AUTOMATIC ONE-LOOP CALCULATIONS IN THE MSSM

Nans BARO

Institut für Theoretische Physik E (Aachen)

in collaboration with
Fawzi BOUDJEMA, Guillaume CHALONS and Andrei SEMENOV

GDR SUSY - Orsay [04/12/08]

Minimal Supersymmetric Standard Model

Sectors SM

Fermions	*Bosons*
u, d (Quark)	
e, ν (Lepton)	
	h^0 (Higgs)
	γ, Z^0, W^+ (EW gauge)
	g (Gluon)

A lot of parameters ($\sim$100 without CP violation)

A lot of interactions ($\sim$ 5000 vertices)

Calculations become extremely tedious and involved.
Even more so at one-loop...

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e, ν (Lepton)	$\tilde{e}_{1,2}$, $\tilde{\nu}$ (Slepton)
$\tilde{H}^0_{1,2}$, $\tilde{H}^+_{1,2}$	h^0, H^0, A^0, H^+ (Higgs)
$\tilde{B}$, $\tilde{W}_3$, $\tilde{W}^+$	γ, Z^0, W^+ (EW gauge)
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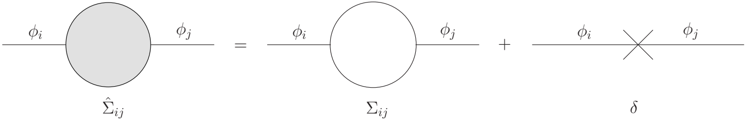
SHIFTS

$g \longrightarrow g + \delta g$
$m_{ij}^2 \longrightarrow m_{ij}^2 + \delta m_{ij}^2$
$\phi_i \longrightarrow (\delta_{ij} + \frac{1}{2}\delta Z_{ij})\phi_j$



ON-SHELL RENORMALISATION SCHEME

- *M_i^2 is the pole of the propagator:* $\hat{\Sigma}_{ii}(M_i^2) = 0$
- *residue at the pole is 1:* $\hat{\Sigma}'_{ii}(M_i^2) = 0$
- *no transition on the external legs:* $\hat{\Sigma}_{ij}(M_i^2) = 0$ and $\hat{\Sigma}_{ji}(M_j^2) = 0$

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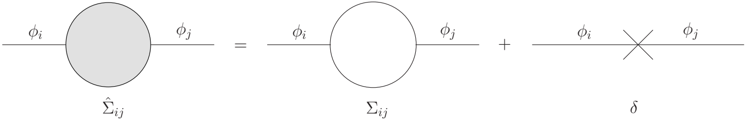

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Renormalisation & Definition of the parameters

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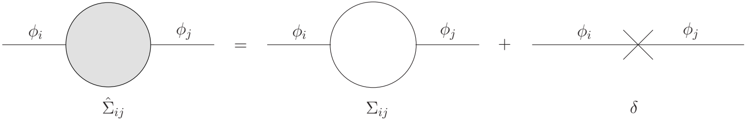

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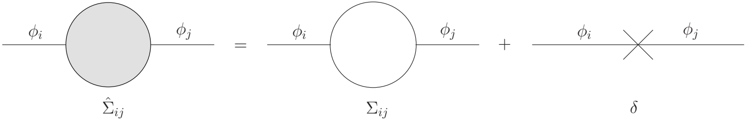

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- *no transition on the external legs*: $\hat{\Sigma}_{ij}(M_i^2) = 0$ and $\hat{\Sigma}_{ji}(M_j^2) = 0 \longrightarrow \delta Z_{ij}$

PROCEDURE AND INGREDIENTS FOR ONE-LOOP CALCULATIONS. EXAMPLE: $[\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \tau^+\tau^-(\gamma)]$

Tree Level 

[9]

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Tree Level 

[9]

Loops 

$$\int \frac{d^4q}{(2\pi)^4} \frac{q_\mu q_\nu ... q_\rho}{D_0 D_1 ... D_{N-1}}$$

[2223,2538,855]

Tree Level 

[9]

Loops 

$$\int \frac{d^4 q}{(2\pi)^4} \frac{q_\mu q_\nu \ldots q_\rho}{D_0 D_1 \ldots D_{N-1}} \supset C_{UV}$$

[2223,2538,855]

