summary Loopverein & Generators

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Outline

- Tools and Automatization
  - Alternative 1-loop calculations: OPP vs generalized unitarity
  - SloopS
  - Photos Monte Carlo
  - Whizard
- EW corrections in the TeV region
- MSSM
  - renormalization in the complex MSSM
  - SUSY Higgs Yukawa couplings to bottom quarks at NNLO

Alternative 1-loop Calculations

new methods

- 1-loop amplitude
  $\mathcal{M} = \sum \text{Coeff} \times \text{loop integral}$
- idea: “direct” construction of coefficients
  $\Rightarrow$ loop amplitude known

The OPP Method (Ossola, Papadopoulos, Pittau, 2007)

Working at the *integrand* level

$$A = \int d^n\bar{q}\; \left[\mathcal{A}(q) + \tilde{\mathcal{A}}(q,\tilde{q},\epsilon)\right]$$

$$\left(\begin{array}{c} \bar{q} = q + \tilde{q} \\ n = 4 + \epsilon \end{array}\right)$$

- For example, in the case of $2 \rightarrow 6$

$$\mathcal{A}(q) = \sum \underbrace{\frac{N_i^{(6)}(q)}{\bar{D}_{i_0}\bar{D}_{i_1}\cdots\bar{D}_{i_5}}} + \underbrace{\frac{N_i^{(5)}(q)}{\bar{D}_{i_0}\bar{D}_{i_1}\cdots\bar{D}_{i_4}}} + \underbrace{\frac{N_i^{(4)}(q)}{\bar{D}_{i_0}\bar{D}_{i_1}\cdots\bar{D}_{i_3}}} + \underbrace{\frac{N_i^{(3)}(q)}{\bar{D}_{i_0}\bar{D}_{i_1}\bar{D}_{i_2}}} + \cdots$$

Alternative 1-loop Calculations

The function to be sampled *numerically* to extract the coefficients of the scalar 1-loop functions

$$
\begin{aligned}
N_i^{(6)}(q) &= \sum_{i_0<i_1<i_2<i_3}^{5} \left[d(i_0 i_1 i_2 i_3) + \tilde{d}(q; i_0 i_1 i_2 i_3) \right] D_{i_4} D_{i_5} \\
&+ \sum_{i_0<i_1<i_2}^{5} \left[c(i_0 i_1 i_2) + \tilde{c}(q; i_0 i_1 i_2) \right] D_{i_3} D_{i_4} D_{i_5} \\
&+ \sum_{i_0<i_1}^{5} \left[b(i_0 i_1) + \tilde{b}(q; i_0 i_1) \right] D_{i_2} D_{i_3} D_{i_4} D_{i_5} \\
&+ \sum_{i_0}^{5} \left[a(i_0) + \tilde{a}(q; i_0) \right] D_{i_1} D_{i_2} D_{i_3} D_{i_4} D_{i_5} \\
&+ \tilde{P}(q) D_{i_0} D_{i_1} D_{i_2} D_{i_3} D_{i_4} D_{i_5}
\end{aligned}
$$

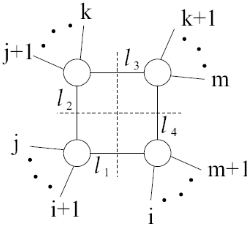
Alternative 1-loop Calculations

[redacted]

Generalized Unitarity: more Cutting (more Gluing)

Bern, Dixon, Dunbar, Kosower, hep-ph/9403226; Ellis, Giele, Kunszt, Melnikov, 0806.3467; Berger et al. (`BlackHat`), 0803.4180

