AUTOMATIC LOOP CALCULATIONS OF NMSSM PROCESSES WITH SLOOPS

Guillaume CHALONS

GDR TERASCALE, LPNHE, November '16

based on
GC, A. Semenov, JHEP 1112 (2011) 055
GC, F. Domingo, PRD86 (2012) 115024
GC, M. J. Dolan, C. McCabe, JCAP 1302 (2013) 016
G. Bélanger, V. Bizouard, GC, PRD89 (2014) 9, 095023
G. Bélanger, V. Bizouard, F. Boudjema, GC, PRD93 (2016) 11, 115031
G. Bélanger, V. Bizouard, F. Boudjema, GC, *to appear*

OVERVIEW OF THE MODEL AND MOTIVATIONS

NMSSM $\equiv$ *Next-to* Minimal Supersymmetric Standard Model :

$$W^{\mathbb{Z}_3}_{NMSSM} = W^{\mu=0}_{MSSM} + \lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{\kappa}{3}\hat{S}^3$$

Important phenomenological consequences :

- Same Pros as MSSM: Hierarchy, Gauge Unification, Dark Matter...
- Solves elegantly the "μ problem" of the MSSM : $\mu_{\mathrm{eff}} = \lambda\langle S\rangle$.
- Richer Higgs spectrum than the MSSM : 2 (1) CP-odd Higgs A_i, 3 (2) CP-even H_i^0, 1 charged $H^{\pm}$.
- Enlarged neutralino sector $(\widetilde{B}^0, \widetilde{W}^0, \widetilde{H}_1^0, \widetilde{H}_2^0, \widetilde{S}^0) \rightarrow (\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0)$

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- ☞ Additional F-term + doublet-singlet mixing makes it easier to get $m_h^{\rm SM} \sim 125$ GeV
- ☞ Evade LHC SUSY constraints by hiding $\not{E}_T$ (visible energy diluted)
- ☞ Easier to get low mass DM (thanks to approx. $U(1)$ R/PQ sym.)
- ☞ Successful EW baryogenesis (allows $1^{\rm st}$ order PT)
- ☞ . . .

NMSSM PRECISION CALCULATION TOOLS ON THE MARKET

- Like in the MSSM, the SM-like Higgs mass gets large rad. cor.
- Rad. cor. in Higgs production/decays can also be large
- To match planned exp. accuracy in Higgs measurements, inclusion of loop corrections mandatory

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AUTOMATIC TOOLS AVAILABLE ON THE MARKET

- NMSSMTools: Spectrum gen. + Decays + DM + Constraints (Das,Domingo,Ellwanger,Gunion,Hugonie,Jean-Louis,Teixeira)
- SPheno and SARAH: Spectrum generator + Decays + Constraints (Porod, Staub, Goodsell,Nickel)
- NMSSMCALC: Higgs masses + decays (Baglio, Gröber, Mühlleitner, Nhung, Rzehak, Spira, Streicher, Walz)
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- Comparison between them CPC 202 (2016), 113 (Staub et. al)

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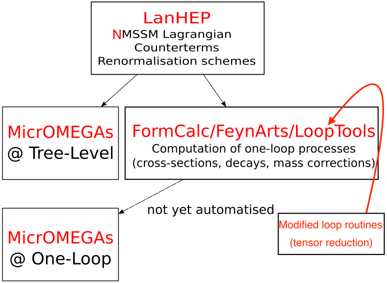
☞ SLOOPS: Automatic generation of any process (mass, decay, cross-section) at **1L** with EW & QCD corrections.

Orsay



SLOOPS

An automatic code for calculation of loops diagrams for $\mathcal{SM}$ and $\mathcal{BSM}$ processes with application to colliders, astrophysics and cosmology.

- Automatic derivation of the CT Feynman rules and computation of the CT's
- Models renormalized: SM, MSSM, NMSSM, Wino DM, **xSM** (w/ & w/o v_s),
- Modularity between different renormalisation schemes.
- Non-linear gauge fixing.
- Checks: results UV,IR finite and gauge independent.

http://code.sloops.free.fr/

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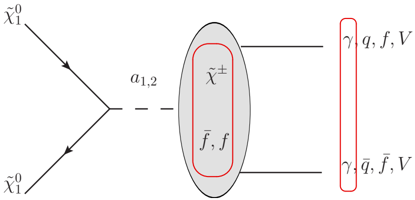
G.C, A. Semenov JHEP 1112 (2011) 055; G.C, M.J. Dolan,C. McCabe JCAP 1302 016

- $\chi\chi \to \gamma\gamma$ is a smoking gun signature of DM and $E_\gamma \sim m_\chi$
- Interesting process to look at to test the good implementation of the framework at LO (no renormalisation needed).

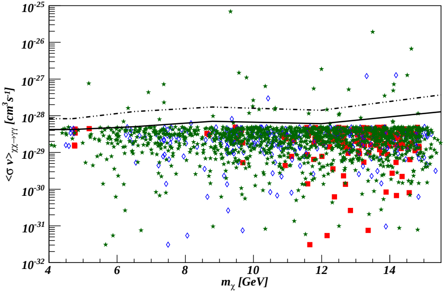
- Main mechanism in the NMSSM



- $\langle\sigma v\rangle_{\gamma\gamma/Z^0}$ computed with SloopS extended to deal with the NMSSM & all contributions
- GI checked thanks to an extended NLG GF for the NMSSM GC,Semenov '11
- Modified version of LOOPTOOLS to handle vanishing Gram determinants at $v = 0$ Boudjema,Semenov,Temes '05

APPLYING FERMI-LAT CONSTRAINTS

- FERMI satellite has a dedicated search for γ-lines
- Concentrate on low-mass m_χ which is specific to NMSSM
- Extension of the work performed in (*Vazquez et. al '10*)
- Limits taken from *Vertongen,Weniger '11* : extended range $m_\chi \in [1, 300]$ GeV.



