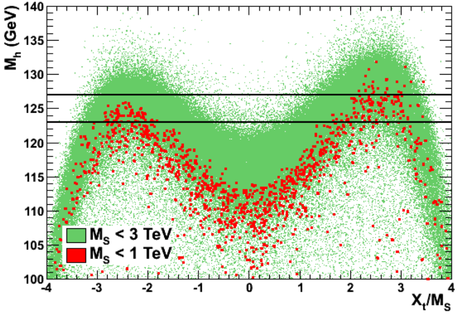
Extra slides

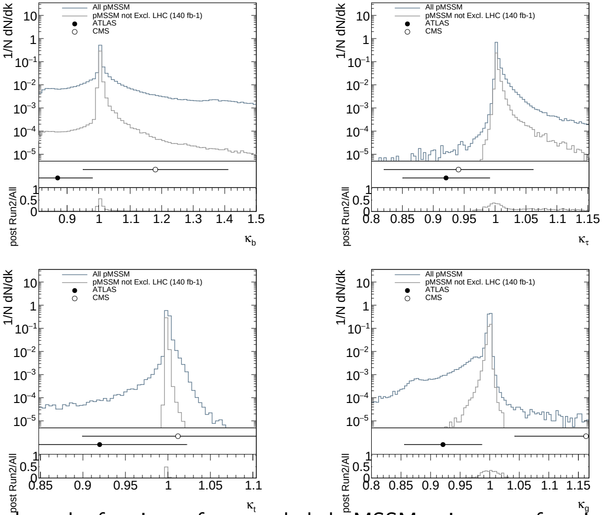


A. Arbey, M. Battaglia, A. Djouadi, F.M., J. Quevillon, Phys.Lett. B708 (2012) 162

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

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

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