HELAC - A package to compute helicity amplitudes and cross sections

(Progress Report)

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Contents

- Reliable cross section computation and event generation for multiparticle processes with **10-12** particles
  - Matrix element computation algorithm based on **Dyson-Schwinger** equations
  - Including: EW, QCD, masses, CKM matrix, running couplings, PDF sets, ...
  - Free from the task of calculating Feynman Diagrams
  - **MC summation** over colours and helicities
  - Much improvement in computational efficiency **$\sim 3^n$**
  - Successfully implemented in Fortran 95 program (gfortran, g95, lahey 95)
- Results & Comparisons
- Summary & Outlook

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NCSR "Demokritos", INP Athens

Some References

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Motivation

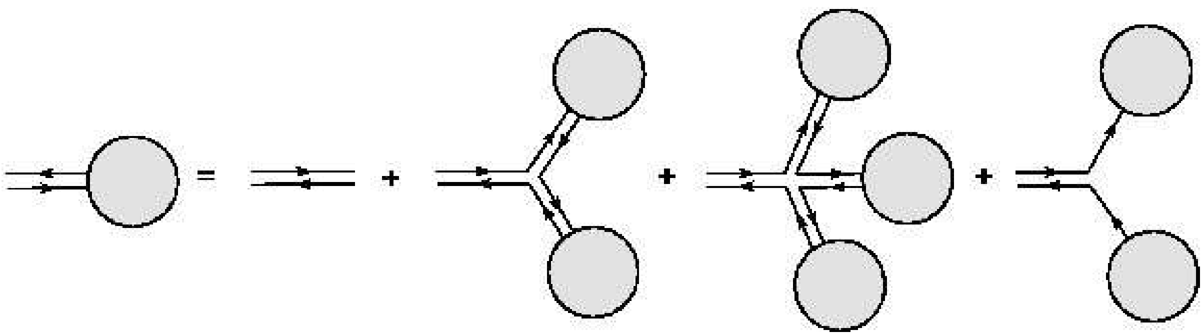
- Goal
  - Multi particle final states in high energy colisions **pp, e^+e^-**
  - Production and decay of top quark pairs
  - Production and decay of Higgs boson
  - Study of quartic gauge boson couplings
  - Background to the discovery processes

- Problems
  - Very large number of Feynman diagrams **~n!**
  - Summation over helicities $2^{n_1} \times 3^{n_2}$
  - Summation over colours $8^{n_g} \times 3^{n_q} \times 3^{n_{\bar{q}}}$
  - Many of these configurations do not contribute to the amplitude !!!

Solution: Automation - Recursive approach based on Dyson-Schwinger equations & MC summation over colours and helicities

Dyson-Schwinger Recursion

- Recursively express the n-point Green's functions in terms of the 1-,2-, ... , (n-1)-point functions
- Diagrammatically for gluon field



- Subamplitude with an off-shell gluon of momentum P
- Contribution from 3-, 4-gluon vertex and quatk-antiquark vertex
- Blobs denote subamplitudes with the same structure

Dyson-Schwinger Recursion

- And can be written as follows

$$[A^{\mu}(P);(A,B)]=\sum_{i=1}^{n}[\delta_{P=p_i}A^{\mu}(p_i);(A,B)_i]$$

$$+\sum_{P=p_1+p_n}[(ig)\Pi^{\mu}_{\rho}V^{\rho\nu\lambda}(P,p_1,p_2)A_{\nu}(p_1)A_{\lambda}(p_2)\sigma(p_1,p_2);(A,B)=(C,D)_1*(E,F)_2]$$

$$-\sum_{P=p_1+p_2+p_3}[(g^2)\Pi^{\mu}_{\sigma}G^{\sigma\nu\lambda\rho}(P,p_1,p_2,p_3)A_{\nu}(p_1)A_{\lambda}(p_2)A_{\rho}(p_3)\sigma(p_1,p_2+p_3);(A,B)]$$

$$(A,B)=(C,D)_1*(E,F)_2*(G,H)_3$$

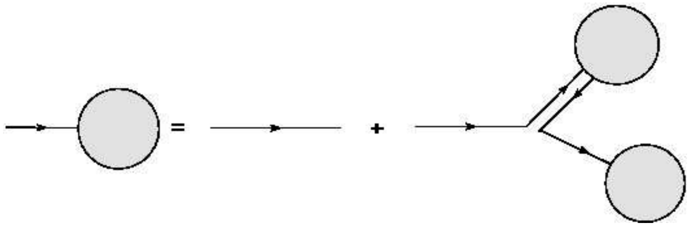
$$+\sum_{P=p_1+p_2}[(ig)\Pi^{\mu}_{\nu}\bar{\psi}(p_1)\gamma^{\nu}\psi(p_2)\sigma(p_1,p_2);(A,B)=(0,D)_1*(C,0)_2]$$