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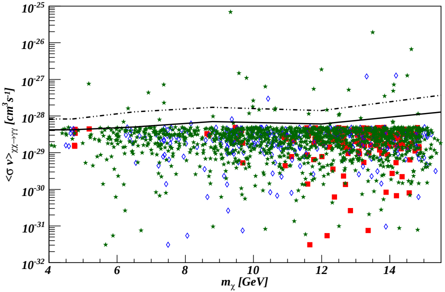

☞ Routine of $\langle\sigma v\rangle_{\gamma\gamma}$ through SLOOPS built-in MicrOMEGAs (MSSM/NMSSM)

APPLICATION TO HIGGS: LOOP-INDUCED DECAYS

- Use of an effective $\mathcal{V}^S_{\text{rad.}}$ (GC, Domingo '12) to compute loop-induced $h_i^0 \to \gamma\gamma/Z^0$ decays at the right kin. in a GI invariant way through the interface of SLOOPS with NMSSMTools (Effective potential now present in standard version of NMSSMTools)
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- In loop-induced H decays, New Physics enters already at the LO level
- ☞ No significant deviation from SM observed in $\mu_{\gamma\gamma}$
- ☞ In the SM $\Gamma^H_{\gamma\gamma}/\Gamma^H_{\gamma Z} \sim 2/3$, is there room to observe a deviation from the SM of this ratio in the NMSSM ?

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$$
\begin{aligned}
100\ \mathrm{GeV} < &\quad \mu &< 500\ GeV\\
100\ \mathrm{GeV} < &\quad M_2 &< 1000\ GeV\\
0\ \mathrm{GeV} < &\quad t_\beta &< 20\\
0 < &\quad \lambda, \kappa &< 0.7\\
100\ \mathrm{GeV} < &\quad A_\lambda &< 1000\ \mathrm{GeV}\\
-1000\ \mathrm{GeV} < &\quad A_\kappa &< -100\ \mathrm{GeV}\\
-3000\ \mathrm{GeV} < &\quad A_t &< 3000\ \mathrm{GeV}\\
400\ \mathrm{GeV} < &\quad m_{\tilde{Q},\tilde{U}_3} &< 2000\ \mathrm{GeV}
\end{aligned}
$$

- $m_h^{\mathrm{SM}} \in [122, 128]$ GeV
- Various constraints from NMSSMTools
- Collider constraints on Higgs from HiggsBounds
- Higgs fits constraints from HiggsSignals

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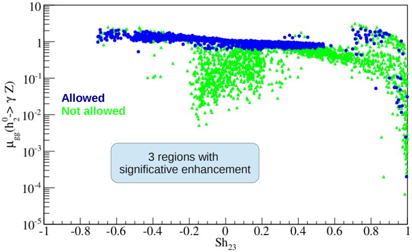
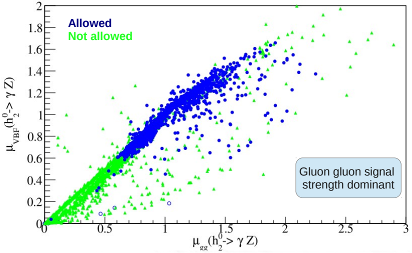
If $h^0_1 \equiv H_{125}$ → $h^0_1 \to \gamma Z^0$ similar to SM expectations, look at $h^0_2 \equiv H_{125}$

POSSIBLE DEVIATIONS IN $h^0_{1,2} \to \gamma Z^0$?

If $h_1^0 \equiv H_{125} \to h_1^0 \to \gamma Z^0$ similar to SM expectations, look at $h_2^0 \equiv H_{125}$

LHC will not measure the BRs but rather μ_{gg} and μ_{VBF} in the γZ^0 channel





- Some enhancement for $a) S_{h23} < -0.5$, $b) S_{h23} > 0.7$, $c) S_{h23} \approx 0.4$
- h_2^0 significant doublet & singlet comp.
- μ_{VBF} mostly correlated with μ_{gg}.
- Large deviation could indicate a need for a lighter Higgs boson

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G. Bélanger, V. Bizouard, F. Boudjema, GC, PRD93 (2016) 11, 115031 and ArXiv:1612.XXXX

SECTORS

- Fermion ⟶ as in the SM
- Gauge ⟶ as in the SM
- Sfermion ⟶ as in the MSSM

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SECTORS

- Fermion $\longrightarrow$ as in the SM
- Gauge $\longrightarrow$ as in the SM
- Sfermion $\longrightarrow$ as in the MSSM
- Higgs
- gaugino

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All in all we have

$$\underbrace{g, g'}_{\text{SM}}, \underbrace{v_u, v_d, s, \lambda, \kappa}_{\text{Higgs } \& \ \tilde{\chi}}, A_\lambda, A_\kappa, m_{H_u}^2, m_{H_d}^2, m_S^2, M_1, M_2$$

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we trade some for physical parameters

$$e, M_Z, s_W, \overbrace{t_\beta, \lambda, \kappa, \mu}^{\text{Higgs } \& \ \tilde{\chi}}, \underbrace{A_\lambda, A_\kappa, t_{h_u^0}, t_{h_d^0}, t_{h_s^0}}_{\text{Higgs}}, \overbrace{M_1, M_2}^{\tilde{\chi}}$$