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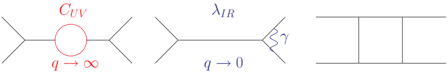
Loops 

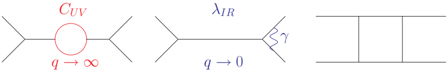
$$\int \frac{d^4q}{(2\pi)^4}\frac{q_\mu q_\nu \ldots q_\rho}{D_0 D_1 \ldots D_{N-1}} \supset C_{UV}, \lambda_{IR}$$

[2223,2538,855]

Procedure and ingredients for one-loop calculations. Example: [$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau^+\tau^-(\gamma)$]

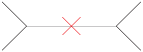
Tree Level 

[9]

Loops 

$$\int \frac{d^4q}{(2\pi)^4}\frac{q_\mu q_\nu \ldots q_\rho}{D_0 D_1 \ldots D_{N-1}} \supset C_{UV}, \lambda_{IR}$$

[2223,2538,855]

Counterterms 

C_{UV}

[42]

PROCEDURE AND INGREDIENTS FOR ONE-LOOP CALCULATIONS. EXAMPLE: $[\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau^+\tau^-(\gamma)]$

Tree Level 

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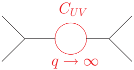
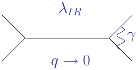
Loops 



$$\int \frac{d^4q}{(2\pi)^4} \frac{q_\mu q_\nu \ldots q_\rho}{D_0 D_1 \ldots D_{N-1}} \supset C_{UV}, \lambda_{IR}$$

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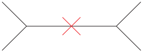
Counterterms  C_{UV}

[42]

Soft$_{(E_\gamma < k_c)}$ / Hard$_{(E_\gamma > k_c)}$ 

λ_{IR}

[22]

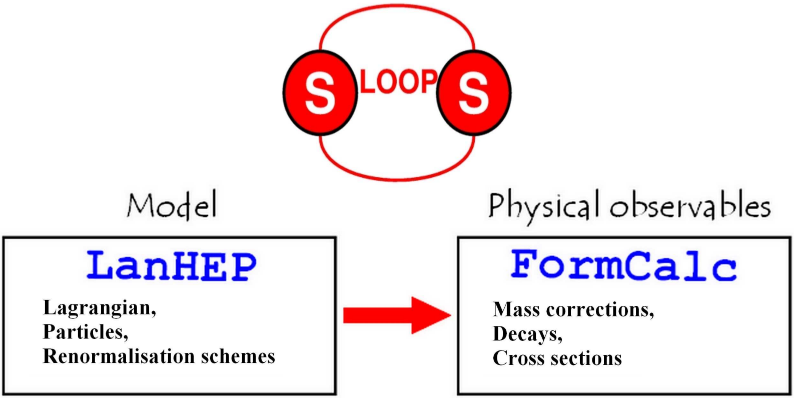
SLOOPS

→ Automatic tools

A code for the calculation of loops diagrams in the MSSM with application to collider physics, astrophysics and cosmology

Complete and coherent renormalisation of the MSSM
On-Shell scheme

CODE


S LOOP S
Model
Physical observables
LanHEP
Lagrangian,
Particles,
Renormalisation schemes
FormCalc
Mass corrections,
Decays,
Cross sections

LANHEP (A.SEMENOV)

Particles, lagrangian, counterterms...

```
vector A/A: (photon, gauge).

scalar h/h:('Light Higgs', mass Mh, width wh), H/H:('Heavy higgs', mass MHH, width wHh).
```

```
lterm -F**2/4 where

F=deriv^mu*B0^nu-deriv^nu*B0^mu.
```

```
let _a1=g*sQ1*tau*sq1/2,
_a2=g*sQ2*tau*sq2/2,
_a3=g*sQ3*tau*sq3/2,
_a4=g*sL1*tau*sl1/2,
_a5=g*sL2*tau*sl2/2,
_a6=g*sL3*tau*sl3/2,
_a7=g*sH1*tau*sh1/2,
_a8=g*sH2*tau*sh2/2.

lterm - ( _a1 + _a2 + _a3 + _a4 + _a5 + _a6 + _a7 + _a8 ) ** 2 /2.
```

```
transform h->h*(1+dZhlhl/2)+H*dZhlhh/2.
```

```
infinitesimal dphlhl = '-ReTilde[SelfEnergy[prt["h"]->prt["h"], Mh]]'.
```