$$\Pi_{\mu\nu}=\frac{-ig_{\mu\nu}}{P^2}$$

$$A,B,C,D,E,F,G,H=1,2,3$$

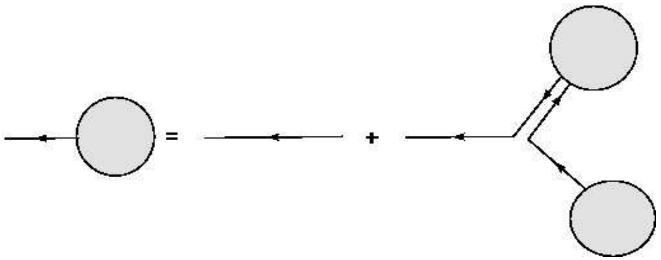
Dyson-Schwinger Recursion

- Quark and Antiquark



$$[\psi(P);(A,0)] = \sum_{i=1}^{n} [\delta_{P=p_1} \psi(p_i);(A,0)_i]$$
$$+ \sum_{P=p_1+p_2} [(ig) S A^\mu(p_1) \gamma_\mu \psi(p_2) \sigma(p_1,p_2);(A,0)=(B,C)_1 * (D,0)_2]$$

$$S = \frac{i P^\mu \gamma_\mu}{P^2}$$



$$[\bar\psi(P);(0,A)] = \sum_{i=1}^{n} [\delta_{P=p_1} \bar\psi(p_i);(0,A)_i]$$
$$+ \sum_{P=p_1+p_2} [(ig) \bar\psi(p_2) A^\mu(p_1) \gamma_\mu \bar S \sigma(p_1,p_2);(0,A)=(B,C)_1 * (0,D)_2]$$

$$\bar S = \frac{-i P^\mu \gamma_\mu}{P^2}$$

Binary Representation

- Of the momenta involved, very convenient to solve the recursive equations !!!
  - Process involving n external particles with momenta $p_i^\mu, \quad i=1,\dots,n$
  - Define the momentum $P^\mu = \sum_{i\in I} p_i^\mu, \qquad I \subset \{1,\dots,n\}$
  - Assign a binary vector $\vec{m} = (m_1,\dots,m_n), \qquad m_i = 0,1$

$$\Leftrightarrow \quad P^\mu \sum_{i=1}^{n} m_i p_i^\mu$$

  - Binary vector can be uniquely represented by the integer

$$m = \sum_{i=1}^{n} 2^{i-1} m_i, \qquad 0 \leqslant m \leqslant 2^n - 1$$

  - All momenta can be now replaced by the integers

$$A_\mu(P) \rightarrow A_\mu(m)$$
$$\psi(P) \rightarrow \psi(m)$$
$$\bar{\psi}(P) \rightarrow \bar{\psi}(m)$$

Binary Representation

- Convenient ordering of integers in binary representation $\Leftrightarrow$ level l

$$l = \sum_{i=1}^{n} m_i$$

- All external momenta are of level 1
- Total amplitude corresponds to the unique level n integer 2^n-1

$$M = A(1) \cdot A_0(2^n - 2)$$

Ordering dictates the natural path of the computation
Starting with level 1 subamplitudes we compute the level 2 ones using Dyson-Schwinger equations and so on up to the level n-1 !!!

Fermi Sign Function

- For fermions a sign change when two identical fermions are interchanged
- Binary representation is still using $\sigma(P_i,P_j)\rightarrow\sigma(m_i,m_j)$

$$P_1\rightarrow(0001),\ P_2\rightarrow(0010),\ P_4\rightarrow(0100),\ P_8\rightarrow(1000)$$

$$P_3= P_1+P_2\rightarrow(0011),\ P_{14}= P_4+P_{10}\rightarrow(1110),\ P_{15}= P_1+P_{14}\rightarrow(1111)$$