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- Min. cond. $\Longrightarrow \boxed{t_{h_i^0} \equiv 0}$, $i = u, d, s$. At 1L $\delta t_{h_i^0} = -t^{loop}_{h_i^0}$
- Remains 8 counterterms to be determined .
- Equivalently, we need to find 8 exp inputs/definitions which are linked unambigously to the original 8 parameters
- $\mathcal{W}_8$ matrix system to invert with $\delta t_\beta, \delta\lambda, \delta\kappa, \delta\mu, \delta A_\lambda, \delta A_\kappa, \delta M_1, \delta M_2$ as variables

Orsay

VARIOUS RENORMALISATION SCHEMES

ON-SHELL SCHEMES WITH MASSES ONLY

☞ $\mathcal{W}_8 = \overbrace{\mathcal{W}_2^{\chi^\pm}}^{M_2,\mu} \oplus \overbrace{\mathcal{W}_4^{\chi^0}}^{M_1,\lambda,\kappa,t_\beta} \oplus \overbrace{\mathcal{W}_2^{A^0}}^{A_\lambda,A_\kappa} \to OS_{ijkl}$ (suited when only gaugino decays)

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Or simply go all $\overline{\rm DR}$

LPT Orsay

Point A($Q_{susy} = 1117.25$GeV, $m_t = 173$GeV, $m_{h_1^0} = 125.45$GeV(1-loop OS))

M_1	700	λ	0.1	A_κ	0	$m_{\tilde{Q}_3}$	1740	$m_{\tilde{D},\tilde{U}_{1,2}}$	1000
M_2	1000	κ	0.1	A_t	4000	$m_{\tilde{U}_3}$	800	$m_{\tilde{L}_3}$	1000
M_3	1000	μ	120	A_b	1000	$m_{\tilde{D}_3}$	1000	$m_{\tilde{l}_3}$	1000
t_β	10	A_λ	150	A_l	1000	$m_{\tilde{Q}_{1,2}}$	1000	$m_{\tilde{L},\tilde{l}_{1,2}}$	1000

$\lambda A_\lambda = 15$GeV, $A_t/A_\lambda \sim 27$

Point B($Q_{susy} = 753.55$GeV, $m_t = 146.94$GeV, $m_{h_1^0} = 124.44$GeV(1-loop OS))

M_1	120	λ	0.67	A_κ	0	$m_{\tilde{Q}_3}$	750	$m_{\tilde{D},\tilde{U}_{1,2}}$	1500
M_2	300	κ	0.2	A_t	1000	$m_{\tilde{U}_3}$	750	$m_{\tilde{L}_3}$	1500
M_3	1500	μ	200	A_b	1000	$m_{\tilde{D}_3}$	1500	$m_{\tilde{l}_3}$	1500
t_β	1.92	A_λ	405	A_l	1000	$m_{\tilde{Q}_{1,2}}$	1500	$m_{\tilde{L},\tilde{l}_{1,2}}$	1500

$\lambda A_\lambda = 271$GeV, $A_t/A_\lambda \sim 2.5$

LPT Orsay

		Point A	Point B
h_1^0	h_d^0	1.1%	22.5%
	h_u^0	**98.6%**	**67.4%**
	h_s^0	0.3%	10.1%
h_2^0	h_d^0	0.1%	0.%
	h_u^0	0.3%	12.5%
	h_s^0	**99.6%**	**87.5%**
h_3^0	h_d^0	**98.8%**	**77.5%**
	h_u^0	1.1%	19.7%
	h_s^0	0.1%	2.8%
A_1^0	a_d^0	0%	1.8%
	a_u^0	0%	0.5%
	a_s^0	**100%**	**97.7%**
A_2^0	a_d^0	**99.0%**	**76.9%**
	a_u^0	1.0%	20.8%
	a_s^0	0.0%	2.3%

Point A: h_u, h_s, h_d, a_s, a_d

Point B: h_u, h_s, h_d, a_s, a_d

		Point A	Point B
$\tilde{\chi}_1^0$	$\tilde{B}^0$	-	**56.6%**
	$\tilde{W}^0$	-	32.3%
	$\tilde{h}^0$	**98.4%**	10.3%
	$\tilde{S}^0$	0.77%	0.8%
$\tilde{\chi}_2^0$	$\tilde{B}^0$	-	4.0%
	$\tilde{W}^0$	-	2.6%
	$\tilde{h}^0$	**99.5%**	19.3%
	$\tilde{S}^0$	-	**74.0%**
$\tilde{\chi}_3^0$	$\tilde{B}^0$	-	10.1%
	$\tilde{W}^0$	-	-
	$\tilde{h}^0$	0.9%	**78.9%**
	$\tilde{S}^0$	**99.1%**	11.0%
$\tilde{\chi}_4^0$	$\tilde{B}^0$	**99.6%**	18.1%
	$\tilde{W}^0$	-	12.3%
	$\tilde{h}^0$	-	**55.8%**
	$\tilde{S}^0$	-	13.7%
$\tilde{\chi}_5^0$	$\tilde{B}^0$	-	11.2%
	$\tilde{W}^0$	**99.3%**	**52.8%**
	$\tilde{h}^0$	0.69%	35.7%
	$\tilde{S}^0$	-	0.4%

Point A: $\tilde{h}$, $\tilde{h}$, $\tilde{s}$, $\tilde{b}$, $\tilde{w}$

Point B: $\tilde{b}$, $\tilde{s}$, $\tilde{h}$, $\tilde{h}$, $\tilde{w}$

Beware. B much more mixing, A quite pure

POINT A: HIGGS DECAYS WITH SINGLET/SINGLINOS

- singlets: $h_2^0, A_1^0, \tilde{\chi}_3^0$, $m_{h_2^0} = 240$ GeV, $m_{h_3^0, A_2^0, H^\pm} \sim 570$ GeV, $Q_{\mathrm{SUSY}} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} = 1117$ GeV

