HELAC(NLO) - STATUS REPORT

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NCSR "Demokritos", Athens

MC4LHC: March 30, 2010, CERN

HELAC TEAM

Current

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M. Worek worek@physik.uni-wuppertal.de

Contributors

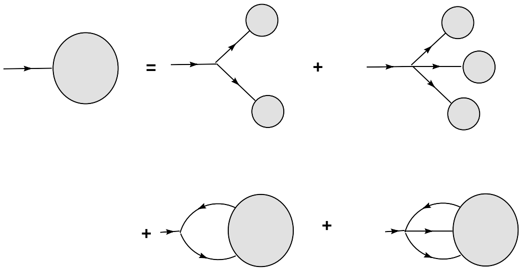
A. Kanaki
A. Cafarella
P. Draggiotis
G. Ossola

HELAC TEAM


HELAC TEAMS
0 500 Miles
0 500 Km
Reykjavik
ICELAND
Norwegian Sea
Arctic Circle
Barents Sea
Murmansk
Archangelsk
FINLAND
Helsinki
Tallinn
St. Petersburg
Moscow
Oslo
Stockholm
NORWAY
SWEDEN
Baltic Sea
North Sea
DENMARK
Copenhagen
Riga
IRELAND
Dublin
U. K.
Edinburgh
London
Paris
FRANCE
Amsterdam
Brussels
Berlin
Prague
Vienna
Bratislava
Budapest
Kiev
UKRAINE
Chisinau
Bucharest
Sofia
Belgrade
Sarajevo
Zagreb
Ljubljana
Bern
Monaco
Rome
Tirane
Skopje
Athens
Ankara
TURKEY
Istanbul
Black Sea
Caspian Sea
RUSSIA
Tbilisi
Yerevan
Baku
Madrid
SPAIN
Lisbon
PORTUGAL
Gibraltar
Rabat
MOROCCO
Algiers
ALGERIA
Tunis
TUNISIA
Tripoli
LIBYA
Valletta
MALTA
Mediterranean Sea
Nicosia
CYPRUS
Beirut
Damascus
SYRIA
Amman
JORDAN
Tel Aviv
Baghdad
IRAQ
SAUDI ARABIA
Cairo
EGYPT

- 1999 HELAC: The first code to calculate recursively tree-order amplitudes for (practically) arbitrary number of particles

A. Kanaki and C. G. Papadopoulos, Comput. Phys. Commun. **132** (2000) 306 [arXiv:hep-ph/0002082].



Dyson-Schwinger Recursive Equations

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- 2000 PHEGAS: The first code to automatically produce phase-space mappings based on all FD

C. G. Papadopoulos, Comput. Phys. Commun. **137** (2001) 247 [arXiv:hep-ph/0007335].

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- Including all SM, in both unitary and F-gauge, masses, CKM, unstable particle widths, complex mass scheme, etc.
- For QCD color connection representation: revival of the 't Hooft ideas ('71) in the modern era.

Color representation

Color-assignment $\rightarrow$ color connections

$$\mathcal{M}^{i_1,i_2,\ldots,i_k}_{j_1,j_2,\ldots,j_k} = \sum_{\sigma} \delta_{i_{\sigma_1},j_1} \delta_{i_{\sigma_2},j_2} \ldots \delta_{i_{\sigma_k},j_k} A_{\sigma}$$

gluons $\rightarrow (i,j)$, quark $\rightarrow (i,0)$, anti-quark $\rightarrow (0,j)$, other $\rightarrow (0,0)$

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Color sum

$$\sum_{\{i\},\{j\}} |\mathcal{M}^{i_1,i_2,\ldots,i_k}_{j_1,j_2,\ldots,j_k}|^2$$

$$\sum_{\sigma,\sigma'} A^*_\sigma \mathcal{C}_{\sigma,\sigma'} A_{\sigma'}$$

$$\mathcal{C}_{\sigma,\sigma'} \equiv \sum_{\{i\},\{j\}} \delta_{i_{\sigma_1},j_1}\delta_{i_{\sigma_2},j_2}\ldots\delta_{i_{\sigma_k},j_k}\delta_{i_{\sigma'_1},j_1}\delta_{i_{\sigma'_2},j_2}\ldots\delta_{i_{\sigma'_k},j_k}$$

