$\tan\beta$ in the MSSM
Definitions, Gauge Invariance, Scheme Dependence
Applications

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based on arXiv:0710.1821, 0807.4668 and 0906.1665

The Higgs Potential, in the MSSM at tree-level

$$V = m_1^2|H_1|^2 + m_2^2|H_2|^2 + m_{12}^2(H_1 \wedge H_2 + h.c.)$$
$$+ \frac{1}{8}(g^2 + g'^2)(|H_1|^2 - |H_2|^2)^2 + \frac{g^2}{2}|H_1^\dagger H_2|^2$$

with $H_1 \wedge H_2 = H_1^a H_2^b \epsilon_{ab} \quad (\epsilon_{12} = -\epsilon_{21} = 1, \epsilon_{ii} = 0)$.

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} = \begin{pmatrix} (v_1 + \phi_1^0 - i\varphi_1^0)/\sqrt{2} \\ -\varphi_1^- \end{pmatrix}, \quad Y_{H_1} = -1$$

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Opposite hypercharges , in principle distinguishable

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$$V = V_{const} + V_{linear} + V_{mass} + V_{cubic} + V_{quartic} \, ,$$

$$\begin{aligned}
V_{linear} &= T_{\phi_1^0}\phi_1^0 + T_{\phi_2^0}\phi_2^0, \\
V_{mass} &= \frac{1}{2}\begin{pmatrix} \phi_1^0 & \phi_2^0 \end{pmatrix} M^2_{\phi^0} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix} \\
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$$\det(N_{GP}) = 0 \quad \mathrm{Tr}(N_{GP}) = v_1^2 + v_2^2$$

Tadpoles and invariants

- The requirement that v_1 and v_2 correspond to the true vacua is a requirement on the vanishing of the tadpoles. $T_{\phi^0_{1,2}} = 0$ can be seen as a trade off for m_1^2 and m_2^2.
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M^2_{H^\pm} &= M^2_{A^0} + M^2_{W^\pm} \quad \text{from } \mathrm{Tr}\left(M^2_{\varphi^\pm}\right)\,. \\
M^2_{h^0} + M^2_{H^0} &= M^2_{A^0} + M^2_{Z^0} \quad \text{from } \mathrm{Tr}\left(M^2_{\phi^0}\right) \\
M^2_{h^0}\, M^2_{H^0} &= M^2_{A^0}\, M^2_{Z^0}\, c^2_{2\beta} \quad \text{from } \det\left(M^2_{\varphi^0}\right)\,.
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Usually one takes $M_{A^0}, M_{Z^0}(v^2), t_\beta(c^2_{2\beta})$ as input parameters, and derive M_{H^0} and M_{h^0}

but **what is $\tan\beta$?**

Basis and Rotations

The mass eigenstates in the Higgs sector are given, through rotation, by

$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = U(\beta) \begin{pmatrix} \varphi_1^0 \\ \varphi_2^0 \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \varphi_1^0 \\ \varphi_2^0 \end{pmatrix},$$

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At the quantum level mixing between fields will be re-introduced, (like in the SM $Z-\gamma$ mixing,..) and one has to re-diagonaliseagain,
not exactly the same and equivalent as to how $\tan\beta$ will be renormalised, defined

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- scheme dependence

  in particular this means that the corresponding counterterm (choice of input/definition) even if gauge invariant and leads to finite results has to be a good one: the (finite) corrections should not be excessively large because of a bad choice of input

  (perturbation should be maintained or trusted).

Higgs Potential

Higgs Potential

Higgs masses

Couplings of Higgses to fermions

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Higgs masses

Couplings of Higgses to fermions

D terms fermion masses,...,

chargino and neutralino properties (mixing)

Practical, gauge parameter independence through a generalised gauge-fixing

slightly a be a bit more formal is Freitas-Stockinger hep-ph/0205281

Non-linear gauge implementation

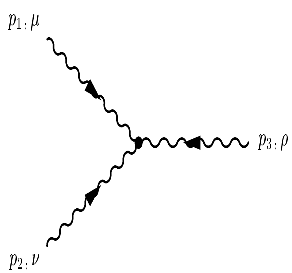
$$\mathcal{L}_{GF} = -\frac{1}{\xi_W}|\partial.W^+ + \xi_W \frac{g}{2} v G^+|^2$$
$$-\frac{1}{2\xi_Z}(\partial.Z + \xi_Z \frac{g}{2c_W} v + G^0)^2 - \frac{1}{2\xi_\gamma}(\partial.A)^2$$

This only affects the propagators. Usually calculations done with $\xi = 1$, otherwise large expressions, higher rank tensors, unphysical thresholds,..

$$\frac{1}{k^2 - M_W^2}\left(g_{\mu\nu} - (1-\xi_W)\frac{k_\mu k_\nu}{k^2 - \xi_W M_W^2}\right)$$

$$\mathcal{L}_{GF} = -\frac{1}{\xi_W}|(\partial_\mu - ie\tilde{\alpha}A_\mu - igc_W\tilde{\beta}Z_\mu)W^{\mu\,+} + \xi_W\frac{g}{2}(v + \tilde{\delta}h + \tilde{\omega}H + i\tilde{\rho}A^0 + i\tilde{\kappa}G^0)G^+|^2$$
$$-\frac{1}{2\xi_Z}(\partial.Z + \xi_Z\frac{g}{2c_W}(v + \tilde{\epsilon}h + \tilde{\gamma}H)G^0)^2 - \frac{1}{2\xi_\gamma}(\partial.A)^2$$