Decays	$t_{134A_1A_2}(Q_{\mathrm{SUSY}})$	$OS_{34h_2A_1A_2H^+}$	$\overline{\mathrm{DR}}(m_{parent})$	$\overline{\mathrm{DR}}(Q_{\mathrm{SUSY}})$

LPT Orsay

POINT A: HIGGS DECAYS WITH SINGLET/SINGLINOS

- singlets: $h_2^0, A_1^0, \tilde{\chi}_3^0$, $m_{h_2^0} = 240$ GeV, $m_{h_3^0, A_2^0, H^\pm} \sim 570$ GeV, $Q_{\mathrm{SUSY}} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} = 1117$ GeV

Decays	$t_{134 A_1 A_2}(Q_{\mathrm{SUSY}})$	$OS_{34 h_2 A_1 A_2 H^+}$	$\overline{\mathrm{DR}}(m_{parent})$	$\overline{\mathrm{DR}}(Q_{\mathrm{SUSY}})$
$h_2^0 \to A_1^0 A_1^0$	(128%)	(-12%)	(0.4%)	(-0.4%)

☞ At LO (with $(A_\kappa = 0)$, $g_{h_2^0 A_1^0 A_1^0}$ stems from $\kappa^2 S^4$

$\to g_{h_2^0 A_1^0 A_1^0} \propto \kappa^2 s \propto (\kappa s)^2 / s \propto \boxed{\lambda/\mu(\kappa s)^2 \sim \lambda / m_{\widetilde{H}^\pm} \times m_{\widetilde{S}^0}^2}$.

LPT Orsay

- singlets: $h_2^0, A_1^0, \tilde{\chi}_3^0$, $m_{h_2^0} = 240$ GeV, $m_{h_3^0, A_2^0, H^\pm} \sim 570$ GeV, $Q_{\rm SUSY} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} = 1117$ GeV

Decays	$t_{134 A_1 A_2}(Q_{\rm SUSY})$	$OS_{34 h_2 A_1 A_2 H^+}$	$\overline{\rm DR}(m_{parent})$	$\overline{\rm DR}(Q_{\rm SUSY})$
$h_2^0 \to A_1^0 A_1^0$	(128%)	(-12%)	(0.4%)	(-0.4%)

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☞ $m_{\widetilde{S}^0}$ constrains $(\kappa s)^2$ and $m_{\widetilde{H}^\pm}$ constrains μ well. Finite shift on λ is key. We have

$$\boxed{\delta\lambda/\lambda|^{\rm t134}_{\rm fin.} = 62.26\% \text{ and } \delta\lambda/\lambda|^{\rm OS}_{\rm fin.} = -7.88\%}$$

and loop correction is $\delta\Gamma/\Gamma \sim 2\delta\lambda/\lambda$ due to finite part of CT.

LPT Orsay

- singlets: $h_2^0, A_1^0, \tilde{\chi}_3^0$, $m_{h_2^0} = 240$ GeV, $m_{h_3^0, A_2^0, H^\pm} \sim 570$ GeV, $Q_{\mathrm{SUSY}} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} = 1117$ GeV

Decays	$t_{134 A_1 A_2}(Q_{\mathrm{SUSY}})$	$OS_{34 h_2 A_1 A_2 H^+}$	$\overline{\mathrm{DR}}(m_{parent})$	$\overline{\mathrm{DR}}(Q_{\mathrm{SUSY}})$
$h_2^0 \to A_1^0 A_1^0$	(128%)	(-12%)	(0.4%)	(-0.4%)

☞ At LO (with $(A_\kappa = 0)$, $g_{h_2^0 A_1^0 A_1^0}$ stems from $\kappa^2 S^4$

$$\to g_{h_2^0 A_1^0 A_1^0} \propto \kappa^2 s \propto (\kappa s)^2/s \propto \boxed{\lambda/\mu(\kappa s)^2 \sim \lambda/m_{\tilde{H}^\pm} \times m^2_{\tilde{S}^0}}.$$

☞ $m_{\tilde{S}^0}$ constrains $(\kappa s)^2$ and $m_{\tilde{H}^\pm}$ constrains μ well. Finite shift on λ is key. We have

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and loop correction is $\delta\Gamma/\Gamma \sim 2\delta\lambda/\lambda$ due to finite part of CT.

☞ Small $\overline{\mathrm{DR}}$ corrections $\to$ pure virtual corrections negligible and κ, s do not run much (confirmed if one inspects the resp. $\beta_{\kappa,s}$ functions).

LPT Orsay

- singlets: $h_2^0, A_1^0, \tilde{\chi}_3^0$, $m_{h_2^0} = 240$ GeV, $m_{h_3^0, A_2^0, H^\pm} \sim 570$ GeV, $Q_{\mathrm{SUSY}} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} = 1117$ GeV

Decays	$t_{134A_1A_2}(Q_{\mathrm{SUSY}})$	$OS_{34h_2A_1A_2H^+}$	$\overline{\mathrm{DR}}(m_{parent})$	$\overline{\mathrm{DR}}(Q_{\mathrm{SUSY}})$
$h_2^0 \to A_1^0 A_1^0$	(128%)	(-12%)	(0.4%)	(-0.4%)
$h_3^0 \to \tilde{\chi}_1^0 \tilde{\chi}_3^0$	(122%)	(-3%)	(2%)	(0.3%)
$h_3^0 \to \tilde{\chi}_2^0 \tilde{\chi}_3^0$	(126%)	(-35%)	(3%)	(1.1%)
$A_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_3^0$	(130%)	(-31%)	(8%)	(6.2%)
$A_2^0 \to \tilde{\chi}_2^0 \tilde{\chi}_3^0$	(122%)	(-5%)	(-0.4%)	(-1.9%)
$H^+ \to \tilde{\chi}_1^+ \tilde{\chi}_3^0$	(125%)	(-18%)	(3%)	(1.1%)

☞ Same usual suspects, corrections in t_{134} accounted for by $\delta\lambda|_{\mathrm{fin.}}$. In $OS_{34h_2A_1A_2H^+}$ renormalisation of δt_β kicks in.