1. Quadruple cuts ⇔ gluing 4 tree-level, *gauge invariant*, amplitudes (Britto, Cachazo, Feng, hep-th/0412103)



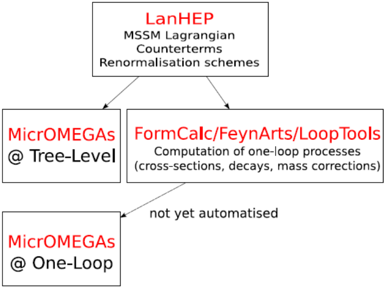
2. q integration frozen ⇒ *coefficient d_i of the box extracted*
3. 3 bubbles are connected together, the box contributions subtracted and the *coefficients c_i of the triangles extracted*

[redacted]

Conclusions

1. New techniques and ideas allowed an impressive progress in the field of 1-loop calculations:
   - I (briefly) discussed and compared the **OPP** method and the **GU** techniques;
   - They have been successfully applied in QCD to compute at NLO $pp \to ttbb$, $pp \to ttjj$, $pp \to W + 3\ jets$, $pp \to W + 4\ jets$, $\cdots$;
   - Computing R in both **OPP** and **GU** still unsatisfactory;
   - Wave function renormalization problem unsolved in **GU**. In **OPP** put by hand (but gauge dependent!).
2. No complete EW calculation is available so far with these new techniques.
3. They will be needed for ILC Physics.
4. The final goal should be delivering public 1-loop codes.

AUTOMATIC TOOL FOR ONE-LOOP CALCULATIONS : SLOOPS



SLOOPS

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

- Evaluation of one-loop diagrams including a complete and coherent renormalisation of each sector of the MSSM with an OS scheme.
- Modularity between different renormalisation schemes.
- Non-linear gauge fixing.
- Checks : results UV,IR finite and gauge independent.

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

SLOOPS applications

application examples

- Higgs and neutralino masses
- Higgs and Chargino decays
- $\tilde{\chi}^{\pm}$, $\tilde{\tau}$, W/Z production at ILC
- cosmology, $\Omega_{\chi} h^2$@$1-2\%$
  $\Rightarrow$ 1-loop corrections needed

THERMAL RELIC

- $\Omega_{\chi} h^2 \propto 1/(\sigma(\chi\chi \to \mathrm{SM}))$
- Relic density calculated through the interface of `SloopS` with `micrOMEGAs` (Bélanger *et al.*)

BUNCH OF FULL ONE-LOOP PROCESSES CALCULATED

Baro, Boudjema, Semenov, *Phys. Lett* **B660**
Baro, Boudjema, G.C, Sun Hao, *Phys. Rev.* **D81** 015005 (2010) (2008) 550

- $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to f\bar{f}$ (bino)
- $\tilde{\chi}_1^0 \tilde{\tau}_1^+ \to \tau^+ \gamma (Z^0)$ (bino)
- $\tilde{\tau}_1^+ \tilde{\tau}_1^+ \to \tau^+ \tau^+$ (bino)
- $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to W^+ W^-, Z^0 Z^0$ (bino-wino, bino-higgsino, higgsino, higgsino-bino, wino)
- $\tilde{\chi}_1^0 \tilde{\chi}_1^+ \to u\bar{d}, t\bar{b}$ (bino-wino, higgsino, higgsino-bino, wino)
- $\tilde{\chi}_1^+ \tilde{\chi}_1^- \to W^+ W^-, Z^0 Z^0$ (wino)

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First and second order spin amplitudes for precision of PHOTOS Monte Carlo

Z. Was*, A. van Hameren, G. Nanava. T. Przedzinski, P. Roig, Q. Xu

*speaking, Institute of Nuclear Physics, Krakow *and* CERN PH-TH, Geneva

- **(1)** From semileptonic B and K mesons decays (measurements of quark mixing), properties of W and Z decays at LHC, to signatures for discovery and properties of New Physics particles bremsstrahlung must be taken into account.
- **(2)** PHOTOS Monte Carlo is used in such studies. Essential: Input from spin calculations was necessary for design of the program and for tests of its physical precision.
- **(3)** *I will mention:* phase space parametrization, crude distribution in single photon emission, double photon emisssion, and multiple emission; all modes needed for tests.
- **(4)** *Technical points like:* event record type HEPEVT, HepMC; intermediate particles explicitly stored in it or not; numerical tests for user installation will be skipped.
- **(5)** *At which precision QED FSR can be separated from the rest, that is:* genuine weak corrections, ISR, ISR×PS, ISR-FSR interference. This important point will be skipped too.