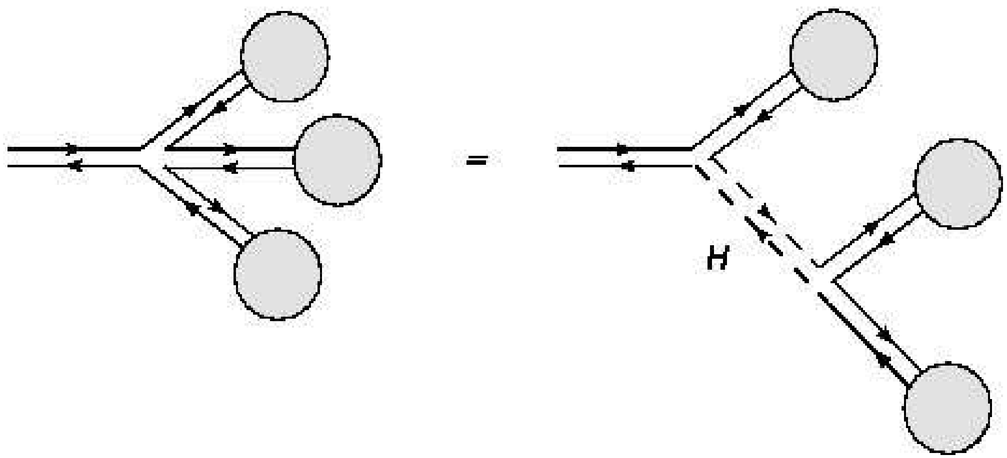
- Sign relative to the permutation of two momenta is computed, hat over binary string means - bit set to zero if external particle is a boson

$$\sigma(m_1,m_2)=(-1)^{\chi(m_1,m_2)}$$

$$\chi(m_1,m_2)=\sum_{i=n}^{2}\hat{m}_{1i}\sum_{j=1}^{i-1}\hat{m}_{2j}$$

Dyson-Schwinger Recursion

- Auxiliary field – reduce computational complexity by replacing each four gluon vertex by a three particle vertex
- Represented by the antisymmetric tensor $H^a_{\mu\nu}$



$$L = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu a}$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

$$L = -\frac{1}{2} H^a_{\mu\nu} H^{\mu\nu a} + \frac{1}{4} H^a_{\mu\nu} F^{\mu\nu a}$$

- Single interaction term is left $f^{abc} H^{\mu\nu a} A^b_\mu A^c_\nu$
- Number of the types of the subamplitudes is doubled, their structureis much simpler saves computational time !!!

Dyson-Schwinger Recursion

- Recursion for gluon changes slightly - only four gluon vertex part, additionally equation for the auxiliary field

$$[A^{\mu}(P);(A,B)]=\sum_{i=1}^{n}[\delta_{P=p_i}A^{\mu}(p_i);(A,B)_i]$$

$$+\sum_{P=p_1+p_n}[(ig)\Pi^{\mu}_{\rho}V^{\rho\nu\lambda}(P,p_1,p_2)A_{\nu}(p_1)A_{\lambda}(p_2)\sigma(p_1,p_2);(A,B)=(C,D)_1*(E,F)_2]$$

$$+\sum_{P=p_1+p_2}[(ig)\Pi^{\mu}_{\sigma}(g^{\sigma\lambda}g^{\nu\rho}-g^{\nu\lambda}g^{\sigma\rho})A_{\nu}(p_1)H_{\lambda\rho}(p_2)\sigma(p_1,p_2);(A,B)]$$

$$(A,B)=(C,D)_1*(E,F)_2*(G,H)_3$$

$$+\sum_{P=p_1+p_2}[(ig)\Pi^{\mu}_{\nu}\bar{\psi}(p_1)\gamma^{\nu}\psi(p_2)\sigma(p_1,p_2);(A,B)=(0,D)_1*(C,0)_2]$$

$$[H^{\mu\nu}(P);(A,B)]=\sum_{P=p_1+p_2}[(ig)(g^{\mu\lambda}g^{\nu\rho}-g^{\nu\lambda}g^{\mu\rho})A_{\lambda}(p_1)A_{\rho}(p_2)\sigma(p_1,p_2);(A,B)=(C,D)_1*(E,F)_2]$$

HELAC

- Algorithm exhibits a computational cost that grows like $\sim 3^n$ in contrast to the $n!$ growth of the Feynman graph approach
- No sever limitation in computing many particle amplitudes, up to 12 external
- All Electroweak and QCD vertices are implemented in the unitary gauge
- Decay width of unstable particles is introduced in the fixed width and complex mass schemes
- All fermions masses can be non zero
- Any process with any type of Standard Model particles can be reliably computed
- Possibility to use higher precision floating point arthmetic
- Speeding up techniques for helicity and colour Monte Carlo treatment

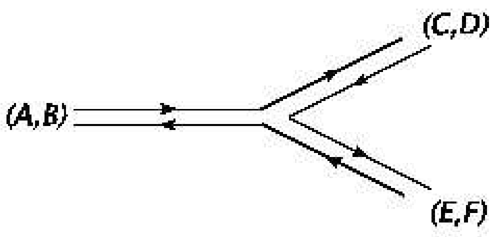
Colour Structure

- Dyson-Schwinger equations for the full amplitude M not for a colour ordered
- New approach $U(N)$ -type, gluon $q\bar{q}$ pair
  - Quark - $(A,0)$
  - Antiquark - $(0,B)$
  - Gluon - (A,B)
- Incoherent sum performed by the Monte Carlo over 'real' colours

$$\sum_{A_i,B_i=1,\dots,3} |M(\{p_i\}_1^n,\{\varepsilon_i\}_1^n,\{A_i,B_i\}_1^n)|^2$$