- singlets: $h_2^0, A_1^0, \tilde{\chi}_3^0$, $m_{h_2^0} = 240$ GeV, $m_{h_3^0, A_2^0, H^\pm} \sim 570$ GeV, $Q_{\rm SUSY} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} = 1117$ GeV

Decays	$t_{134A_1A_2}(Q_{\rm SUSY})$	$OS_{34h_2A_1A_2H^+}$	$\overline{\rm DR}(m_{parent})$	$\overline{\rm DR}(Q_{\rm SUSY})$
$h_2^0 \to A_1^0 A_1^0$	(128%)	(-12%)	(0.4%)	(-0.4%)
$h_3^0 \to \tilde{\chi}_1^0 \tilde{\chi}_3^0$	(122%)	(-3%)	(2%)	(0.3%)
$h_3^0 \to \tilde{\chi}_2^0 \tilde{\chi}_3^0$	(126%)	(-35%)	(3%)	(1.1%)
$A_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_3^0$	(130%)	(-31%)	(8%)	(6.2%)
$A_2^0 \to \tilde{\chi}_2^0 \tilde{\chi}_3^0$	(122%)	(-5%)	(-0.4%)	(-1.9%)
$H^+ \to \tilde{\chi}_1^+ \tilde{\chi}_3^0$	(125%)	(-18%)	(3%)	(1.1%)
$h_3^0 \to h_1^0 h_2^0$	(116%)	(79%)	(52%)	(-1.7%)

☞ For t_{134} & $OS_{34h_2A_1A_2H^+}$: same reasons as before

LPT Orsay

POINT A: HIGGS DECAYS WITH SINGLET/SINGLINOS

- singlets: $h_2^0, A_1^0, \tilde{\chi}_3^0$, $m_{h_2^0} = 240$ GeV, $m_{h_3^0, A_2^0, H^\pm} \sim 570$ GeV, $Q_{\mathrm{SUSY}} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} = 1117$ GeV

Decays	$t_{134 A_1 A_2}(Q_{\mathrm{SUSY}})$	$OS_{34 h_2 A_1 A_2 H^+}$	$\overline{\mathrm{DR}}(m_{parent})$	$\overline{\mathrm{DR}}(Q_{\mathrm{SUSY}})$
$h_2^0 \to A_1^0 A_1^0$	(128%)	(-12%)	(0.4%)	(-0.4%)
$h_3^0 \to \tilde{\chi}_1^0 \tilde{\chi}_3^0$	(122%)	(-3%)	(2%)	(0.3%)
$h_3^0 \to \tilde{\chi}_2^0 \tilde{\chi}_3^0$	(126%)	(-35%)	(3%)	(1.1%)
$A_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_3^0$	(130%)	(-31%)	(8%)	(6.2%)
$A_2^0 \to \tilde{\chi}_2^0 \tilde{\chi}_3^0$	(122%)	(-5%)	(-0.4%)	(-1.9%)
$H^+ \to \tilde{\chi}_1^+ \tilde{\chi}_3^0$	(125%)	(-18%)	(3%)	(1.1%)
$h_3^0 \to h_1^0 h_2^0$	(116%)	(79%)	(52%)	(-1.7%)

- ☞ For t_{134} & $OS_{34 h_2 A_1 A_2 H^+}$: same reasons as before
- ☞ Large corrections $\overline{\mathrm{DR}}$? Pt A has small mixing: $g_{h_1 h_2 h_3} \simeq g_{h_u h_s h_d} \sim \lambda \boxed{A_\lambda} + 2\kappa\mu$.

$$16\pi^2 \frac{1}{A_\lambda} \frac{dA_\lambda}{A_\lambda} \sim 3 h_t^2 \frac{A_t}{A_\lambda} \quad \text{recall} \quad \boxed{A_t / A_\lambda \sim 27!!}$$

LPT Orsay

- singlets: $h_2^0, A_1^0, \tilde{\chi}_3^0$, $m_{h_2^0} = 240$ GeV, $m_{h_3^0, A_2^0, H^\pm} \sim 570$ GeV, $Q_{\rm SUSY} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} = 1117$ GeV

Decays	$t_{134 A_1 A_2}(Q_{\rm SUSY})$	$OS_{34 h_2 A_1 A_2 H^+}$	$\overline{\rm DR}(m_{parent})$	$\overline{\rm DR}(Q_{\rm SUSY})$
$h_2^0 \to A_1^0 A_1^0$	(128%)	(-12%)	(0.4%)	(-0.4%)
$h_3^0 \to \tilde{\chi}_1^0 \tilde{\chi}_3^0$	(122%)	(-3%)	(2%)	(0.3%)
$h_3^0 \to \tilde{\chi}_2^0 \tilde{\chi}_3^0$	(126%)	(-35%)	(3%)	(1.1%)
$A_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_3^0$	(130%)	(-31%)	(8%)	(6.2%)
$A_2^0 \to \tilde{\chi}_2^0 \tilde{\chi}_3^0$	(122%)	(-5%)	(-0.4%)	(-1.9%)
$H^+ \to \tilde{\chi}_1^+ \tilde{\chi}_3^0$	(125%)	(-18%)	(3%)	(1.1%)
$h_3^0 \to h_1^0 h_2^0$	(116%)	(79%)	(52%)	(-1.7%)