Automatic generation of $\sim$ 5000 vertices involving the counterterms!

```
 (*------ h h h ------*)
C[ S[3], S[3], S[3] ] == 3/4 I * {
{ -2 A00555 , A00519 dZhhhl -3 A00555 dZhlhl -4 A01380 dZg

+ 6 A01380 dZw3 + 2 A00555 dXwz - A01381 dXH + 2 A01382 dZb + 2 A01383 dZbw3} }
```

```
 (*------ H+ H+ H- H- ------*)
C[ S[6], S[6], -S[6], -S[6] ] == -1/2 I * {

{ A03898 , 2 A03899 dZg -3 A03899 dZw3 -2 A03900 dZf1 + 2 A03901 dZf2 - A03902 dZb - A03903

dZbw3 } }
```

Features of the code

- Optimisation with classes
- Flexibility (between renormalisation schemes)
- Non linear gauge fixing

FormCalc (T.Hahn)

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Usual Gauge Fixing

$$
\begin{aligned}
\mathcal{L}^{GF} \quad = \quad & -\frac{1}{\xi_W}|\partial_\mu W^{+\,\mu} \\
& + i\xi_W \frac{g}{2} v G^+|^2 \\
& -\frac{1}{2\xi_Z}(\partial_\mu Z^{0\,\mu} + \xi_Z \frac{g}{2c_W} v G^0)^2 - \frac{1}{2\xi_A}(\partial_\mu A^\mu)^2
\end{aligned}
$$

$\xi = 1$ (loop library)

Non linear

Checks

- UV finite
- IR finite
- Gauge independent

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$$

$$\frac{-i}{q^2 - m^2_{Z^0} + i\epsilon}\left[g_{\mu\nu} + (\xi_Z - 1)\,\frac{q_\mu q_\nu}{q^2 - \xi_Z m^2_{Z^0}}\right]$$

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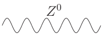

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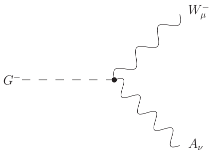
&\quad + i\xi_W\frac{g}{2}(\mathrm{v} + \tilde{\delta}h^0 + \tilde{\omega}H^0 + i\tilde{\kappa}G^0 + i\tilde{\rho}A^0)G^+|^2 \\
&\quad -\frac{1}{2\xi_Z}(\partial_\mu Z^{0\,\mu} + \xi_Z\frac{g}{2c_W}(\mathrm{v} + \tilde{\epsilon}h^0 + \tilde{\gamma}H^0)G^0)^2 - \frac{1}{2\xi_A}(\partial_\mu A^\mu)^2
\end{aligned}
$$



$$em_{W^+}(1 + \tilde{\alpha})g_{\mu\nu}$$

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Input parameters

The MSSM contains 8×3 SUSY breaking parameters for sfermions, 3×3 fermion masses and 12 parameters for gauge couplings, scalar potential and the SUSY breaking gaugino masses:

$$\underbrace{g, g', g_s}_{\text{gauge}}, \underbrace{v_1, v_2}_{\text{v.e.v.}}, \underbrace{m_1, m_2, m_{12}}_{\text{scalar potential}}, \mu, \underbrace{M_1, M_2, M_3, M_{\tilde{Q}_L}, M_{\tilde{u}_R}, M_{\tilde{d}_R}}_{\text{SUSY breaking}}, \underbrace{A_u, A_d}_{\text{trilinear}}$$

Set of parameters directly connected to the **physical** quantities:

$$\underbrace{\alpha(0), m_W, m_Z}_{\text{EW}}, \underbrace{t_\beta = v_2/v_1, m_A, T_1, T_2}_{\text{Higgs}}, \underbrace{m_{\chi_1^+}, m_{\chi_2^+}}_{\text{Chargino}}, \underbrace{m_{\chi_1^0}}_{\text{Neutralino}}, \underbrace{g_s, m_{\tilde{g}}}_{\text{QCD}}, \underbrace{m_{\tilde{u}_1}, m_{\tilde{d}_1}, m_{\tilde{d}_2}, \Gamma_u, \Gamma_d}_{\text{Squark}}$$

How to define $\tan(\beta)$?

t_β doesn't represent a physical/measurable quantity

We have many different ways/schemes to define it:

$\overline{DR}$

δt_β is a pure divergence

DCPR

δt_β is defined by the condition: $\hat{\Sigma}_{A^0 Z^0}(m^2_{A^0}) = 0$

MH

δt_β is defined from the measurement of the heaviest CP-even Higgs mass m_{H^0} (we loose a correction but the definition is physical)

$A\tau\tau$

δt_β is defined from the decay $A^0 \to \tau^+\tau^-$ (vertex $\propto m_\tau t_\beta$)

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Checks on the code

Tree Level calculations

Comparison with public codes: `Grace` and `CompHEP`

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

... ... # 200 processes checked

One-loop corrections that do not need renormalisation

Comparison with public codes: `PLATON` and `DarkSUSY`

Boudjema, Semenov, Temes, *Phys. Rev.* **D72** (2005) 055024, hep-ph/0507127

- $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma\gamma$
- $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow gg$
- $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow Z^0\gamma$

APPLICATIONS IN THE HIGGS SECTOR

B., Boudjema, Semenov, *Phys. Rev.* **D** (in press), 0807.4668 [hep-ph]

H^+, h^0

Comparison with Freitas, Stockinger, *Phys. Rev.* **D66** (2002) 095014, hep-ph/0205281

$t_\beta = 3$	*mhmax*	*large* μ	*nomix*
Tree Level	72.51	72.51	72.51
DCPR	134.28	97.57	112.26
MH	140.25	86.68	117.37
$A\tau\tau$	134.25	97.59	112.27
$\overline{\text{DR}}$ $\overline{\mu} = m_{A^0}$	134.87	98.10	112.86

Light Higgs mass m_{h^0}

$A^0 \to \tau^+\tau^-$, $A^0 \to Z^0h^0$, $H^0 \to Z^0Z^0$, $H^0 \to \tau^+\tau^-$

$t_\beta = 3$	*mhmax*	*large* μ	*nomix*
Tree Level	9.35×10^{-3}	9.35×10^{-3}	9.35×10^{-3}
DCPR	-1.09×10^{-4}	-7.96×10^{-5}	-1.09×10^{-4}
MH	$+6.28\times10^{-3}$	-7.91×10^{-3}	$+4.47\times10^{-3}$
$A\tau\tau$	-1.45×10^{-4}	-7.09×10^{-5}	-1.01×10^{-4}
$\overline{\text{DR}}$ $\overline{\mu} = m_{A^0}$	$+5.08\times10^{-4}$	$+3.24\times10^{-4}$	$+4.17\times10^{-4}$

$H^0 \to \tau^+\tau^-$ at one-loop with no QED

B., Boudjema, in preparation

ONE-LOOP CORRECTION TO MASSES

- Sfermion $\tilde{\tau}, \tilde{b}$ Comparison with Hollik, Rzehak, *Eur. Phys. J.* **C32** (2003) 127, hep-ph/0305328
- Neutralino $\tilde{\chi}^0_{2,3,4}$ Comparison with Fritzsche, Hollik, *Eur. Phys. J.* **C24** (2002) 619, hep-ph/0203159

CHARGINO DECAYS

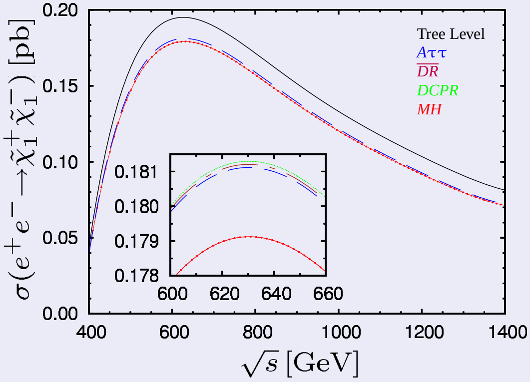
Comparison with Fujimoto *et al.*, *Phys. Rev.* **D75** (2007) 113002, hep-ph/0701200