- quite a handful of gauge parameters, but with $\xi_i = 1$, no “unphysical threshold”, no higher rank tensors, gauge parameter dependence in gauge/Goldstone/ghosts vertices.
- more important: no need for higher (than the minimal set)for higher rank tensors and tedious algebraic manipulations



p_1 (μ)	p_2 (ν)	p_3 (ρ)	
W^-	W^+	A	$e\Big[g^{\mu\nu}(p_1-p_2)^\rho$ $+(1+\tilde{\alpha}/\xi_W)(p_3^\nu g^{\mu\rho} - p_3^\mu g^{\nu\rho})$ $+(1-\tilde{\alpha}/\xi_W)(p_2^\mu g^{\nu\rho} - p_1^\nu g^{\mu\rho})\Big]$
W^-	W^+	Z	$e\frac{c_W}{s_W}\Big[g^{\mu\nu}(p_1-p_2)^\rho$ $+(1+\tilde{\beta}/\xi_W)(p_3^\nu g^{\mu\rho} - p_3^\mu g^{\nu\rho})$ $+(1-\tilde{\beta}/\xi_W)(p_2^\mu g^{\nu\rho} - p_1^\nu g^{\mu\rho})\Big]$

- we take the gauge fixing to be renormalised (not necessary to have *all* Green’s functions finite.)

- From $X_L = (m_1, m_2, m_{12}, g, g', v_1, v_2)$ we take e, M_W, M_Z (as in SM) and $M_{A^0}, T_{\phi_1^0}, T_{\phi_2^0}$; On Shell scheme, GI with "t_β" to be defined.

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- shifts in parameters $X_L \rightarrow X_L + \delta X_L$ implies $e \rightarrow e + \delta e, T_{\phi_1^0} \rightarrow T_{\phi_1^0} + \delta T_{\phi_1^0}, \cdots v_i \rightarrow v_i - \delta v_i (t_\beta \rightarrow t_\beta + \delta t_\beta)$

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- In any case filed renormalisation (before or after rotation) still needed this will imply

$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix}_0 = \overbrace{U(\beta) Z_{\varphi^0} U(-\beta)}^{Z_P} \begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} Z^{1/2}_{G^0 G^0} & Z^{1/2}_{G^0 A^0} \\ Z^{1/2}_{A^0 G^0} & Z^{1/2}_{A^0 A^0} \end{pmatrix} \begin{pmatrix} G^0 \\ A^0 \end{pmatrix}.$$

Example of two-point functions

$$\left\{ \begin{array}{l} \hat{\Sigma}_{G^0 G^0}(q^2) = \Sigma_{G^0 G^0}(q^2) + \delta M^2_{G^0} - q^2 \delta Z_{G^0} \\ \hat{\Sigma}_{G^0 A^0}(q^2) = \Sigma_{G^0 A^0}(q^2) + \delta M^2_{G^0 A^0} - \frac{1}{2} q^2 \delta Z_{G^0 A^0} - \frac{1}{2}(q^2 - M^2_{A^0}) \delta Z_{A^0 G^0} \\ \hat{\Sigma}_{A^0 A^0}(q^2) = \Sigma_{A^0 A^0}(q^2) + \delta M^2_{A^0} - (q^2 - M^2_{A^0}) \delta Z_{A^0} \end{array} \right.$$

$$\left\{ \begin{array}{l} \hat{\Sigma}_{G^\pm G^\pm}(q^2) = \Sigma_{G^\pm G^\pm}(q^2) + \delta M^2_{G^\pm} - q^2 \delta Z_{G^\pm} \\ \hat{\Sigma}_{G^\pm H^\pm}(q^2) = \Sigma_{G^\pm H^\pm}(q^2) + \delta M^2_{G^\pm H^\pm} - \frac{1}{2} q^2 \delta Z_{G^\pm H^\pm} - \frac{1}{2}(q^2 - M^2_{H^\pm}) \delta Z_{H^\pm G^\pm} \\ \hat{\Sigma}_{H^\pm H^\pm}(q^2) = \Sigma_{H^\pm H^\pm}(q^2) + \delta M^2_{H^\pm} - (q^2 - M^2_{H^\pm}) \delta Z_{H^\pm} \end{array} \right.$$

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Renormalisation Conditions, On-Shell in...Nut Shell

- (e, M_W, M_Z) as in the SM
- The minimum condition requires the one-loop tadpole contribution generated by one-loop diagrams, $T^{\text{loop}}_{\phi_i^0}$ is cancelled by the tadpole counterterm. $\delta T_{\phi_i^0} = -T^{\text{loop}}_{\phi_i^0}$
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What about A^0Z^0 and A^0G^0 transitions?

Dabelstein-Chankowski-Pokorski-Rosiek Scheme (DCPR)

$$\frac{\delta t_\beta}{t_\beta}^{\text{DCPR}} = -\frac{1}{M_{Z^0} s_{2\beta}} Re\Sigma_{A^0 Z^0}(M_{A^0}^2) \, .$$

This is not gauge invariant! based on $\hat{\Sigma}_{A^0 Z^0}(M_{A^0}^2) = 0$ which is widely used (together with $\hat{\Sigma}_{A^0 G^0}(M_{A^0}^2) = 0$) but which is not true in all gauges.
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Moreover in our approach $\delta Z_{G^0 A^0}$ and $\delta \tan\beta$ come together