☞ For t_{134} & $OS_{34 h_2 A_1 A_2 H^+}$: same reasons as before

☞ Large corrections $\overline{\rm DR}$? Pt A has small mixing: $g_{h_1 h_2 h_3} \simeq g_{h_u h_s h_d} \sim \lambda \boxed{A_\lambda} + 2\kappa\mu$.

$$16\pi^2 \frac{1}{A_\lambda} \frac{dA_\lambda}{A_\lambda} \sim 3h_t^2 \frac{A_t}{A_\lambda} \quad \text{recall} \quad \boxed{A_t/A_\lambda \sim 27!!}$$

☞ Correction in $\overline{\rm DR}$ driven by running of A_λ

POINT A: HIGGS DECAYS WITH SINGLET/SINGLINOS

- singlets: $h_2^0, A_1^0, \tilde{\chi}_3^0$, $m_{h_2^0} = 240$ GeV, $m_{h_3^0, A_2^0, H^\pm} \sim 570$ GeV, $Q_{\rm SUSY} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} = 1117$ GeV

Decays	$t_{134 A_1 A_2}(Q_{\rm SUSY})$	$OS_{34 h_2 A_1 A_2 H^+}$	$\overline{\rm DR}(m_{parent})$	$\overline{\rm DR}(Q_{\rm SUSY})$
$h_2^0 \to A_1^0 A_1^0$	(128%)	(-12%)	(0.4%)	(-0.4%)
$h_3^0 \to \tilde{\chi}_1^0 \tilde{\chi}_3^0$	(122%)	(-3%)	(2%)	(0.3%)
$h_3^0 \to \tilde{\chi}_2^0 \tilde{\chi}_3^0$	(126%)	(-35%)	(3%)	(1.1%)
$A_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_3^0$	(130%)	(-31%)	(8%)	(6.2%)
$A_2^0 \to \tilde{\chi}_2^0 \tilde{\chi}_3^0$	(122%)	(-5%)	(-0.4%)	(-1.9%)
$H^+ \to \tilde{\chi}_1^+ \tilde{\chi}_3^0$	(125%)	(-18%)	(3%)	(1.1%)
$h_3^0 \to h_1^0 h_2^0$	(116%)	(79%)	(52%)	(-1.7%)

- For t_{134} & $OS_{34 h_2 A_1 A_2 H^+}$: same reasons as before
- Large corrections $\overline{\rm DR}$? Pt A has small mixing: $g_{h_1 h_2 h_3} \simeq g_{h_u h_s h_d} \sim \lambda \boxed{A_\lambda} + 2\kappa\mu$.

$$16\pi^2 \frac{1}{A_\lambda} \frac{dA_\lambda}{A_\lambda} \sim 3h_t^2 \frac{A_t}{A_\lambda} \quad \text{recall} \quad \boxed{A_t/A_\lambda \sim 27!!}$$

- Correction in $\overline{\rm DR}$ driven by running of A_λ
- An MSSM-like point with large A_t to reproduce correct $m_H^{\rm SM}$ entitled to large EW rad. cor., even in $\overline{\rm DR}$, for decays driven by A_λ. For Pt A can be absorbed by setting $\bar{\mu} = Q_{\rm SUSY}$. $Q_{\rm SUSY}$ always the right choice ?

LPT Orsay

- Mixing important $\lambda = 0.67$, no pure state, in principle better extraction of counterterms

POINT B: HIGGS DECAYS WITH SINGLET/SINGLINOS

- Mixing important $\lambda = 0.67$, no pure state, in principle better extraction of counterterms

Decays	SloopS $t_{123}(Q_{\mathrm{SUSY}})$	SloopS $OS_{12h_2A_1A_2H^+}$	$\overline{\mathrm{DR}}(m_{parent})$	$\overline{\mathrm{DR}}(Q_{\mathrm{SUSY}})$
$h_3^0 \to \tilde{\chi}_1^0\tilde{\chi}_2^0$	10.8%	(14%)	(5%)	(3%)
$h_3^0 \to A_1^0 Z$	(8.4%)	(3%)	(-3%)	(-8 %)
$h_3^0 \to h_2^0 h_1^0$	(-131.4%)	(-25%)	(-106%)	(-50%)
$h_3^0 \to h_2^0 h_2^0$	(41.8 %)	(6%)	(13%)	(-28%)
$A_2^0 \to \tilde{\chi}_1^+\tilde{\chi}_1^-$	(8.2 %)	(7%)	(2%)	(1%)
$A_2^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0$	(18.1%)	(32%)	(2%)	(2%)
$A_2^0 \to Z h_2^0$	(-10.27 %)	(12%)	(-16%)	(-9%)
$A_2^0 \to A_1^0 h_1^0$	(-40.9 %)	(-0.3%)	(-32%)	(-17%)
$H^+ \to \tilde{\chi}_1^+\tilde{\chi}_2^0$	(8.4%)	(6%)	(10%)	(8%)
$H^+ \to W^+ h_2^0$	(-11%)	(11%)	(-18%)	(-10%)
$H^+ \to W^+ A_1^0$	(7.9%)	(2%)	(-3%)	(-9%)
$H^+ \to \tilde{\chi}_1^+\tilde{\chi}_1^0$	(12.5 %)	(21%)	(9%)	(9%)

