6+ fermions with HELAC/PHEGAS

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- **Reliable cross section computation and event generation for multiparticle processes, with $\sim$ 10-12 particles in the final state.**

- – **HELAC:** A.Kanaki and C.G.Papadopoulos, CPC 132 (2000) 306, hep-ph/0002082.

  Matrix element computation algorithm, based on Dyson-Schwinger equations, including: EWK, QCD, fermion masses, reliable arithmetic, running couplings and masses . . ..

  – **PHEGAS:** C.G.Papadopoulos, CPC 137 (2001) 247, hep-ph/0007335

  Monte-Carlo phase space integration/generation based on optimized multichannel approach.

  hep-ph/0012004 and Tokyo 2001,(CPP2001) Computational particle physics, p. 20-25

HELAC

- **Construction of the skeleton solution of the Dyson-Schwinger equations. At this stage only integer arithmetic is performed. This is part of the initialization phase.**
- **Dressing-up the skeleton with momenta, provided by `PHEGAS` and wave functions, propagators, n-point functions in general.**
- **Unitary and Feynman gauges implemented. Due to multi-precision arithmetic,tests of gauge invariance can be extended to arbitrary precision.**
- **All fermions masses can be non-zero.**
- **All Electroweak and QCD vertices are implemented, including Higgs and would-be Goldstone bosons.**

Colour Configuration - EWK$\oplus$QCD

- $\star$ quarks $1 \dots n$
- $\star$ antiquarks $\sigma_i(1 \dots n)$ and
- $\star$ gluons $= q\bar{q}$

Each color-configuration amplitude is proportional to

$$D_i = \delta_{1,\sigma_i(1)}\delta_{2,\sigma_i(2)} \dots \delta_{n,\sigma_i(n)}$$

where σ_i represents the i-th permutation of the set $1, 2, \dots, n$.

$$\mathcal{C}_{ij} = \sum D_i D_j = N_c^{\alpha} \ , \ \ \alpha = \langle \sigma_1, \sigma_2 \rangle$$

♠ exact color treatment $\Rightarrow$ low color charge

Problem: number of colour connection configurations: $\sim n!$ where n is the number of gluons or $q\bar{q}$ pairs. $\Rightarrow$ Monte-Carlo over continuous colour-space.

PHEGAS

- **Phase space**

$$d\Phi_n = (2\pi)^{4-3n} \prod_{i=1}^{n} \frac{d^3 p_i}{2E_i} \delta\left(\sum E_i - w\right) \delta^3\left(\sum \vec{p}_i\right)$$

- `RAMBO`, `VEGAS`**-based nice but completely inefficient!**

$$d\sigma_n = \mathrm{FLUX} \times |\mathcal{M}_{2\to n}|^2 d\Phi_n$$

  need appropriate mappings of peaking structures, plus optimization!

- **Efficiency $\Rightarrow$ to a large number of generators, each one for a specific class of processes.**

Multichannel approach

$$\mathcal{I} = \int f(\vec{x}) d\mu(\vec{x}) = \int \frac{f(\vec{x})}{p(\vec{x})} p(\vec{x}) d\mu(\vec{x})$$

$$p(\vec{x}) = \sum_{i=1}^{M_{ch}} \alpha_i \, p_i(\vec{x}) \qquad \sum_{i=1}^{M_{ch}} \alpha_i = 1$$

$$\mathcal{I} \to \left\langle \frac{f(\vec{x})}{p(\vec{x})} \right\rangle \qquad \mathcal{E}^2 N \to \left\langle \left(\frac{f(\vec{x})}{p(\vec{x})} \right)^2 - \mathcal{I}^2 \right\rangle$$

$\star$ **Optimize $\alpha_i \Rightarrow$ Minimize $\mathcal{E}$** $\star$

R.Kleiss and R.Pittau, Comput. Phys. Commun. 83, 141 (1994).

6 (and more) fermion production

- Input parameters and cuts as defined in hep-ph/0206070 and the WG
- DS (Dyson-Schwinger) elements, HC (helicity configurations) and CC colour connections) determine the matrix element computational cost.
- FG (Feynman graphs) determine the phase-space generation cost. This is drastically reduced by using 'removing channels' techniques.