- Colour structure of three gluon vertex

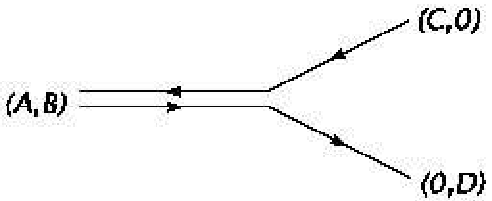
$$\sum_{a_i} f^{a_1 a_2 a_3} t^{a_1}_{AB} t^{a_2}_{CD} t^{a_3}_{EF} = -\frac{i}{4}(\delta_{AD}\delta_{CF}\delta_{EB} - \delta_{AF}\delta_{CB}\delta_{ED})$$



Colour Structure

- Colour structure of quark-antiquark vertex

$$\sum_a t^a_{AB} t^a_{CD} = \frac{1}{2}\left(\delta_{AD}\delta_{CB} - \frac{1}{N_C}\delta_{AB}\delta_{CD}\right)$$



- Colour merging rules – example

$$(A,B) \Leftarrow (C,0)\times(0,D)$$
$$(A,B) \Leftarrow (C,D)\times(E,F)$$

$$(A,B)=(C,0)\times(0,D)=(C,D) \qquad \text{if} \quad C\neq D$$

$$(A,B)=(C,0)\times(0,D)=(1,1)_{w_1}+(2,2)_{w_2}+(3,3)_{w_3} \qquad \text{if} \quad C=D$$

$$(1,0)\times(0,1)=(1,1)_{2/3}+(2,2)_{-1/3}+(3,3)_{-1/3}$$

Colour Structure

- Summ over colour performed by considering all possible configurations N_c^n
- One particular colour-anticolour configuration randomly selected MC
- Necessary condition – number of colour and anticolour of each type is the same
- $|M|^2$ is multiplied by the number of non zero color configurations N_{CC}

$$N_{CC}^{ALL} = N_C^{n_q + n_{\bar{q}}} = 3^{n_q + n_{\bar{q}}}$$

$$N_{CC} = \sum_{A=0}^{n_q} \sum_{B=0}^{n_q - A} \sum_{C=0}^{n_q - A - B} \left(\frac{n_q!}{A!B!C!} \right)^2 \delta(n_q = A + B + C)$$

Process	N_{cc}^{ALL}	N_{cc}	N_{cc}/N_{cc}^{ALL}	N_{cc}^{F} (%)
$gg \to 2g$	6561	639	0.0974	59.1
$gg \to 3g$	59049	4653	0.0788	68.4
$gg \to 4g$	531441	35169	0.0662	77.4
$gg \to 5g$	4782969	272835	0.0570	85.0
$gg \to 6g$	43046721	2157759	0.0501	90.4
$gg \to 7g$	387420489	17319837	0.0447	94.0
$gg \to 8g$	3486784401	140668065	0.0403	96.4

Colour Structure

- Number of colour configurations – in the last column the number of non vanishing colour configurations inside the N_{cc}

Process	N_{cc}^{ALL}	N_{cc}	N_{cc}/N_{cc}^{ALL}	N_{cc}^{F} (%)
$gg \to u\bar{u}$	729	93	0.1276	93.5
$gg \to gu\bar{u}$	6561	639	0.0974	91.6
$gg \to 2gu\bar{u}$	59049	4653	0.0788	92.6
$gg \to 3gu\bar{u}$	531441	35169	0.0662	94.6
$gg \to 4gu\bar{u}$	4782969	272835	0.0570	96.4
$gg \to 5gu\bar{u}$	43046721	2157759	0.0501	97.8
$gg \to 6gu\bar{u}$	387420489	17319837	0.0447	98.6
$gg \to c\bar{c}c\bar{c}$	6561	639	0.0974	99.1
$gg \to gc\bar{c}c\bar{c}$	59049	4653	0.0788	98.8
$gg \to 2gc\bar{c}c\bar{c}$	531441	35169	0.0662	99.0
$gg \to 3gc\bar{c}c\bar{c}$	4782969	272835	0.0570	99.3
$gg \to 4gc\bar{c}c\bar{c}$	43046721	2157759	0.0501	99.6

MC over Helicity

- Summation over helicities – explicit summation over all helicity configurations
- Monte Carlo approach
- For gluon the polarisation vector is introduced

$$\varepsilon^{\mu}_{\phi}(p)=e^{i\phi}\varepsilon^{\mu}_{+}(p)+e^{-i\phi}\varepsilon^{\mu}_{-}(p) \qquad \phi\in(0,2\pi)$$