- Due to large mixing, dependence on parameters much more involved.
- Still renormalisation of λ, t_β and running of A_λ (although smaller due to smaller A_t/A_λ) lead the corrections
- OS scheme gives reasonable corrections
- For $\overline{\mathrm{DR}}$ even $\bar{\mu} = Q_{\mathrm{SUSY}}$ does not absorb all the corrections most probably because A_λ is not the only driver of the decay

LPT Orsay

SUMMARY

- Using SloopS, in principle up to $2 \longrightarrow 3$ processes at the 1L level can be evaluated
- Full on-shell renormalisation (all sectors) of the NMSSM at one-loop completed.
- Various schemes investigated $\rightarrow$ large scheme dependence for some observables, depending on the scenario
- Currently impossible to choose what is the best scheme for reconstructing parameters. As long as only predictions are concerned, $\overline{\mathrm{DR}}$ scheme sufficient but large pure EW corrections are possible in some scenarios (in particular when singlets are involved in MSSM-like points). Not always clear how to tame them by choosing appropriate $\bar{\mu}$
- Applications to astrophysics, colliders and cosmology (future)
- SloopS is not limited to SUSY model, any renormalisable model (ex: xSM, wino-DM model) can be implemented

LPT Orsay

BACKUP

GC, F. Domingo, PRD86 (2012) 115024; G. Bélanger, V. Bizouard, GC, PRD89 (2014) 9, 095023

- We know $m_h^{\mathrm{SM}} \equiv m_H$ gets large rad. cor.

GC, F. Domingo, PRD86 (2012) 115024; G. Bélanger, V. Bizouard, GC, PRD89 (2014) 9, 095023

- We know $m_h^{\mathrm{SM}} \equiv m_H$ gets large rad. cor.
- To get the right kinematics for its decays, better take $m_H^{\mathrm{corr}} = \sqrt{s}$ on the external leg for comparison with exp.

LPT Orsay

GC, F. Domingo, PRD86 (2012) 115024; G. Bélanger, V. Bizouard, GC, PRD89 (2014) 9, 095023

- We know $m_h^{\mathrm{SM}} \equiv m_H$ gets large rad. cor.
- To get the right kinematics for its decays, better take $m_H^{\mathrm{corr}} = \sqrt{s}$ on the external leg for comparison with exp.
- Couplings of H to scalars/Goldstones also $\propto m_H \longrightarrow$ one should ensure that $m_H^{\mathrm{kin}} \equiv m_H^{\mathrm{coup}}$ to maintain gauge invariance

LPT Orsay

GC, F. Domingo, PRD86 (2012) 115024; G. Bélanger, V. Bizouard, GC, PRD89 (2014) 9, 095023

- We know $m_h^{\rm SM} \equiv m_H$ gets large rad. cor.
- To get the right kinematics for its decays, better take $m_H^{\rm corr} = \sqrt{s}$ on the external leg for comparison with exp.
- Couplings of H to scalars/Goldstones also $\propto m_H \longrightarrow$ one should ensure that $m_H^{\rm kin} \equiv m_H^{\rm coup}$ to maintain gauge invariance
- Define an effective rad. Higgs potential

LPT Orsay

GC, F. Domingo, PRD86 (2012) 115024; G. Bélanger, V. Bizouard, GC, PRD89 (2014) 9, 095023

- We know $m_h^{\mathrm{SM}} \equiv m_H$ gets large rad. cor.
- To get the right kinematics for its decays, better take $m_H^{\mathrm{corr}} = \sqrt{s}$ on the external leg for comparison with exp.
- Couplings of H to scalars/Goldstones also $\propto m_H$ $\longrightarrow$ one should ensure that $m_H^{\mathrm{kin}} \equiv m_H^{\mathrm{coup}}$ to maintain gauge invariance
- Define an effective rad. Higgs potential

$$
\begin{aligned}
\mathcal{V}^S_{\mathrm{rad.}} \quad = & \quad m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + \frac{\lambda_1}{2}|H_d|^4 + \frac{\lambda_2}{2}|H_u|^4 + \lambda_3|H_u|^2|H_d|^2 + \lambda_4|H_u\cdot H_d|^2 \\
+ & \quad m_S^2|S|^2 + \kappa^2|S|^4 + \left[\frac{A_S}{3}S^3 + h.c.\right] \\
+ & \quad \lambda_P^u|S|^2|H_u|^2 + \lambda_P^d|S|^2|H_d|^2 + \left[A_{ud}SH_u\cdot H_d + \lambda_P^M S^{*\,2}H_u\cdot H_d + h.c.\right]
\end{aligned}
$$

The tree-level conditions resulting from the NMSSM read:

$$
\begin{aligned}
&\lambda_1^0 = \frac{g^2+g'^2}{4} = \lambda_2^0 \quad ; \lambda_3^0 = \frac{g^2-g'^2}{4} \quad ; \lambda_4^0 = \lambda^2 - \frac{g^2}{2} \quad ; \lambda_P^{u\,0} = \lambda^2 = \lambda_P^{d\,0} \; ; \\
&\lambda_P^{M\,0} = \lambda\kappa \quad ; A_S^0 = \kappa A_\kappa \quad ; A_{ud}^0 = \lambda A_\lambda \quad ; \kappa^{0\,2} = \kappa^2
\end{aligned}
$$

APPLICATION TO COLLIDERS: HIGGS PHYSICS

GC, F. Domingo, PRD86 (2012) 115024; G. Bélanger, V. Bizouard, GC, PRD89 (2014) 9, 095023