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Color-assignment → color connections

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Color sum

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$$\sum_{\sigma,\sigma'} A^*_\sigma \mathcal{C}_{\sigma,\sigma'} A_{\sigma'}$$

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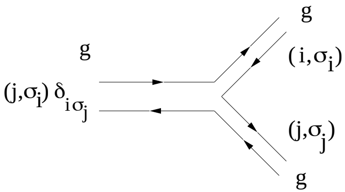
Color-connection Feynman Rules



HELAC TREE ORDER CURRENT VERSION

- 2007 HELAC: http://helac-phegas.web.cern.ch/helac-phegas/

  A. Cafarella, C. G. Papadopoulos and M. Worek, Comput. Phys. Commun. **180** (2009) 1941 [arXiv:0710.2427 [hep-ph]].

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- 2007 `HELAC`: http://helac-phegas.web.cern.ch/helac-phegas/
- Generate all subprocesses for pp, $p\bar{p}$ collisions, calculate cross sections, produce Les Houches accord file

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- Very easy to use: just edit the `user.inp` file and then execute the command `./run.sh`

```
# Compulsory information
colpar 1        # colliding particles: 1=pp, 2=ppbar, 3=e+e-
inist  35 35     # initial state; enter 0 to sum over initial states
finst  35 35     # final state
energy 14000     # collision energy (GeV)

# For reference, here is the particle numbering:
# ve e u d vm mu c s vt ta t  b  a  z  w+ w- g  h chi f+ f- jet
# 1  2 3 4  5  6 7 8  9 10 11 12 31 32 33 34 35 41 42 43 44  100
# The respective antiparticles have a minus sign (for example: positron is -2)
# A jet in the final state is denoted by the number 100

# Enter here your additional commands if you wish to alterate the default values
```

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- Generate all subprocesses for pp, $p\bar{p}$ collisions, calculate cross sections, produce Les Houches accord file
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- Generate all subprocesses for pp, $p\bar{p}$ collisions, calculate cross sections, produce Les Houches accord file
- Very easy to use: just edit the `user.inp` file and then execute the command `./run.sh`
- Including kt-reweight for jet matching
- Latest: $W + 5$ jets at LHC

The HELAC-NLO adventure

The HELAC-NLO adventure

- 2006 OPP: The method that enables us to think seriously about NLO calculations.
  Based on previous work by Bern, Dixon, Kosower, Britto, Cachazo, Feng.

  Z. Bern, L. J. Dixon, D. C. Dunbar and D. A. Kosower, Nucl. Phys. B **425** (1994) 217 [arXiv:hep-ph/9403226].

  R. Britto, F. Cachazo and B. Feng, Nucl. Phys. B **725** (2005) 275 [arXiv:hep-th/0412103].

  Complete framework: numerical (fast) & algebraic (stable)

  G. Ossola, C. G. Papadopoulos and R. Pittau, Nucl. Phys. B **763** (2007) 147 [arXiv:hep-ph/0609007].

- 2006 OPP: The method that enables us to think seriously about NLO calculations.

$$
\begin{aligned}
\int A &= \sum_{i_0<i_1<i_2<i_3}^{m-1} d(i_0 i_1 i_2 i_3) D_0(i_0 i_1 i_2 i_3) \\
&+ \sum_{i_0<i_1<i_2}^{m-1} c(i_0 i_1 i_2) C_0(i_0 i_1 i_2) \\
&+ \sum_{i_0<i_1}^{m-1} b(i_0 i_1) B_0(i_0 i_1) \\
&+ \sum_{i_0}^{m-1} a(i_0) A_0(i_0) \\
&+ \text{rational terms}
\end{aligned}
$$

Algebra & Integrals

- 2006 OPP: The method that enables us to think seriously about NLO calculations.