- By integrating over ϕ we obtain summ over helicities

$$\frac{1}{2}\pi\int_{0}^{2\pi} d\phi\,\varepsilon^{\mu}_{\phi}(p)(\varepsilon^{\nu}_{\phi}(p))^{*}=\sum_{\lambda=\pm}\varepsilon^{\mu}_{\lambda}(p)(\varepsilon^{\nu}_{\lambda}(p))^{*}$$

- For the quark for example we have

$$u_{\phi}(p)=e^{i\phi}u_{+}(p)+e^{-i\phi}u_{-}(p)$$

$$\sum_{\lambda=\pm}u_{\lambda}(p)\bar{u}_{\lambda}(p)=p^{\mu}\gamma_{\mu}$$

Results & Comparisons

- Summation over all possible colour configurations versus MC summation

LHC

pp $\Rightarrow$ $\sqrt{s}=14\,\text{TeV}$

$p_{T_i}>60\,\text{GeV}$

$|y_i|<2.5$

$\Delta R_{ij}>1.0$

$\alpha_s=0.13$

Process	$\sigma_{\text{EXACT}} \pm \epsilon$ (nb)	ϵ (%)	$\sigma_{\text{MC}} \pm \epsilon$ (nb)	ϵ (%)
$gg \to 2g$	$(0.46572 \pm 0.00258)\times 10^{4}$	0.5	$(0.46849 \pm 0.00308)\times 10^{4}$	0.6
$gg \to 3g$	$(0.15040 \pm 0.00159)\times 10^{3}$	1.0	$(0.15127 \pm 0.00110)\times 10^{3}$	0.7
$gg \to 4g$	$(0.11873 \pm 0.00224)\times 10^{2}$	1.9	$(0.12116 \pm 0.00134)\times 10^{2}$	1.1
$gg \to 5g$	$(0.10082 \pm 0.00198)\times 10^{1}$	1.9	$(0.09719 \pm 0.00142)\times 10^{1}$	1.5
$gg \to 6g$	$(0.74717 \pm 0.01490)\times 10^{-1}$	2.0	$(0.76652 \pm 0.01862)\times 10^{-1}$	2.4
$gg \to u\bar{u}$	$(0.36435 \pm 0.00199)\times 10^{2}$	0.5	$(0.36619 \pm 0.00132)\times 10^{2}$	0.4
$gg \to gu\bar{u}$	$(0.35768 \pm 0.00459)\times 10^{1}$	1.3	$(0.35466 \pm 0.00291)\times 10^{1}$	0.8
$gg \to 2gu\bar{u}$	$(0.49721 \pm 0.00758)\times 10^{0}$	1.5	$(0.50053 \pm 0.00725)\times 10^{0}$	1.4
$gg \to 3gu\bar{u}$	$(0.50598 \pm 0.01441)\times 10^{-1}$	2.8	$(0.52908 \pm 0.01264)\times 10^{-1}$	2.4
$gg \to 4gu\bar{u}$	$(0.51549 \pm 0.02017)\times 10^{-2}$	3.9	$(0.51581 \pm 0.01245)\times 10^{-2}$	2.4
$gg \to c\bar{c}c\bar{c}$	$(0.25190 \pm 0.00528)\times 10^{-2}$	2.1	$(0.24903 \pm 0.00373)\times 10^{-2}$	1.5
$gg \to gc\bar{c}c\bar{c}$	$(0.60196 \pm 0.01908)\times 10^{-3}$	3.2	$(0.58817 \pm 0.00926)\times 10^{-3}$	1.6
$gg \to 2gc\bar{c}c\bar{c}$	$(0.95682 \pm 0.03441)\times 10^{-4}$	3.6	$(0.92212 \pm 0.02485)\times 10^{-4}$	2.7