Z. Was *Loop Verein, Cern, October, 2010*

Summary

1. PHOTOS Monte Carlo is for simulation of multiphoton FSR bremsstrahlung.
2. Program is designed to help generate correlated samples: events with and without FSR bremsstrahlung.
3. For processes mediated by Z/γ' and W's high precision is investigated.
4. Important for program construction were presented here studies of spin amplitudes. Structure of their gauge invariant parts is used in definition of photon emission kernel.
5. Remaining parts of amplitudes are needed for discussion of systematic errors, for optimalization of program performance or for construction correcting weights.
6. For some processes eg. where matrix element is obtained from scalar QED introduction of data constrained form factors may be necessary.
7. New version of program, using `HepMC` event record of C++ is available for tests.

Whizard 2.x: Monte Carlo Generator for ILC

Components

- O'Mega matrix element compiler:
  - maximally factorized matrix elements
  - exponential, not factorial, complexity (recursion relations)
  - model independent algorithm
- VAMP adaptive multi channel sampling:
  - multiple independent VEGAS grids
  - efficient integration of complicated phase spaces
  - unweighted event generation
- WHIZARD core:
  - phase space parametrization
  - unstable particle decays with spin correlations
  - interfaces, I/O
  - supervisor
  - scripting language

Available Models

- QED
- QCD
- Standard Model
- SM with anomalous top and gauge couplings
- Z'
- Supersymmetry: MSSM (cross checked with MadGraph and Sherpa), NMSSM, PSSSM
- Extra Dimensions, UED
- 3-Site Higgsless Model
- Little Higgs: Littlest, Simplest
- all FeynRules models
- your own . . .

Whizard 2.x: Monte Carlo Generator for ILC

UNIVERSITÄT WÜRZBURG

Remaining Challenges

- efficient and complete implementations of the Fortran 2003 standard
  - procedure pointers (required for dynamic linking) only correcty implemented by NAG and gfortran 4.5
- use more symmetries to reduce the code size
  - compiled code for multi jet cross sections at LHC can become larger than a giga[sic!]byte
- allow completely general vertex structures (MadGraph is working on this too)
- loops (proof-of-principle implementations by other groups exist, but completely general and fully automatic implementations are still science fiction . . .)
- get it from

  `http://projects.hepforge.org/whizard/`

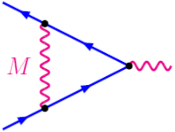
EW corrections in the TeV region

"Typical" size of electroweak corrections: $\frac{\alpha_{\text{weak}}}{\pi} \approx 10^{-2}$

new aspects at LHC: $\sqrt{\hat{s}} \approx$ 1-2TeV $\gg M_{W,Z}$

strong enhancement of negative corrections

one-loop example: massive U(1)



$$\Rightarrow \text{ Born} * \left[1 + \frac{\alpha}{4\pi}\left(-\ln^2\frac{s}{M^2} + 3\ln\frac{s}{M^2} - \frac{7}{2} + \frac{\pi^2}{3}\right)\right]$$

$\frac{s}{M^2}$	$-\ln^2\frac{s}{M^2}$	$+3\ln\frac{s}{M^2}$	$-\frac{7}{2}+\frac{\pi^2}{3}$	Σ	$*\,4\,\frac{\alpha_{\text{weak}}}{4\pi}$
$\left(\frac{1000}{80}\right)^2$	-25.52	$+15.15$	-0.21	-10.6	-13%
$\left(\frac{2000}{80}\right)^2$	-41.44	$+19.31$	-0.21	-22.3	-27%