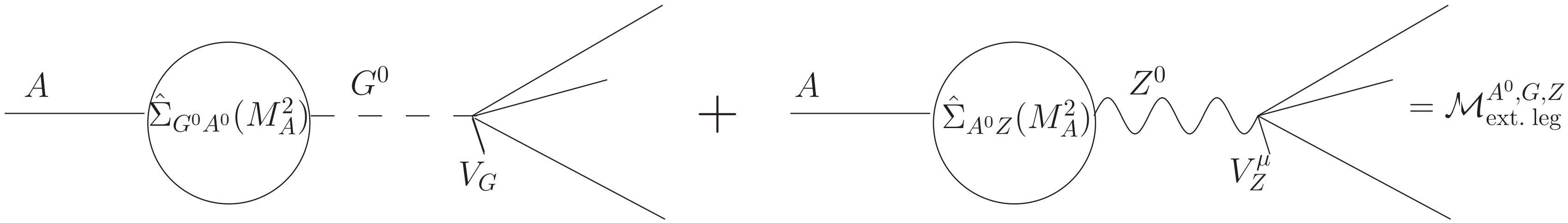
$$\hat{\Sigma}_{A^0 Z^0}(q^2) = \Sigma_{A^0 Z^0}(q^2) + \frac{M_{Z^0}}{2}\left(\delta Z_{G^0 A^0} + s_{2\beta}\frac{\delta t_\beta}{t_\beta}\right)$$

BRST transformation on the ("ghost") operator
$\langle 0|\overline{c}^{Z}(x)A^0(y)|0\rangle = 0, \longrightarrow$

$$q^2\hat{\Sigma}_{A^0Z^0}(q^2) \quad + \quad M_{Z^0}\hat{\Sigma}_{A^0G^0}(q^2) = (q^2 - M_{Z^0}^2)\frac{1}{(4\pi)^2}\frac{e^2 M_{Z^0}}{s_{2W}^2}s_{2\beta}\mathcal{F}_{GA}^{\tilde{\epsilon},\tilde{\gamma}}(q^2)$$
$$+ \quad \frac{M_{Z^0}}{2}(q^2 - M_{A^0}^2)\left(\frac{1}{(4\pi)^2}\frac{2e^2}{s_{2W}^2}\mathcal{F}_{cc}^{\tilde{\epsilon},\tilde{\gamma}}(q^2) + s_{2\beta}\frac{\delta t_\beta}{t_\beta} - \delta Z_{A^0G^0}\right).$$

$\mathcal{F}_{GA}^{\tilde{\epsilon},\tilde{\gamma}}(q^2)$ and $\mathcal{F}_{cc}^{\tilde{\epsilon},\tilde{\gamma}}(q^2)$ are functions which vanish in the linear gauge with $\tilde{\epsilon} = \tilde{\gamma} = 0$.
The constraint shows that even in the linear gauge $q^2\hat{\Sigma}_{A^0Z^0}(q^2) + M_{Z^0}\hat{\Sigma}_{A^0G^0}(q^2)$ is zero only for $q^2 = M_{A^0}^2$ and not for *any* q^2.
but in linear gauge can impose both $\hat{\Sigma}_{A^0Z^0}(M_A^2) = \hat{\Sigma}_{A^0G^0}(M_A^2) = 0$
no longer in a general gauge!
similar thing in the charged sector

we can still avoid one-loop corrections and counterterms in the external legs associated with an external pseudoscalar A^0. Of concern to us are the transition $A^0 - Z^0$ and $A^0 - G^0$.



$$\mathcal{M}^{A^0,G,Z}_{\rm ext.\ leg} = \frac{\hat{\Sigma}_{A^0G^0}(M_{A^0}^2)V_G \; + \; q.V_Z\hat{\Sigma}_{A^0Z^0}(M_{A^0}^2)}{M_{A^0}^2 - M_{Z^0}^2}$$

$$= \frac{V_G}{M_{A^0}^2 - M_{Z^0}^2}\left(\hat{\Sigma}_{A^0G^0}(M_{A^0}^2) \; + \; M_{Z^0}\hat{\Sigma}_{A^0Z^0}(M_{A^0}^2)\right) .$$

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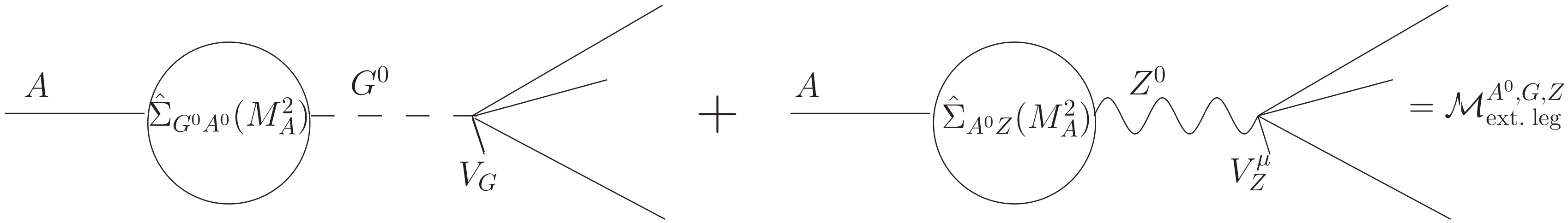

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impose

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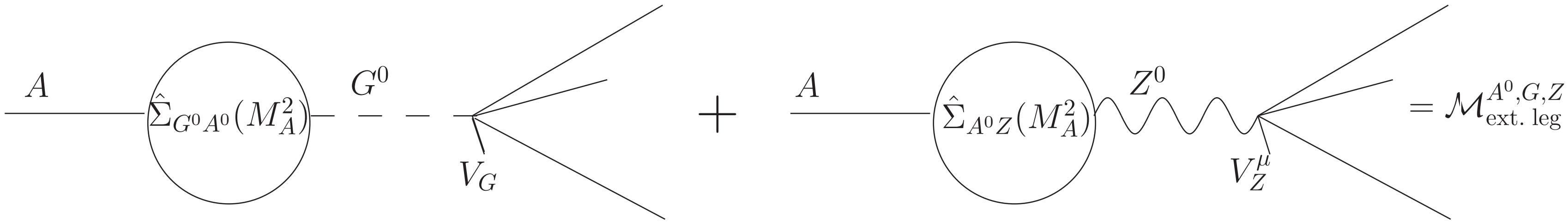