$$
\begin{aligned}
N(q) &= \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d(i_0 i_1 i_2 i_3) + \tilde{d}(q; i_0 i_1 i_2 i_3)\right] \prod_{i \neq i_0, i_1, i_2, i_3}^{m-1} D_i \\
&+ \sum_{i_0<i_1<i_2}^{m-1} \left[c(i_0 i_1 i_2) + \tilde{c}(q; i_0 i_1 i_2)\right] \prod_{i \neq i_0, i_1, i_2}^{m-1} D_i \\
&+ \sum_{i_0<i_1}^{m-1} \left[b(i_0 i_1) + \tilde{b}(q; i_0 i_1)\right] \prod_{i \neq i_0, i_1}^{m-1} D_i \\
&+ \sum_{i_0}^{m-1} \left[a(i_0) + \tilde{a}(q; i_0)\right] \prod_{i \neq i_0}^{m-1} D_i
\end{aligned}
$$

Solving for known values of the loop momentum q

- 2006 OPP: The method that enables us to think seriously about NLO calculations.
- 2007 CutTools: Reduction at the integrand level + rational terms
  Latest version to appear soon

G. Ossola, C. G. Papadopoulos and R. Pittau, JHEP **0803** (2008) 042 [arXiv:0711.3596 [hep-ph]].

G. Ossola, C. G. Papadopoulos and R. Pittau, JHEP **0805** (2008) 004 [arXiv:0802.1876 [hep-ph]].

The HELAC-NLO adventure

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- AVH_OLO: One-loop scalar integrals including complex masses, IR regulators

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- 2008 `HELAC1L`: Based on `HELAC` to produce virtual one-loop amplitudes

A. van Hameren, C. G. Papadopoulos and R. Pittau, JHEP **0909** (2009) 106 [arXiv:0903.4665 [hep-ph]].

THE HELAC-NLO ADVENTURE

- 2006 `OPP`: The method that enables us to think seriously about NLO calculations.
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- `AVH_OLO`: One-loop scalar integrals including complex masses, IR regulators
- 2008 `HELAC1L`: Based on `HELAC` to produce virtual one-loop amplitudes
- 2009 `HELAC-Dipoles`: Based on `HELAC` to *automatically* produce Catani-Seymour dipoles, I-operator, KP-operator, arbitrary masses

M. Czakon, C. G. Papadopoulos and M. Worek, JHEP **0908** (2009) 085 [arXiv:0905.0883 [hep-ph]].

HELAC-1L

A. van Hameren, C. G. Papadopoulos and R. Pittau, JHEP **0909** (2009) 106 [arXiv:0903.4665 [hep-ph]].

Process		**6** D_i	**5** D_i	**4** D_i	**3** D_i	**2** D_i	R_2	**CT**	**Total**
$gg \to t\bar{t}b\bar{b}$	non-planar	18	120	268	220	112	51	6	795
	planar	13	32	35	40	48	25	2	195
$gg \to t\bar{t}gg$	non-planar	168	576	480	224	56	50	14	1568
	planar	2	14	40	60	60	34	3	213

HELAC-1L

$pp \to t\bar{t}b\bar{b}$			
$u\bar{u} \to t\bar{t}b\bar{b}$			
	ϵ^{-2}	ϵ^{-1}	ϵ^{0}
HELAC-1L	-2.347908989000179E-07	-2.082520105681483E-07	3.909384299635230E-07
$I(\epsilon)$	-2.347908989000243E-07	-2.082520105665445E-07	
$gg \to t\bar{t}b\bar{b}$			
HELAC-1L	-1.435108168334016E-06	-2.085070773763073E-06	3.616343483497464E-06
$I(\epsilon)$	-1.435108168334035E-06	-2.085070773651439E-06	

	p_x	p_y	p_z	E
$u(g)$	0	0	250	250
$\bar{u}(g)$	0	0	-250	250
t	12.99421901255723	-9.591511769543683	75.05543670827210	190.1845561691092
$\bar{t}$	53.73271578143694	-0.2854146459513714	17.68101382654795	182.9642163285034
b	-41.57664370692741	3.895531135098977	-91.94931862397770	100.9874727883170
$\bar{b}$	-25.15029108706678	5.981395280396083	-0.7871319108423604	25.86375471407044