EW corrections in the TeV region

observations

- subleading terms important
- 2-loop may be relevant

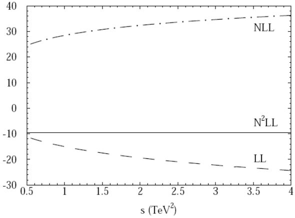
higher loops needed

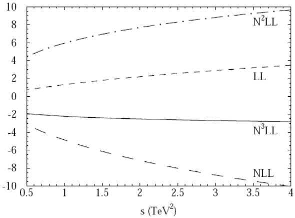
(recent) 2-loop results in high energy limit for [Kuehn et al '03-'10]

- fermion-fermion-vector form factor. up to N^4LL.
- 4f scattering, $e^+e^- \to q\bar{q}$. up to N^3LL
- W pair production at linear collider and LHC. up to N^2LL.

EW corrections in the TeV region

Separate logarithmic contributions to $R(e^+e^- \to q\bar{q})$ in % to the Born approximation





one-loop LL $(\ln^2(s/M^2))$, NLL $(\ln^1(s/M^2))$ and N^{2}LL $(\ln^0(s/M^2))$

two-loop LL $(\ln^4(s/M^2))$, NLL $(\ln^3(s/M^2))$, NNLL $(\ln^2(s/M^2))$ and N^{3}LL $(\ln^1(s/M^2))$

Large cancellations!

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real W/Z radiation will compensate these effects.

can real radiation be separated?

Renormalization in the complex MSSM

Effects of complex parameters in the Higgs sector:

Complex parameters enter via loop corrections:

– μ : Higgsino mass parameter

– $A_{t,b,\tau}$: trilinear couplings $\Rightarrow X_{t,b,\tau} = A_{t,b} - \mu^* \{\cot\beta, \tan\beta\}$ complex

– $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)

– $m_{\tilde{g}}$: gluino mass

$\Rightarrow$ can induce $\mathcal{CP}$-violating effects

Result:

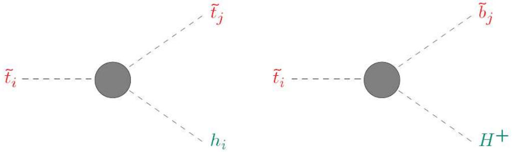
$$(A, H, h) \to (h_3, h_2, h_1 (= \phi))$$

with

$$M_{h_3} > M_{h_2} > M_{h_1}$$

Renormalization in the complex MSSM

Examples for processes with (external) stops and Higgs bosons:



- important decay modes of stops
- A_t and A_b directly enter the vertex incl. complex phases!
- possible source of Higgs bosons at the LHC/ILC
- ...

⇒ higher-order corrections important!

⇒ simultaneous renormalization of stop and sbottom sector required!

⇒ including complex phases!

Sven Heinemeyer, IWLC 10 (Geneva), 20.10.2010 4

want BR ⇒ need all decays

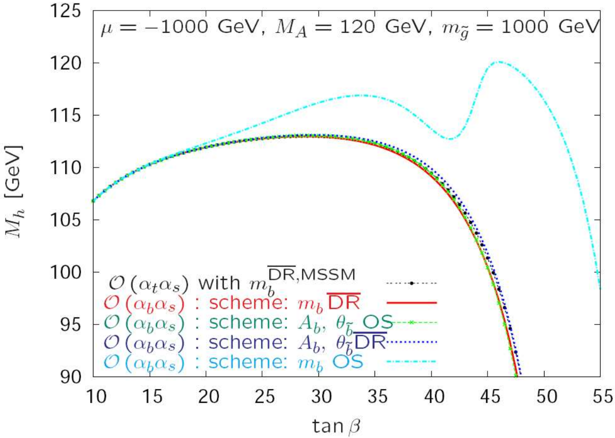
⇒ (nearly) all sectors of the cMSSM have to be renormalized simultaneously

Renormalization in the complex MSSM

studied several renormalization schemes to find best scheme

effect of bad renormalization scheme

"OS" scheme: $\delta A_b = \frac{1}{m_b}\left[-(A_b - \mu^* \tan\beta)\,\delta m_b + \ldots\right]$



$\Rightarrow$ fails already for Higgs boson self-energies

5. Conclusions & Outlook

- $\tilde{t}$ and $\tilde{b}$ sector important for collider phenomenology

- Simultaneous renormalization of both sectors crucial for higher-order corrections – on-shell properties for external squarks!