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To be consistent with the Ward identity

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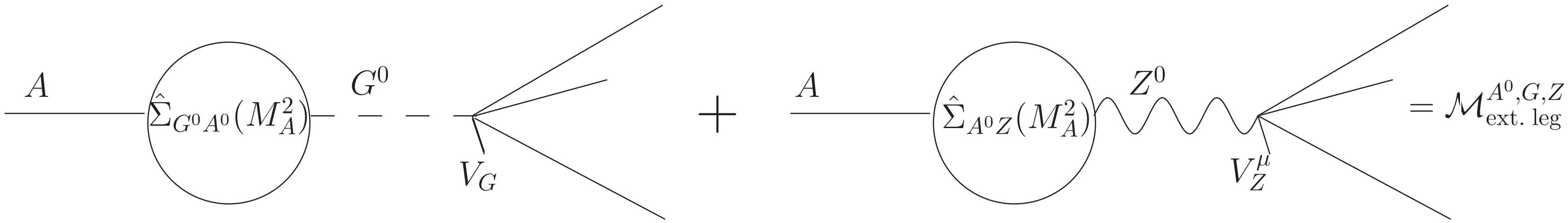

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$$\delta Z_{G^0A^0} = -s_{2\beta}\frac{\delta t_\beta}{t_\beta} - 2\frac{\Sigma^{\rm tad}_{A^0Z^0}(M^2_{A^0})}{M_{Z^0}} + \frac{2}{(4\pi)^2}\frac{e^2}{s^2_{2W}}s_{2\beta}\mathcal{F}^{\tilde{\epsilon},\tilde{\gamma}}_{GA}(M^2_{A^0}) .$$

- $A_{\tau\tau}$-scheme.

$$\mathcal{L}^0_{A_{\tau\tau}} == i\frac{gm_\tau}{2M_{W^\pm}} \tan\beta\, \bar{\tau}\gamma_5\tau\, A^0$$

- t_β is extracted from the decay $A^0 \rightarrow \tau^+\tau^-$ to which the QED corrections have been subtracted, which in this neutral decay constitutes a gauge invariant subset. This leads to a gauge-independent counterterm and is physically unambiguous defined. Not exactly a definition from within the Higgs potential but nonetheless from Higgs physics/phenomenology.
- Criticism that it is not defined from $2-$point functions is unfounded. Remember G_μ/M_W. Technically one has the tools
- sure it is flavour dependent But, one needs to measure this partial width with enough precision. !

- $DCPR$-scheme .

$$\frac{\delta t_\beta}{t_\beta}^{DCPR} = -\frac{1}{M_Z s_{2\beta}} Re\Sigma_{A^0 Z^0}(M^2_{A^0})\,.$$

(in DCPR $H_i \to (1+\frac{1}{2}\delta Z_{H_i})H_i \;\; i=1,2$, then $v_i \to v_i\left(1-\frac{\tilde{\delta} v_i}{v_i}+\frac{1}{2}\delta Z_{H_i}\right)$
impose $\frac{\tilde{\delta} v_1}{v_1}=\frac{\tilde{\delta} v_2}{v_2}$ such that in effect $\frac{\delta t_\beta}{t_\beta}=\frac{1}{2}(\delta Z_{H_2}-\delta Z_{H_1})$,
a physical quantity related to a wave function renormalisation constant is (almost) always dubious!)

- MH-scheme.

$Re\hat{\Sigma}_{H^0H^0}(M^2_{H^0}) = 0$

Here the heaviest CP-even Higgs mass M_{H^0} is taken as input. This definition is obviously gauge independent and process independent, but expect it to be unstable

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$$t_\beta = \sqrt{\frac{M_{A^0}M_{Z^0} + M_{H^0}\sqrt{M^2_{A^0} + M^2_{Z^0} - M^2_{H^0}}}{M_{A^0}M_{Z^0} - M_{H^0}\sqrt{M^2_{A^0} + M^2_{Z^0} - M^2_{H^0}}}}\,.$$

$$\frac{\delta t_\beta}{t_\beta} \simeq \frac{1}{M^2_{H^0}/M^2_{A^0} - 1}\left(-\frac{\delta M^2_{A^0}}{M^2_{A^0}} + \frac{\delta M^2_{H^0}}{M^2_{H^0}}\right)\,.$$

$\longrightarrow 0$ in the decoupling regime

- $\overline{DR}$-scheme.

  - In this scheme the counterterm for $\tan\beta$ is taken (from some quantity to be a pure divergence proportional to the ultraviolet (UV) factor, $C_{UV} = 1/\epsilon + ...$, in dimensional reduction.
  - In HHW prescription of Hollik, Heinemeyer and Weiglein (not GI in general) $\frac{\delta t_\beta}{t_\beta}^{\overline{\text{DR}}-\text{HHW}} = \frac{1}{2c_{2\alpha}}(Re\Sigma'_{h^0h^0}(M^2_{h^0}) - Re\Sigma'_{H^0H^0}(M^2_{H^0}))^\infty$.
  - Pierce and Papadopoulos have defined δt_β by relating it to the *divergent* part of $M^2_{H^0} - M^2_{h^0}$ (GI)