Results & Comparisons

- Higher number of external partons
- 10^6 Monte Carlo points passing cuts

CTEQ6L1 PDF's

- Customary PS generator
- PHEGAS
- HAAG
- RAMBO

Process	$\sigma_{MC} \pm \varepsilon$ (nb)	ε (%)
$gg \to 7g$	$(0.53185 \pm 0.01149)\times 10^{-2}$	2.1
$gg \to 8g$	$(0.33330 \pm 0.00804)\times 10^{-3}$	2.4
$gg \to 9g$	$(0.13875 \pm 0.00430)\times 10^{-4}$	3.1 !!!
$gg \to 5gu\bar{u}$	$(0.38044 \pm 0.01096)\times 10^{-3}$	2.8
$gg \to 3gc\bar{c}c\bar{c}$	$(0.95109 \pm 0.02456)\times 10^{-5}$	2.6
$gg \to 4gc\bar{c}c\bar{c}$	$(0.81400 \pm 0.02583)\times 10^{-6}$	3.2
$gg \to Zu\bar{u}gg$	$(0.18948 \pm 0.00344)\times 10^{-3}$	1.8
$gg \to W^+\bar{u}dgg$	$(0.62704 \pm 0.01458)\times 10^{-3}$	2.3
$gg \to ZZu\bar{u}gg$	$(0.16217 \pm 0.00420)\times 10^{-6}$	2.6
$gg \to W^+W^-u\bar{u}gg$	$(0.27526 \pm 0.00752)\times 10^{-5}$	2.7
$d\bar{d} \to Zu\bar{u}gg$	$(0.38811 \pm 0.00569)\times 10^{-5}$	1.5
$d\bar{d} \to W^+\bar{c}sgg$	$(0.18765 \pm 0.00453)\times 10^{-5}$	2.4
$d\bar{d} \to ZZgggg$	$(0.99763 \pm 0.02976)\times 10^{-7}$	2.9
$d\bar{d} \to W^+W^-gggg$	$(0.52355 \pm 0.01509)\times 10^{-6}$	2.9

Results & Comparisons

- Comparison of the computational time for $|M|^2$
- t_{EXACT} - time for the processes with summation over all possible colour flows for colour ordered amplitudes
- t_{MC} - time for the processes with the Monte Carlo summation over 'real' colours for full amplitudes

Process	t^{CF}_{EXACT}	t_{MC}	t_{EXACT}/t_{MC}
$gg \to 2g$	0.315×10^0	0.554×10^0	0.57
$gg \to 3g$	0.329×10^1	0.143×10^1	2.30
$gg \to 4g$	0.383×10^2	0.372×10^1	10.29
$gg \to 5g$	0.517×10^3	0.105×10^2	49.24
$gg \to 6g$	0.987×10^4	0.362×10^2	272.65 !!!
$gg \to u\bar{u}$	0.260×10^0	0.466×10^0	0.56
$gg \to gu\bar{u}$	0.196×10^1	0.123×10^0	1.59
$gg \to 2gu\bar{u}$	0.166×10^2	0.348×10^1	4.77
$gg \to 3gu\bar{u}$	0.171×10^3	0.129×10^2	13.25
$gg \to 4gu\bar{u}$	0.197×10^4	0.307×10^2	64.17
$gg \to c\bar{c}c\bar{c}$	0.697×10^1	0.605×10^1	1.15
$gg \to gc\bar{c}c\bar{c}$	0.568×10^2	0.217×10^2	2.62
$gg \to 2gc\bar{c}c\bar{c}$	0.619×10^3	0.401×10^2	15.44

Results & Comparisons

ILC

- SM parameters are given in the G_μ scheme

$$m_W = 80.419\,\mathrm{GeV}, \quad \Gamma_W = 2.12\,\mathrm{GeV}$$
$$m_Z = 91.1882\,\mathrm{GeV}, \quad \Gamma_Z = 2.4952\,\mathrm{GeV}$$
$$G_\mu = 1.6639 \times 10^{-5}\,\mathrm{GeV}^{-2}$$
$$\sin^2\theta_W = 1 - m_W^2/m_Z^2$$

$$\alpha_s = 0.0925\,(0.0891) \quad \Leftrightarrow \quad \sqrt{s} = 360\,(500)\,\mathrm{GeV}$$
$$\alpha_{EM} = \frac{\sqrt{2}\,G_\mu m_W^2 \sin_\theta^2}{\pi}$$

$$m_H = 130\,\mathrm{GeV}, \quad \Gamma_H = 0.00429\,\mathrm{GeV}$$

- Fermions masses and all cuts CKM neglected

$$m_\mu = 105.6583\,\mathrm{MeV}, \quad m_\tau = 1.777\,\mathrm{GeV}$$
$$m_u = 5\,\mathrm{MeV}, \quad m_d = 10\,\mathrm{MeV}$$
$$m_s = 200\,\mathrm{MeV}, \quad m_c = 1.3\,\mathrm{GeV}$$
$$m_b = 4.8\,\mathrm{GeV}$$
$$m_t = 174.3\,\mathrm{GeV}, \quad \Gamma_t = 1.6\,\mathrm{GeV}$$

$$\theta(l,\mathrm{beam}) > 5^\circ, \quad \theta(l,l') > 5^\circ, \quad E_l > 10\,\mathrm{GeV}$$
$$\theta(q,\mathrm{beam}) > 5^\circ, \quad \theta(l,q) > 5^\circ, \quad E_q > 10\,\mathrm{GeV}$$
$$m(q,q') > 10\,\mathrm{GeV}$$