- We know $m_h^{\mathrm{SM}} \equiv m_H$ gets large rad. cor.
- To get the right kinematics for its decays, better take $m_H^{\mathrm{corr}} = \sqrt{s}$ on the external leg for comparison with exp.
- Couplings of H to scalars/Goldstones also $\propto m_H \longrightarrow$ one should ensure that $m_H^{\mathrm{kin}} \equiv m_H^{\mathrm{coup}}$ to maintain gauge invariance
- Define an effective rad. Higgs potential

$$
\begin{aligned}
\mathcal{V}^S_{\mathrm{rad.}} \quad = \quad & m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + \frac{\lambda_1}{2}|H_d|^4 + \frac{\lambda_2}{2}|H_u|^4 + \lambda_3|H_u|^2|H_d|^2 + \lambda_4|H_u \cdot H_d|^2 \\
+ \quad & m^2_S|S|^2 + \kappa^2|S|^4 + \left[\frac{A_S}{3}S^3 + h.c.\right] \\
+ \quad & \lambda_P^u|S|^2|H_u|^2 + \lambda_P^d|S|^2|H_d|^2 + \left[A_{ud}SH_u \cdot H_d + \lambda_P^M S^{*\,2} H_u \cdot H_d + h.c.\right]
\end{aligned}
$$

The tree-level conditions resulting from the NMSSM read:

$$
\begin{aligned}
&\lambda_1^0 = \frac{g^2 + g'^2}{4} = \lambda_2^0 \quad ; \lambda_3^0 = \frac{g^2 - g'^2}{4} \quad ; \lambda_4^0 = \lambda^2 - \frac{g^2}{2} \quad ; \lambda_P^{u\,0} = \lambda^2 = \lambda_P^{d\,0} \; ; \\
&\lambda_P^{M\,0} = \lambda\kappa \quad ; A_S^0 = \kappa A_\kappa \quad ; A_{ud}^0 = \lambda A_\lambda \quad ; \kappa^{0\,2} = \kappa^2
\end{aligned}
$$

Reproduction of the corr. Higgs masses by a redefinition beyond LO such that $\lambda_i = \lambda_i^0 + \Delta\lambda_i$

Orsay

$$
\begin{cases}
\Delta\lambda_1 = \frac{1}{2v^2}\left[\frac{m_{h_i^0}^2 S_{i1}^2}{\cos^2\beta} - m_{a_i^0}^2 P_{i1}^{\prime 2}\tan^2\beta - M_Z^2\right] \\
\Delta\lambda_2 = \frac{1}{2v^2}\left[\frac{m_{h_i^0}^2 S_{i2}^2}{\sin^2\beta} - \frac{m_{a_i^0}^2 P_{i1}^{\prime 2}}{\tan^2\beta} - M_Z^2\right] \\
\Delta\lambda_3 = \frac{1}{2v^2}\left[2m_{H^\pm}^2 + \frac{2m_{h_i^0}^2 S_{i1}S_{i2}}{\sin 2\beta} - m_{a_i^0}^2 P_{i1}^{\prime 2} - 2M_W^2 + M_Z^2\right] \\
\Delta\lambda_4 = \frac{1}{v^2}\left[m_{a_i^0}^2 P_{i1}^{\prime 2} - m_{H^\pm}^2 + M_W^2 - \lambda^2 v^2\right] \\
\Delta A_{ud} = \frac{1}{3}\left[\frac{\sin 2\beta}{s} m_{a_i^0}^2 P_{i1}^{\prime 2} + \frac{1}{v} m_{a_i^0}^2 P'_{i1}P'_{i2}\right] - \lambda A_\lambda \\
\Delta\lambda_P^M = \frac{1}{3s}\left[\frac{\sin 2\beta}{2s} m_{a_i^0}^2 P_{i1}^{\prime 2} - \frac{1}{v} m_{a_i^0}^2 P'_{i1}P'_{i2}\right] - \lambda\kappa \\
\Delta A_S = \frac{1}{3s}\left[\frac{v^2\sin^2 2\beta}{2s^2} m_{a_i^0}^2 P_{i1}^{\prime 2} - m_{a_i^0}^2 P_{i2}^{\prime 2} - \frac{v\sin 2\beta}{2s} m_{a_i^0}^2 P'_{i1}P'_{i2}\right] - \kappa A_\kappa \\
\Delta\kappa^2 = \frac{1}{4s^2}\left[m_{h_i^0}{}^2 S_{i3}^2 + \frac{1}{3} m_{a_i^0}^2 P_{i2}^{\prime 2} - \frac{v^2\sin^2 2\beta}{3s^2} m_{a_i^0}^2 P_{i1}^{\prime 2}\right] - \kappa^2 \\
\Delta\lambda_P^u = \frac{m_{h_i^0}^2 S_{i2}S_{i3}}{2sv\sin\beta} + \frac{1}{3s\tan\beta}\left[\frac{\sin 2\beta}{s} m_{a_i^0}^2 P_{i1}^{\prime 2} - \frac{1}{2v} m_{a_i^0}^2 P'_{i1}P'_{i2}\right] - \lambda^2 \\
\Delta\lambda_P^d = \frac{m_{h_i^0}^2 S_{i1}S_{i3}}{2sv\cos\beta} + \frac{\tan\beta}{3s}\left[\frac{\sin 2\beta}{s} m_{a_i^0}^2 P_{i1}^{\prime 2} - \frac{1}{2v} m_{a_i^0}^2 P'_{i1}P'_{i2}\right] - \lambda^2
\end{cases}
$$

- This form of $\mathcal{V}^S_{\mathrm{rad.}}$ is accurate at LL level. Implemented in SLOOPS