HELAC-1L

$pp \to VVb\bar{b}$ and $pp \to VV+$ 2 jets			
$u\bar{u} \to W^+W^-b\bar{b}$			
	ϵ^{-2}	ϵ^{-1}	ϵ^{0}
HELAC-1L	-2.493916939359002E-07	-4.885901774740355E-07	1.592538533368835E-07
$I(\epsilon)$	-2.493916939359001E-07	-4.885901774752593E-07	
$gg \to W^+W^-b\bar{b}$			
HELAC-1L	-2.686310592221201E-07	-6.078682316434646E-07	-2.431624440346638E-07
$I(\epsilon)$	-2.686310592221206E-07	-6.078682340168020E-07	

	p_x	p_y	p_z	E
$u(g)$	0	0	250	250
$\bar{u}(g)$	0	0	-250	250
W^+	22.40377113462118	-16.53704884550758	129.4056091248114	154.8819879118765
W^-	92.64238702192333	-0.4920930146078141	30.48443210132545	126.4095336206695
b	-71.68369328357026	6.716416578342183	-158.5329205583824	174.1159068988160
$\bar{b}$	-43.36246487297426	10.31272528177322	-1.357120667754454	44.59257156863792

HELAC-1L

$pp \to V+$ 3 jets			
$u\bar{d} \to W^+ggg$			
	ϵ^{-2}	ϵ^{-1}	ϵ^{0}
HELAC-1L	-1.995636628164684E-05	-5.935610843551600E-05	-5.323285370666314E-05
$I(\epsilon)$	-1.995636628164686E-05	-5.935610843566534E-05	
$u\bar{u} \to Zggg$			
HELAC-1L	-7.148261887172997E-06	-2.142170009323704E-05	-1.906378375774021E-05
$I(\epsilon)$	-7.148261887172976E-06	-2.142170009540120E-05	

	p_x	p_y	p_z	E
u	0	0	250	250
$\bar{d}$	0	0	-250	250
W^+	23.90724239064912	-17.64681636854432	138.0897548661186	162.5391101447744
g	98.85942812363483	-0.5251163702879512	32.53017998659339	104.0753327455388
g	-76.49423931754684	7.167141557113385	-169.1717405928078	185.8004692730082
g	-46.27243119673712	11.00479118171890	-1.448194259904179	47.58508783667868

HELAC-1L

$pp \to t\bar{t}+$ 2 jets			
$u\bar{u} \to t\bar{t}gg$			
	ϵ^{-2}	ϵ^{-1}	ϵ^{0}
HELAC-1L	-6.127108113312741E-05	-1.874963444741646E-04	-3.305349683690902E-04
$I(\epsilon)$	-6.127108113312702E-05	-1.874963445081074E-04	
$gg \to t\bar{t}gg$			
HELAC-1L	-3.838786514961561E-04	-9.761168899507888E-04	-5.225385984750410E-04
$I(\epsilon)$	-3.838786514961539E-04	-9.761168898436521E-04	

	p_x	p_y	p_z	E
$u(g)$	0	0	250	250
$\bar{u}(g)$	0	0	-250	250
t	12.99421901255723	-9.591511769543683	75.05543670827210	190.1845561691092
$\bar{t}$	53.73271578143694	-0.2854146459513714	17.68101382654795	182.9642163285034
g	-41.57664370692741	3.895531135098977	-91.94931862397770	100.9874727883170
g	-25.15029108706678	5.981395280396083	-0.7871319108423604	25.86375471407044