Results & Comparisons

ILC

$e^+e^- \Rightarrow \sqrt{s}=360(500)GeV$

- Cross section for possible signals and backgrounds of top quark pair production
- First row for **360 GeV**
- Second row for **500 GeV**
- QCD coupling constant switch on and off
- Difference of taking into account the QCD or neglecting it of the order of **2-3%**
- Cross section of fully hadronic channel is larger then any other individual $b\bar{b}+4$ jets mode

Top-quark channels

Final state	QCD	AMEGIC++ [fb]	HELAC [fb]
$b\bar{b}u\bar{d}d\bar{u}$	yes	32.90(15)	33.05(14)
	yes	49.74(21)	50.20(13)
	no	32.22(34)	32.12(19)
	no	49.42(44)	50.55(26)
$b\bar{b}u\bar{u}gg$	–	11.23(10)	11.136(41)
	–	9.11(13)	8.832(43)
$b\bar{b}gggg$	–	18.82(13)	18.79(11)
	–	24.09(18)	23.80(17)
$b\bar{b}u\bar{d}e^-\bar{\nu}_e$	yes	11.460(36)	11.488(15)
	yes	17.486(66)	17.492(41)
	no	11.312(37)	11.394(18)
	no	17.366(68)	17.353(31)
$b\bar{b}e^+\nu_e e^-\bar{\nu}_e$	–	3.902(31)	3.885(7)
	–	5.954(55)	5.963(11)
$b\bar{b}e^+\nu_e\mu^-\bar{\nu}_\mu$	–	3.847(15)	3.848(7)
	–	5.865(24)	5.868(10)
$b\bar{b}\mu^+\nu_\mu\mu^-\bar{\nu}_\mu$	–	3.808(16)	3.861(19)
	–	5.840(30)	5.839(12)

Results & Comparisons

ILC

- Vector boson fusion channels
- Switching on and off QCD coupling constant – differences few %
- Taking into account H or neglecting it changes total cross sections by a factor of 2 or larger

Vector fusion with Higgs exchange

Final state	QCD	AMEGIC++ [fb]	HELAC [fb]
$e^-e^+u\bar{u}d\bar{d}$	yes	0.6842(85)	0.6858(31)
	yes	1.237(15)	1.265(5)
	no	0.6453(62)	0.6527(35)
	no	1.206(14)	1.2394(75)
$e^-e^+u\bar{u}e^-e^+$	–	6.06(36)e-03	6.113(87)e-03
	–	6.58(23)e-03	6.614(80)e-03
$e^-e^+u\bar{u}\mu^-\mu^+$	–	9.24(12)e-03	9.04(11)e-03
	–	9.25(17)e-03	9.145(74)e-03
$\nu_e\bar{\nu}_e u\bar{d}d\bar{u}$	yes	1.15(3)	1.176(6)
	yes	2.36(7)	2.432(12)
	no	1.14(3)	1.134(5)
	no	2.35(7)	2.429(13)
$\nu_e\bar{\nu}_e u\bar{d}e^-\bar{\nu}_e$	–	0.426(11)	0.4309(48)
	–	0.916(30)	0.9121(48)
$\nu_e\bar{\nu}_e u\bar{d}\mu^-\bar{\nu}_\mu$	–	0.425(12)	0.4221(30)
	–	0.878(27)	0.8888(47)

Vector fusion without Higgs exchange

Final state	QCD	AMEGIC++ [fb]	HELAC [fb]
$e^-e^+u\bar{u}d\bar{d}$	yes	0.4838(50)	0.4842(25)
	yes	1.0514(97)	1.0445(51)
	no	0.4502(31)	0.4524(23)
	no	1.0239(79)	1.0227(43)
$e^-e^+u\bar{u}e^-e^+$	–	3.757(98)e-03	3.577(43)e-03
	–	4.082(56)e-03	4.214(46)e-03
$e^-e^+u\bar{u}\mu^-\mu^+$	–	5.201(61)e-03	5.119(70)e-03
	–	5.805(67)e-03	5.828(49)e-03
$\nu_e\bar{\nu}_e u\bar{d}d\bar{u}$	yes	0.15007(53)	0.15070(64)
	yes	0.4755(21)	0.4711(24)
	no	0.12828(42)	0.12793(55)
	no	0.4417(19)	0.4398(21)
$\nu_e\bar{\nu}_e u\bar{d}e^-\bar{\nu}_e$	–	0.04546(13)	0.04564(19)
	–	0.16033(63)	0.16011(78)
$\nu_e\bar{\nu}_e u\bar{d}\mu^-\bar{\nu}_\mu$	–	0.04230(12)	0.04180(16)
	–	0.14383(53)	0.14439(65)