Examples, non gauge invariance

Parameter	Value
s_W	0.48076
e	0.31345
g_s	1.238
M_{Z^0}	91.1884
m_e	0.000511

Parameter	Value
m_μ	0.1057
m_τ	1.777
m_u	0.046
m_d	0.046
m_c	1.42

Constant	Value
m_s	0.2
m_t	174.3
m_b	3
M_{A^0}	500
t_β	3;50

mhmax	Value
μ	-200
M_2	200
M_3	800
$M_{\tilde{F}_L}$	1000
$M_{\tilde{f}_R}$	1000
A_f	2000+μ/t_β

nomix	Value
μ	-200
M_2	200
M_3	800
$M_{\tilde{F}_L}$	1000
$M_{\tilde{f}_R}$	1000
A_f	μ/t_β

large μ	Value
μ	1000
M_2	400
M_3	200
$M_{\tilde{F}_L}$	400
$M_{\tilde{f}_R}$	400
A_f	-300+μ/t_β

Examples, finite and infinite part of $\tan\beta$

$$\delta t_\beta = \delta t_\beta^{\mathsf{fin}} + \delta t_\beta^{\infty} C_{UV}$$

$$\mathrm{nlgs} = 10 \rightarrow \tilde{\alpha} = 10, \tilde{\beta} = 10, \ldots\ldots\ldots$$

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δt_β^{∞}	nlgs = 0	nlgs = 10
DCPR	-3.19$\times 10^{-2}$	-1.04 $\times 10^{-1}$
OS_{M_H}	-3.19$\times 10^{-2}$	-3.19$\times 10^{-2}$
$\text{OS}_{A_{\tau\tau}}$	-3.19$\times 10^{-2}$	-3.19$\times 10^{-2}$
$\overline{\text{DR}}$-HHW	-3.19$\times 10^{-2}$	+5.32 $\times 10^{-2}$
$\overline{\text{DR}}$-PP	-3.19$\times 10^{-2}$	-3.19$\times 10^{-2}$

for the set *mhmax* at $t_\beta = 3$.

$$\delta t_\beta = \delta t_\beta^{\text{fin}} + \delta t_\beta^{\infty} C_{UV} \qquad \text{nlgs} = 10 \to \tilde{\alpha} = 10, \tilde{\beta} = 10, \ldots\ldots\ldots$$

δt_β^{∞}	nlgs = 0	nlgs = 10
DCPR	-3.19$\times 10^{-2}$	-1.04 $\times 10^{-1}$
OS_{M_H}	-3.19$\times 10^{-2}$	-3.19$\times 10^{-2}$
$\mathrm{OS}_{A_{\tau\tau}}$	-3.19$\times 10^{-2}$	-3.19$\times 10^{-2}$
$\overline{\text{DR}}$-HHW	-3.19$\times 10^{-2}$	+5.32 $\times 10^{-2}$
$\overline{\text{DR}}$-PP	-3.19$\times 10^{-2}$	-3.19$\times 10^{-2}$

$\delta t_\beta^{\text{fin}}$	nlgs = 0	nlgs = 10
DCPR	-0.10	-0.27
OS_{M_H}	+0.92 (30%)	+0.92 (30%)
$\mathrm{OS}_{A_{\tau\tau}}$	-0.10 (3%)	-0.10 (3%)
$\overline{\text{DR}}$-HHW	0	0
$\overline{\text{DR}}$-PP	0	0

for the set *mhmax* at $t_\beta = 3$.

scheme dependence in the usual linear gauge (finite part) with $\xi_{W,Z,\gamma}=1$

$t_\beta = 3$	*mhmax*	*large* μ	*nomix*	$t_\beta = 50$	*mhmax*	*large* μ	*nomix*
DCPR	-0.10	-0.06	-0.08	DCPR	+3.42	+14.57	+0.48
OS_{M_H}	+0.92	-1.31	+0.64	OS_{M_H}	-385.53	-2010.84	-290.18
$\mathrm{OS}_{A_{\tau\tau}}$	-0.10	-0.06	-0.08	$\mathrm{OS}_{A_{\tau\tau}}$	+0.12	-4.72	+0.16
$\overline{\mathrm{DR}}$	0	0	0	$\overline{\mathrm{DR}}$	0	0	0

$$\frac{\delta t_\beta}{t_\beta}^{DCPR} \simeq -\frac{t_\beta}{s_{2\beta}}\frac{g^2}{c_W^2 M_Z^2}\frac{1}{4\pi^2}\left(3m_b^2 B_0(M_{A^0}^2, m_b^2, m_b^2) + m_\tau^2 B_0(M_{A^0}^2, m_\tau^2, m_\tau^2)\right) .$$

$$\propto \quad t_\beta^2$$

Examples, Mass of M_h

$t_\beta = 3$	*mhmax*	*large* μ	*nomix*
$M_{h^0}^{TL} = 72.51$			
DCPR	134.28	97.57	112.26
OS_{M_H}	140.25	86.68	117.37
$\mathrm{OS}_{A_{\tau\tau}}$	134.25	97.59	112.27
$\overline{\mathrm{DR}}$ $\overline{\mu} = M_{A^0}$	134.87	98.10	112.86
$\overline{\mathrm{DR}}$ $\overline{\mu} = M_t$	134.47	97.55	112.38

$t_\beta = 50$	*mhmax*	*large* μ	*nomix*
$M_{h^0}^{TL} = 91.11$			
DCPR	144.50	35.88	124.80
OS_{M_H}	143.76	13.21	124.16
$\mathrm{OS}_{A_{\tau\tau}}$	144.50	35.73	124.80
$\overline{\mathrm{DR}}$ $\overline{\mu} = M_{A^0}$	144.50	35.77	124.80
$\overline{\mathrm{DR}}$ $\overline{\mu} = M_t$	144.50	35.77	124.80