HELAC-1L

$pp \to b\bar{b}b\bar{b}$			
$u\bar{u} \to b\bar{b}b\bar{b}$			
	ϵ^{-2}	ϵ^{-1}	ϵ^{0}
HELAC-1L	-9.205269484951069E-08	-2.404679886692200E-07	-2.553568662778129E-07
$I(\epsilon)$	-9.205269484951025E-08	-2.404679886707971E-07	
$gg \to b\bar{b}b\bar{b}$			
HELAC-1L	-2.318436429821683E-05	-6.958360737366907E-05	-7.564212339279291E-05
$I(\epsilon)$	-2.318436429821662E-05	-6.958360737341511E-05	

	p_x	p_y	p_z	E
$u(g)$	0	0	250	250
$\bar{u}(g)$	0	0	-250	250
b	24.97040523056789	-18.43157602837212	144.2306511496888	147.5321146846735
$\bar{b}$	103.2557390255471	-0.5484684659584054	33.97680766420219	108.7035966213640
b	-79.89596300367462	7.485866671764871	-176.6948628845280	194.0630765341365
$\bar{b}$	-48.33018125244035	11.49417782256567	-1.512595929362970	49.70121215982584

HELAC-DIPOLES

$\mathcal{E}_0$ - massless emitter, $\mathcal{S}_0$ - massless spectator, $\mathcal{E}_M$ - massive emitter, $\mathcal{S}_M$ - massive spectator, $\mathcal{E}_I$ - initial state emitter, $\mathcal{E}_F$ - final state emitter, $\mathcal{S}_I$ - initial state spectator, $\mathcal{S}_F$ - final state spectator, ✓ - check, ■ - does not occur.

	$\mathcal{E}_0/\mathcal{S}_0$	$\mathcal{E}_0/\mathcal{S}_M$	$\mathcal{E}_M/\mathcal{S}_0$	$\mathcal{E}_M/\mathcal{S}_M$
$\mathcal{E}_I/\mathcal{S}_I$				
$g \to gg$	✓	■	■	■
$g \to qq$	✓	■	■	■
$q \to qg$	✓	■	■	■
$q \to gq$	✓	■	■	■
$\mathcal{E}_I/\mathcal{S}_F$				
$g \to gg$	✓	✓	■	■
$g \to qq$	✓	✓	■	■
$q \to qg$	✓	✓	■	■
$q \to gq$	✓	✓	■	■

	$\mathcal{E}_0/\mathcal{S}_0$	$\mathcal{E}_0/\mathcal{S}_M$	$\mathcal{E}_M/\mathcal{S}_0$	$\mathcal{E}_M/\mathcal{S}_M$
$\mathcal{E}_F/\mathcal{S}_I$				
$g \to gg$	✓	■	■	■
$g \to qq$	✓	■	✓	■
$q \to qg$	✓	■	✓	■
$q \to gq$	✓	■	✓	■
$\mathcal{E}_F/\mathcal{S}_F$				
$g \to gg$	✓	✓	■	■
$g \to qq$	✓	✓	✓	✓
$q \to qg$	✓	✓	✓	✓
$q \to gq$	✓	✓	✓	✓

Table 1: *Independent dipole splitting formulae, which need to be tested in order to ensure the correctness of the code. In the splitting description, e.g. $g \to gg$, the left hand side particle always denotes the virtual state.*

HELAC-DIPOLES

PROCESS	REAL EMISSION + DIPOLES [msec]	REAL EMISSION [msec]	NR OF DIPOLES
$gg \to ggg$	3.8	1.0	27
$gg \to gggg$	8.5	2.6	56
$gg \to ggggg$	300	42	100
$u\bar{d} \to W^+gggg$	9.3	2.4	56
$gg \to t\bar{t}b\bar{b}g$	12	2.9	55

Table 2: *The CPU time needed to evaluate the real emission matrix element together with all of the dipole subtraction terms per phase-space point (this corresponds to $\alpha_{max} = 1$). All numbers have been obtained on an Intel 2.53 GHz Core 2 Duo processor with the Intel Fortran compiler using the -fast option.*

HELAC-DIPOLES

- Arbitrary processes QCD+EW

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- Massive and massless external states

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- Restrictions on PS α_{min} and α_{max}