  $\Rightarrow$ $\tilde{t}/\tilde{b}$ renormalization in the cMSSM

  $\Rightarrow$ simultaneous renormalization of all sectors in the cMSSM

- Sbottom sector: six (+X) schemes defined and tested
  analytical deficiencies found in all schemes
  most "robust": RS2: "m_b, A_b $\overline{\text{DR}}$" $\leftarrow$ preferred scheme
  RS6: "A_b vertex, ReY_b OS"

- Numerical analysis: RS2: "m_b, A_b $\overline{\text{DR}}$" shows very robust and stable behavior over nearly all (tested) cMSSM parameter space

  Evaluation of $\Gamma(\tilde{t}_2 \to \tilde{t}_1 h_i)$ and BR$(\tilde{t}_2 \to \tilde{t}_1 h_i)$

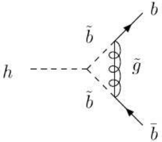
  $\Rightarrow$ sizable effects in Γ and BR
  $\Rightarrow$ have to be included for ILC analyses (and possibly for LHC)

SUSY Higgs Yukawa couplings at NNLO

bottom Yukawa couplings in MSSM for large tan β

- dominate Higgs boson production & decay processes
  $gg \to \phi$ dominant for tan $\beta \lesssim 10$
  $gg \to \phi b\bar{b}$ dominant for tan $\beta > 10$
- large NLO SUSY corrections to bottom Yukawa couplings

- large SUSY–QCD corrections to $\phi^0 \to b\bar{b}$ $\quad (\Delta\Gamma/\Gamma \sim 10\%)$



$+\cdots \quad \propto \frac{\alpha_s}{\pi} \frac{M_{\tilde{g}}\mu \text{tg}\beta}{M^2_{SUSY}}$

Hall, . . .
Carena, . . .
Nierste, . . .
Guasch, . . .
etc.

resummation possible [Carena, Garcia, Nierste, Wagner] [Guasch, Haefliger, Spira]

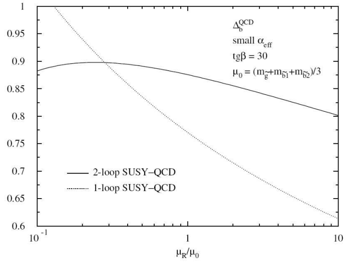
$$\mathcal{L}_{eff} = -\lambda_b \overline{b_R} \left[\phi_1^0 + \frac{\Delta_b}{\text{tg}\beta} \phi_2^{0*} \right] b_L + h.c.$$

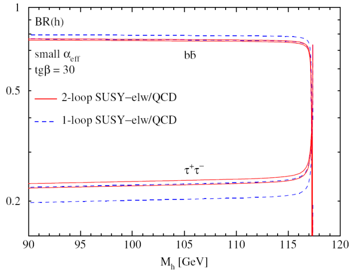
valid to all orders in Δ_b

SUSY Higgs Yukawa couplings at NNLO

- 2-loop SUSY QCD corrections to Δ_b [Noth, Spira]
- need 2-loop self energies at zero momentum
- impact
  scale dependence reduced
  BR uncertainty reduced
- applications $e^+e^- \to b\bar{b}\phi, t\bar{b}H^-$

Noth, Spira





Conclusions

- for ILC to reach full potential higher order corrections mandatory
- fully automated NLO generators for ILC desirable
  significant recent progress in new methods
  well underway for QCD/LHC, first steps taken for EW/ILC
  will be available
- potentially large radiative corrections in MSSM
  careful treatment of all effects needed