Results & Comparisons

ILC

- Higgs-strahlung, Higgs boson is radiated off Z-boson in the s channel
- Higgs boson and QCD channels switch on and off

$$Z \to \mu^+ \mu^-$$
$$H \to W^+ W^- \to 4f$$
$$H \to ZZ \to 4f$$

Higgs production through Higgs-strahlung

Final state	QCD	AMEGIC++ [fb]	HELAC [fb]
$\mu^-\mu^+\mu^-\bar{\nu}_\mu e^-\bar{\nu}_e$	–	0.03244(27)	0.03210(15)
	–	0.03747(29)	0.03749(32)
$\mu^-\mu^+u\bar{d}e^-\bar{\nu}_e$	–	0.0924(8)	0.09306(46)
	–	0.1106(22)	0.10901(66)
$\mu^-\mu^+\mu^-\mu^+e^-e^+$	–	2.828(67)e-03	2.923(52)e-03
	–	2.731(65)e-03	2.691(42)e-03
$\mu^-\mu^+u\bar{u}d\bar{d}$	yes	0.2534(24)	0.2540(16)
	yes	0.2634(22)	0.2642(15)
	no	0.2441(23)	0.2471(15)
	no	0.2593(22)	0.2589(14)
$\mu^-\mu^+u\bar{u}u\bar{u}$	yes	1.125(8)e-02	1.135(22)e-02
	yes	8.767(65)e-03	8.978(58)e-03
	no	7.929(57)e-03	8.078(92)e-03
	no	6.098(35)e-03	6.013(26)e-03

Backgrounds to Higgs-strahlung

Final state	QCD	AMEGIC++ [fb]	HELAC [fb]
$\mu^-\mu^+\mu^-\bar{\nu}_\mu e^-\bar{\nu}_e$	–	0.01845(14)	0.01843(13)
	–	0.03054(23)	0.03092(19)
$\mu^-\mu^+u\bar{d}e^-\bar{\nu}_e$	–	0.05284(57)	0.05209(33)
	–	0.08911(53)	0.08925(48)
$\mu^-\mu^+\mu^-\mu^+e^-e^+$	–	2.204(52)e-03	2.346(49)e-03
	–	2.280(66)e-03	2.277(62)e-03
$\mu^-\mu^+u\bar{u}d\bar{d}$	yes	0.1412(10)	0.1404(11)
	yes	0.2092(12)	0.2075(13)
	no	0.1358(20)	0.1341(12)
	no	0.2040(12)	0.2015(11)
$\mu^-\mu^+u\bar{u}u\bar{u}$	yes	5.937(24)e-03	5.937(25)e-03
	yes	6.134(29)e-03	6.108(27)e-03
	no	2.722(10)e-03	2.710(11)e-03
	no	3.290(12)e-03	3.303(12)e-03

Results & Comparisons

ILC

- Determination of Higgs potential – self couplings of H have to be checked
- Higgs bosons emerge in Higgs-strahlung-like topologies abd decay into $b\bar{b}$
- Final states $e^+e^- \to \mu^+\mu^- 4b$, $Z \to \mu^+\mu^-$
- Contributions mediated by Higgs bosons included or neglected factor **~3-4**
- **QCD** effects checked as well

Triple Higgs coupling

Final state	QCD	AMEGIC++ [fb]	HELAC [fb]
$\mu^-\mu^+ b\bar{b}b\bar{b}$	yes	2.560(26)e-02	2.583(26)e-02
	yes	3.096(60)e-02	3.019(43)e-02
	no	1.711(55)e-02	1.666(28)e-02
	no	2.34(12)e-02	2.36(10)e-02

Backgrounds to triple Higgs coupling

Final state	QCD	AMEGIC++ [fb]	HELAC [fb]
$\mu^-\mu^+ b\bar{b}b\bar{b}$	yes	7.002(32)e-03	7.044(22)e-03
	yes	6.308(24)e-03	6.364(21)e-03
	no	2.955(11)e-03	2.972(12)e-03
	no	3.704(15)e-03	3.695(13)e-03

Les Houches Interface

- Evolution of the parton level final states through parton shower and hadronisation phases done by PYTHIA (new p_T ordered parton shower)
  - Les Houches Accord interfacing routines
- Weighted/Unweighted events, colour flow information, events written to file
  - For particular colour configuration coresponding colour flows are found
  - Colour flow assigned to each event on the basis of the relative probabilities of all possible colour flows

Summary

- Exact **LO** matrix element and cross sections calculation for any process in **SM**
- **EW, QCD, EW&QCD**
- Any number of externl particles
- Computational efficiency 3^n
- Free from task of calculating Feynman diagrams
- Parton level event generation (weighted/unweighted events)
- Fermions mass
- **PDF** sets
- **CKM** matrix
- Selection of kinematical cuts

- Code available in **Fortran 95**