$A^0 \to \tau^+\tau^-$, the non QED one-loop corrections

$t_\beta = 3$	*mhmax*	*large* μ	*nomix*
$\Gamma^{TL} = 9.40 \times 10^{-3}$			
DCPR	+3.56$\times 10^{-5}$	-8.71$\times 10^{-6}$	-7.37$\times 10^{-6}$
OS_{M_H}	+6.41$\times 10^{-3}$	-7.82$\times 10^{-3}$	+4.56$\times 10^{-3}$
$\mathrm{OS}_{A_{\tau\tau}}$	0	0	0
$\overline{\text{DR}}$ $\overline{\mu} = M_{A^0}$	+6.51$\times 10^{-4}$	+3.94$\times 10^{-4}$	+5.18$\times 10^{-4}$
$\overline{\text{DR}}$ $\overline{\mu} = M_t$	+2.30$\times 10^{-4}$	-2.66$\times 10^{-5}$	+9.67$\times 10^{-5}$

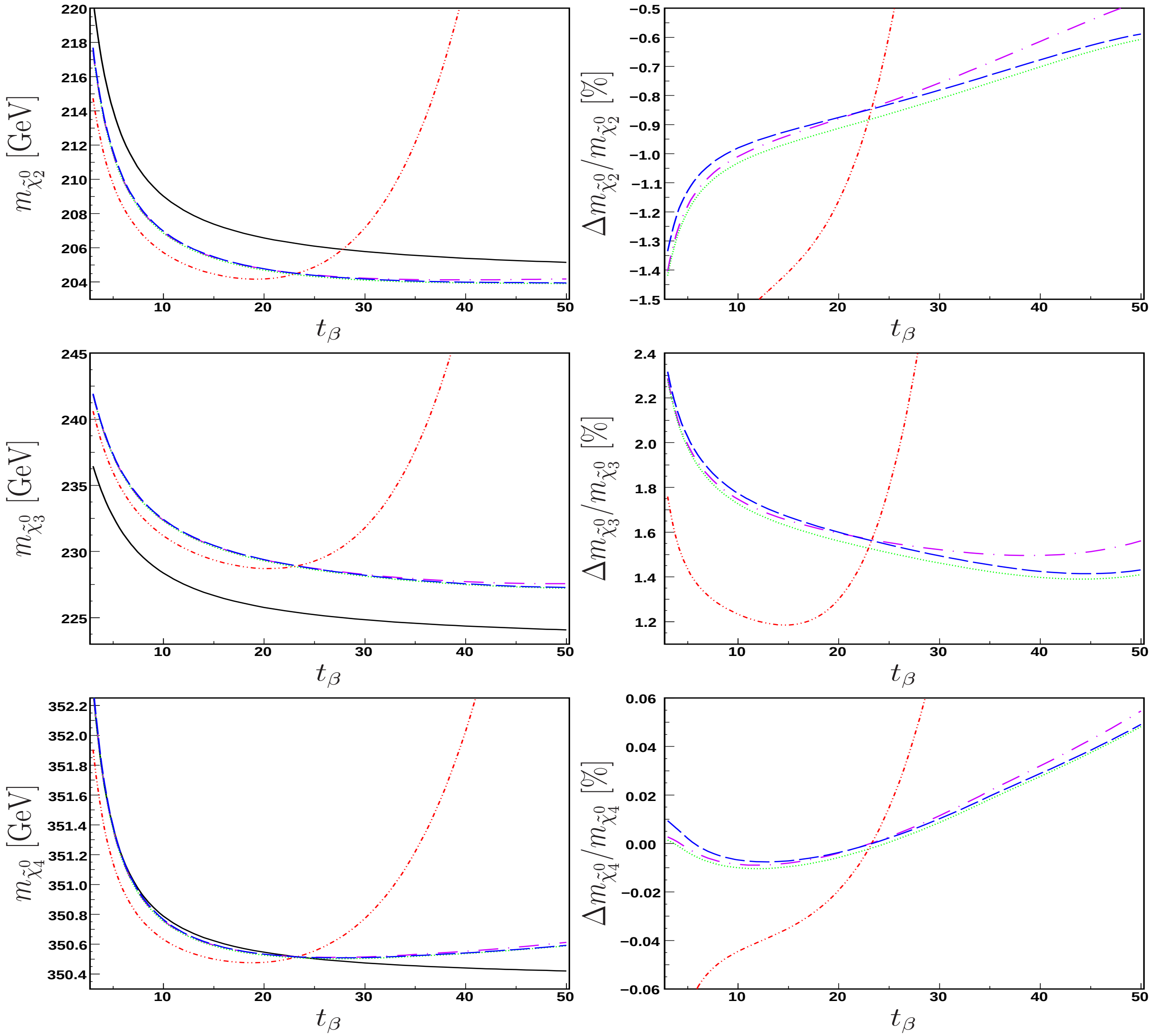
$t_\beta = 50$	*mhmax*	*large* μ	*nomix*
$\Gamma^{TL} = 2.61 \times 10^{0}$			
DCPR	+3.45$\times 10^{-1}$	+2.01$\times 10^{0}$	+3.35$\times 10^{-2}$
OS_{M_H}	-4.03$\times 10^{1}$	-2.09$\times 10^{2}$	-3.03$\times 10^{1}$
$\mathrm{OS}_{A_{\tau\tau}}$	0	0	0
$\overline{\text{DR}}$ $\overline{\mu} = M_{A^0}$	-1.21$\times 10^{-2}$	+4.92$\times 10^{-1}$	-1.66$\times 10^{-2}$
$\overline{\text{DR}}$ $\overline{\mu} = M_t$	-3.00$\times 10^{-2}$	+4.75$\times 10^{-1}$	-3.44$\times 10^{-2}$