FS	CC	DS	FG	HC	σ (fb)	T
$b\bar{b}u\bar{u}d\bar{d}$	2	139+256	821	16	49.05(9)	
	6	981/6	1417	16	49.92(12)	
$b\bar{b}u\bar{u}gg$	-	-	-	-	-	
	22	3276/22	1145	32	5.939(51)	
$b\bar{b}gggg$	-	-	-	-	-	
	65	6112/65	856	64	71.21(72)	
$b\bar{b}u\bar{d}e^-\bar{\nu}_e$	1	215	420	6	17.210(20)	
$b\bar{b}e^+\nu_e e^-\bar{\nu}_e$	1	434	1170	12	5.866(9)	
$b\bar{b}\mu^+\nu_\mu e^-\bar{\nu}_e$	1	200	360	6	5.822(7)	
$b\bar{b}\mu^+\nu_\mu \mu^-\bar{\nu}_\mu$	1	241	405	8	5.809(5)	
$b\bar{b}\mu^+\nu_\mu \tau^-\bar{\nu}_\tau$	1	121	180	4	5.798(4)	
$b\bar{b}u\bar{d}\mu^-\bar{\nu}_\mu$	1	130	210	4	17.107(18)	
	2	145+47	242	4	17.204(18)	

FS=final states CC=colour connections DS=Dyson-Schwinger FG=Feynman graphs HC=helicity configurations Input parameters: hep/ph 0206070 *:average number of DS per colour connection

FS	CC	DS	FG	HC	σ(fb)	T
$b\bar{b}u\bar{u}d\bar{d}$	2	139+256	821	16	48.87(34)	
$b\bar{b}u\bar{u}gg$	-	-	-	-	-	
$b\bar{b}gggg$	-	-	-	-	-	
$b\bar{b}u\bar{d}e^-\bar{\nu}_e$	1	215	420	6	16.88(5)	
$b\bar{b}e^+\nu_e e^-\bar{\nu}_e$	1	434	1170	12	5.95(18)	
$b\bar{b}\mu^+\nu_\mu e^-\bar{\nu}_e$	1	200	360	6	5.712(19)	
$b\bar{b}\mu^+\nu_\mu \mu^-\bar{\nu}_\mu$	1	241	405	8	5.760(27)	

Input parameters: Working Group

FS	CC	DS	FG	HC	σ(fb)	T
$e^-e^+u\bar{u}d\bar{d}$	2	403+235	1640	24	1.212(22)	
$e^-e^+u\bar{u}e^-e^+$	1	749	3474	40	0.0064(3)	
$e^-e^+u\bar{u}\mu^-\mu^+$	1	403	1158	24	0.0086(5)	
$\nu_e\bar{\nu}_e u\bar{d}d\bar{u}$	2	150+246	618	8	1.60(20)	
$\nu_e\bar{\nu}_e u\bar{d}e^-\bar{\nu}_e$	1	303	614	3	0.88(6)	
$\nu_e\bar{\nu}_e u\bar{d}\mu^-\bar{\nu}_\mu$	1	142	196	2	0.77(5)	

Input parameters: Working Group

FS	CC	DS	FG	HC	σ (fb)	T
$\mu^+\mu^-\mu^+\nu_\mu e^-\bar{\nu}_e$	1	334	716	9	0.0373(6)	
$\mu^+\mu^- u\bar{d}e^-\bar{\nu}_e$	1	213	418	6	0.1073(9)	
$\mu^+\mu^-\mu^+\mu^- e^- e^+$	1	648	2316	36	0.00281(16)	
$\mu^+\mu^- u\bar{u}e^- e^+$	1	403	1158	24	0.0099(8)	
$\mu^+\mu^- u\bar{u}d\bar{d}$	2	138+256	820	16	0.2525(33)	
$\mu^+\mu^- u\bar{u}u\bar{u}$	2	256+256	1158	24	0.00587(13)	

Input parameters: Working Group

FS	CC	DS	FG	HC	σ (fb)	T
$\mu^-\mu^+b\bar{b}b\bar{b}$	2	256+256	1158	24	0.00827(18)	
$b\bar{b}b\bar{b}u\bar{d}\mu^-\nu_\mu$	2	938+938	23116	18	0.001576(17)	
$u\bar{d}e^-\bar{\nu}_e\gamma$	1	119	108	6	10.87(18)	

Input parameters: Working Group

Higher-order corrections

- **Fermion-loop corrections have been implemented and studied for up to 3-point vertices.**
- **We have started the computation of 4-point contributions.**
  - `FORM` **has been used to reduce the expressions to Passarino-Veltman coefficient functions**
  - `FF` **has been updated to include level-4 tensor coefficient functions for 4-point integrals.**
  - **Implementation and checking in** `HELAC` **is in progress.**
- **This implementation will allow to study 4 fermion+γ and 6 fermion production including the running of electroweak couplings.**

Outlook

PHEGAS/HELAC: a framework for high-energy phenomenology

- **Standard Model fully included**

⋆ **High color charge processes: multijet production**

P.Draggiotis, R.H.Kleiss and C.G.Papadopoulos, Phys. Lett. B439 (1998) 157;
Eur. Phys. J. C 24 (2002) 447 hep-ph/0202201

⋆ **Higher order corrections**

- Direct approach. Ongoing work to better understand Dyson-Schwinger equations and loop calculations: stepping equations, recursive actions, etc.
- Running couplings and masses: 4-point FL contributions and BBC non-local approch to go beyond 4-fermion final states.