Decays [GeV]	Tree Level	`Grace`	`SloopS` *MH*
$\tilde{\chi}^+_1 \to \nu_\tau \tilde{\tau}^+_1$	3.91×10^{-2}	$3.78 \times 10^{-2}(-3\%)$	$3.79 \times 10^{-2}(-3\%)$
$\tilde{\chi}^+_1 \to \tau^+ \tilde{\nu}_\tau$	1.47×10^{-2}	$1.48 \times 10^{-2}(0\%)$	$1.47 \times 10^{-2}(0\%)$
$\tilde{\chi}^+_1 \to W^+ \tilde{\chi}^0_1$	9.65×10^{-4}	$1.28 \times 10^{-3}(+33\%)$	$1.19 \times 10^{-3}(+23\%)$
$\tilde{\chi}^+_2 \to \nu_\tau \tilde{\tau}^+_2$	1.54×10^{-1}	$1.48 \times 10^{-1}(-4\%)$	$1.40 \times 10^{-1}(-9\%)$
$\tilde{\chi}^+_2 \to \tau^+ \tilde{\nu}_\tau$	6.89×10^{-2}	$5.70 \times 10^{-2}(-17\%)$	$5.27 \times 10^{-2}(-24\%)$
$\tilde{\chi}^+_2 \to W^+ \tilde{\chi}^0_1$	1.93×10^{-1}	$2.07 \times 10^{-1}(+7\%)$	$2.02 \times 10^{-1}(+5\%)$
$\tilde{\chi}^+_2 \to W^+ \tilde{\chi}^0_2$	8.67×10^{-1}	$9.93 \times 10^{-1}(+15\%)$	$9.75 \times 10^{-1}(+12\%)$
$\tilde{\chi}^+_2 \to Z^0 \tilde{\chi}^+_1$	7.53×10^{-1}	$8.56 \times 10^{-1}(+14\%)$	$8.06 \times 10^{-1}(+7\%)$

B., Boudjema, in preparation

LINEAR COLLIDER

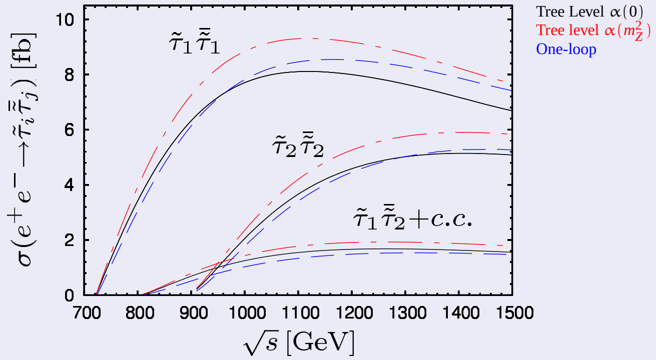
Comparison with Fujimoto *et al.*, *Phys. Rev.* **D75** (2007) 113002, hep-ph/0701200



B., Boudjema, in preparation

LINEAR COLLIDER

Comparison with Kovarik, Weber, Eberl, Majerotto, *Phys. Rev.* **D72** (2005) 053010, hep-ph/0506021



Applications to Dark Matter

A few examples

B., Boudjema, Semenov, *Phys. Lett.* **B660** (2007), 0710.1821[hep-ph]

- $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau^+\tau^-$ — Neutralino Bino
- $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^-/Z^0Z^0$ — Neutralino Mixed
- $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau^+\tau^-$
  $\tilde{\chi}_1^0\tilde{\tau}_1^\pm \to \tau^\pm\gamma/\tau^\pm Z^0$ — Coannihilation with a stau
  $\tilde{\tau}_1^\pm\tilde{\tau}_1^\mp \to \tau^\pm\tau^\mp$
- $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^-/Z^0Z^0/b\bar{b}/\tau^+\tau^-$ — QCD corrections

Coannihilation with a chargino

B., Chalons, in preparation (see this afternoon!)

- $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to W^+W^-$
  $\tilde{\chi}_1^0\tilde{\chi}_2^0 \to W^+W^-$
  $\tilde{\chi}_1^0\tilde{\chi}_1^\pm \to W^\pm Z^0/u\bar{d}$

CONCLUSION

- Complete renormalisation of the MSSM
- Mass corrections, Decays, Cross-sections at colliders
- Relic density at one-loop in various scenarios
- Other renormalisation schemes (Chargino/Neutralino, Sfermion)
- Automatisation of $e^+e^- \to XX$ or $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to XX$ at one-loop
- MSSM including CP violation
- Interface with `MicrOMEGAs`...
- Renormalisation of the QCD sector

Public/Private website: http://code.sloops.free.fr/