$H^0 \to Z^0 Z^0$ and $A^0 \to Z^0 h^0$ (suppressed at tree-level)

$t_\beta = 3$	*mhmax*	*large* μ	*nomix*
$\Gamma^{TL} = 8.97 \times 10^{-3}$			
DCPR	+1.59$\times 10^{-2}$	-6.32$\times 10^{-3}$	+8.47$\times 10^{-3}$
OS_{M_H}	+1.40$\times 10^{-2}$	-4.00$\times 10^{-3}$	+7.12$\times 10^{-3}$
$\mathrm{OS}_{A_{\tau\tau}}$	+1.59$\times 10^{-2}$	-6.32$\times 10^{-3}$	+8.47$\times 10^{-3}$
$\overline{\text{DR}}$ $\overline{\mu} = M_{A^0}$	+1.57$\times 10^{-2}$	-6.44$\times 10^{-3}$	+8.32$\times 10^{-3}$
$\overline{\text{DR}}$ $\overline{\mu} = M_t$	+1.58$\times 10^{-2}$	-6.32$\times 10^{-3}$	+8.44$\times 10^{-3}$

$t_\beta = 50$	*mhmax*	*large* μ	*nomix*
$\Gamma^{TL} = 6.40 \times 10^{-5}$			
DCPR	+2.18$\times 10^{-5}$	-5.14$\times 10^{-4}$	+3.89$\times 10^{-5}$
OS_{M_H}	+1.01$\times 10^{-2}$	+4.66$\times 10^{-3}$	+7.81$\times 10^{-4}$
$\mathrm{OS}_{A_{\tau\tau}}$	+3.02$\times 10^{-5}$	-4.65$\times 10^{-4}$	+3.97$\times 10^{-5}$
$\overline{\text{DR}}$ $\overline{\mu} = M_{A^0}$	+3.05$\times 10^{-5}$	-4.77$\times 10^{-4}$	+4.01$\times 10^{-5}$
$\overline{\text{DR}}$ $\overline{\mu} = M_t$	+3.09$\times 10^{-5}$	-4.76$\times 10^{-4}$	+4.05$\times 10^{-5}$

Neutralino masses, ($M_A = 100$GeV)



Tree-level and at one-loop by using the $A_{\tau\tau}$-scheme, the $\overline{DR}$ scheme the $DCPR$-scheme and the MH-scheme as a function of t_β.

Conclusions 1

- Many more examples, for other decays and cross sections (including relic density calc.), worked out and scheme dependence investigated

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- MH-scheme is GI but most often not recommended (cancelation of large terms from 2-point function of CP even Higgses in Higgs sector not at work), true for other formal GI schemes defined from the Higgs potential (see Freitas and Stockinger, hep-ph-0205281)

- DCPR not GI and even in linear gauge may also show problems, introduces large corrections, for high $\tan\beta$

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- Issue of mixing very subtle (renormalisation of CKM matrix in the SM, many people), sfermion mixing in the MSSM (see Baro and FB'09, Espinosa and Yamada hep-ph/0207351)
- Scheme dependence of the MSSM needs to be further studied

SLOOPS

N. Baro, FB, G. Chalons, S. Hao, Ninh Le Duc, A. Semenov, (D. Temes)

- Need for an automatic tool for susy calculations
- handles large numbers of diagrams both for tree-level
- and loop level
- able to compute loop diagrams at $v = 0$: dark matter, LSP, move at galactic velocities, $v = 10^{-3}$
- ability to check results: UV and IR finiteness but also gauge parameter independence for example
- ability to include different models easily and switch between different renormalisation schemes
- Used for SM one-loop multi-leg: new powerful loop libraries (with Ninh Le Duc)

Strategy: Exploiting and interfacing modules from different codes

Lagrangian of the model defined in LanHEP

- particle content
- interaction terms
- shifts in fields and parameters
- ghost terms constructed by BRST

$\downarrow$ $\qquad\qquad$ $\downarrow$

Generic Model
-kinematical structures

Classes Model
-Feynman rules, including CT

$\Downarrow$

Evaluation via FeynArts-FormCalc

LoopTools modified!!
tensor reduction inappropriate for small relative velocities
(Zero Gram determinants)

$\Uparrow$

Renormalisation scheme

- definition of renorm. const. in the classes model

Non-Linear gauge-fixing constraints, gauge parameter dependence checks

From the Lagrangian to the Feynman Rules

```
vector
    A/A: (photon, gauge),
    Z/Z:('Z boson', mass MZ = 91.1875, gauge),
    'W+'/'W-': ('W boson', mass MW = MZ*CW, gauge).
scalar  H/H:(Higgs, mass MH = 115).



transform A->A*(1+dZAA/2)+dZAZ*Z/2, Z->Z*(1+dZZZ/2)+dZZA*A/2,
    'W+'->'W+'*(1+dZW/2),'W-'->'W-'*(1+dZW/2).
transform H->H*(1+dZH/2), 'Z.f'->'Z.f'*(1+dZZf/2),
    'W+.f'->'W+.f'*(1+dZWf/2),'W-.f'->'W-.f'*(1+dZWf/2).

let pp = { -i*'W+.f',  (vev(2*MW/EE*SW)+H+i*'Z.f')/Sqrt2 },
PP=anti(pp).



lterm -2*lambda*(pp*anti(pp)-v**2/2)**2
     where
    lambda=(EE*MH/MW/SW)**2/16, v=2*MW*SW/EE .

let Dpp^mu^a = (deriv^mu+i*g1/2*B0^mu)*pp^a +
     i*g/2*taupm^a^b^c*WW^mu^c*pp^b.
let DPP^mu^a = (deriv^mu-i*g1/2*B0^mu)*PP^a
    -i*g/2*taupm^a^b^c*{'W-'^mu,W3^mu,'W+'^mu}^c*PP^b.
lterm DPP*Dpp.
```

Gauge fixing and BRS transformation

```
let G_Z = deriv*Z+(MW/CW+EE/SW/CW/2*nle*H)*'Z.f'.

lterm -G_A**2/2 - G_Wp*G_Wm - G_Z**2/2.

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```

Output of Feynman Rules with Counterterms !!

```
M$CouplingMatrices = {

  (*------    H   H   ------*)
   C[ S[3], S[3] ] == - I *
{
 { 0 , dZH },
 { 0 , MH^2 dZH + dMHsq }
},
  (*------    W+.f   W-.f   ------*)
   C[ S[2], -S[2] ] == - I *
{
 { 0 , dZWf },
 { 0, 0 }
}, (*------    A   Z   ------*)
   C[ V[1], V[2] ] == 1/2 I / CW^2 MW^2 *
{
 { 0, 0 },
 { 0 , dZZA },
 { 0, 0 }
},

(*------    H   H   H   ------*)
   C[ S[3], S[3], S[3] ] == -3/4 I EE / MW / SW *
{
 { 2 MH^2 , 3 MH^2 dZH -2 MH^2 / SW dSW - MH^2 / MW^2 dMWsq
},
  (*------    H  W+.f  W-.f   ------*)
   C[ S[3], S[2], -S[2] ] == -1/4 I EE / MW / SW *
{
 { 2 MH^2 , MH^2 dZH + 2 MH^2 dZWf -2 MH^2 / SW dSW - MH^2 /
},

  (*------    W-.C   A.c   W+   ------*)
   C[ -U[3], U[1], V[3] ] == - I EE *
{
 { 1 },
 { - nla }
},
```

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lterm -'Z.C'*brst(G_Z).
```

```
RenConst[ dMHsq ] := ReTilde[SelfEnergy[prt["H"] -> prt["H"], MH]]
RenConst[ dZH ] := -ReTilde[DSelfEnergy[prt["H"] -> prt["H"], MH]]
RenConst[ dZZf ] := -ReTilde[DSelfEnergy[prt["Z.f"] -> prt["Z.f"],
MZ]] RenConst[ dZWf ] := -ReTilde[DSelfEnergy[prt["W+.f"] ->
prt["W+.f"], MW]]
```

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```
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 { 0 , MH^2 dZH + dMHsq }
},
  (*------    W+.f  W-.f   ------*)
   C[ S[2], -S[2] ] == - I *
{
 { 0 , dZWf },
 { 0, 0 }
}, (*------    A   Z   ------*)
   C[ V[1], V[2] ] == 1/2 I / CW^2 MW^2 *
{
 { 0, 0 },
 { 0 , dZZA },
 { 0, 0 }
},


(*------    H   H   H   ------*)
   C[ S[3], S[3], S[3] ] == -3/4 I EE / MW / SW *
{
 { 2 MH^2 , 3 MH^2 dZH -2 MH^2 / SW dSW - MH^2 / MW^2 dMWsq
},
  (*------    H  W+.f  W-.f   ------*)
   C[ S[3], S[2], -S[2] ] == -1/4 I EE / MW / SW *
{
 { 2 MH^2 , MH^2 dZH + 2 MH^2 dZWf -2 MH^2 / SW dSW - MH^2 /
},

  (*------    W-.C  A.c  W+   ------*)
   C[ -U[3], U[1], V[3] ] == - I EE *
{
 { 1 },
 { - nla }
},
```

Tree Level calculations

Comparison with public codes: Grace and CompHEP

Cross-section [pb]	SloopS	CompHEP	Grace
$h^0 h^0 \to h^0 h^0$	3.932×10^{-2}	3.932×10^{-2}	3.929×10^{-2}
$W^+ W^- \to \tilde{t}_1 \bar{\tilde{t}}_1$	7.082×10^{-1}	7.082×10^{-1}	7.083×10^{-1}
$e^+ e^- \to \tilde{\tau}_1 \bar{\tilde{\tau}}_2$	2.854×10^{-3}	2.854×10^{-3}	2.854×10^{-3}
$H^+ H^- \to W^+ W^-$	6.643×10^{-1}	6.643×10^{-1}	6.644×10^{-1}
Decay [GeV]			
$A^0 \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$	1.137×10^{0}	1.137×10^{0}	1.137×10^{0}
$\tilde{\chi}_1^+ \to \tilde{t} \bar{\tilde{b}}_1$	5.428×10^{0}	5.428×10^{0}	5.428×10^{0}
$H^0 \to \tilde{\tau}_1 \bar{\tilde{\tau}}_1$	7.579×10^{-3}	7.579×10^{-3}	7.579×10^{-3}
$H^+ \to \tilde{\chi}_1^+ \tilde{\chi}_1^0$	1.113×10^{-1}	1.113×10^{-1}	1.113×10^{-1}

... ... # 200 processes checked

- Default: on-shell, GI, renormalisation in **ALL** sectors

SloopS: SUSY renormalisation at one-loop

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- possibility to switch to other schemes easily (DRbar,..)

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- Wave-function renormalisation to get rid of all mixing between *physical fields* when on-shell.
- Issues with definition of $\tan\beta$, many defs not gauge invariant!
- Same for mixing angle in the sfermion sector.
- Good scale dependence of ren. csts.