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- Helicity (& color) sampling for partons
- Random helicities for non-partons
- Restrictions on PS α_{min} and α_{max}

```
--------------------------------------------------
Dipole Subtraction Configuration
--------------------------------------------------
only real emission:                 F
only last particle soft/collinear:        F
only divergent dipoles:                 T
random polarization for non-partons:      T
sign mode (0-both,1-positive,2-negative):          0
helicity sum (0-fast,1-slow,2-flat MC):          1
events with polarization sum=              100000
events for sampling optimization=             20000
event increment for sampling update=           10000
alphaMinCut=                        1.000000000000000E-006
alphaMaxII=                        1.00000000000000
alphaMaxIF=                         1.00000000000000
alphaMaxFI=                         1.00000000000000
alphaMaxFF=                          1.00000000000000
kappa=                          0.000000000000000E+000
jet veto included:                 F
pt of vetoing jet=                  50.0000000000000
color sampling: F
--------------------------------------------------
--------------------------------------------------
Number of Dipoles:          55
Number of Processes:          7
--------------------------------------------------
--------------------------------------------------
```

HOW HELAC-NLO WORKS-VIRTUAL

Generate $w = 1$ events (Les Houches format) using HELAC at tree order. Information included: LH + color assignment, helicity. Optimization!

Generate $w = 1$ events (Les Houches format) using HELAC at tree order. Information included: LH + color assignment, helicity. Optimization!

```
<event>
   6   81  1.000000E+00  1.726000E+02  7.546772E-03  1.180000E-01
    21  -1    0    0  103  101  0.000000000000000E+00  0.000000000000000E+00  4.885658920243087E+02  4.885658920243087E+02  0.000000000000000E+00  0.000000E+00  9.0000E+00
    21  -1    0    0  104  102  0.000000000000000E+00  0.000000000000000E+00 -4.885658920243087E+02  4.885658920243087E+02  0.000000000000000E+00  0.000000E+00  9.0000E+00
     6   1    1    2  103    0  1.648551153938704E+02 -2.128833463956879E+01  1.563411288268662E+01  2.401366022681282E+02  1.726000000000000E+02  0.000000E+00  9.0000E+00
    -6   1    1    2    0  102 -6.677109609683933E+01  6.109017946596872E+01 -3.256227583127494E+02  3.794882475549945E+02  1.726000000000000E+02  0.000000E+00  9.0000E+00
     5   1    1    2  104    0  4.725480269309031E+00  2.281431584259000E+01  1.753945210216305E+02  1.769351891952198E+02  0.000000000000000E+00  0.000000E+00  9.0000E+00
    -5   1    1    2    0  101 -1.028094995663402E+02 -6.261616066898994E+01  1.345941244084323E+02  1.805717450302747E+02  0.000000000000000E+00  0.000000E+00  9.0000E+00
#  9.193930413382987E-08      4      3      4     14     13
#   0.000000000000000E+00  0.000000000000000E+00  0.000000000000000E+00  0.000000000000000E+00  7.869627745360847E-01 -1.175027485420859E+00 -7.869627745360847E-01
-1.175027485420859E+00
#   0.000000000000000E+00  0.000000000000000E+00  0.000000000000000E+00  0.000000000000000E+00  1.376454726499085E+00 -3.246111302748730E-01 -1.376454726499085E+00
-3.246111302748730E-01
#   1.863667555432868E+01 -3.562491121497572E+00 -9.077135267012881E+00  6.153194387677511E+00 -1.970622777463714E+01 -1.717507312227297E+00 -6.433090024792207E+00
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6.683084353093276E+00
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-1.755067698199695E+01
# pdf  3.605966723564206E-02  1.350916463377768E-01
</event>
```

HOW HELAC-NLO WORKS-VIRTUAL

Do this sum by MC (sample a configuration $\{i\} = 1, 2, 3$ $\{j\} = 1, 2, 3$)

$$\sum_{\{i\},\{j\}} |\mathcal{M}^{i_1,i_2,\ldots,i_k}_{j_1,j_2,\ldots,j_k}|^2$$

Express in terms of color connections A_σ

$$\mathcal{M}^{i_1,i_2,\ldots,i_k}_{j_1,j_2,\ldots,j_k} = \sum_\sigma \delta_{i_{\sigma_1},j_1}\delta_{i_{\sigma_2},j_2}\ldots\delta_{i_{\sigma_k},j_k} A_\sigma$$

Very significant reduction in CPU-time

Process	n_{conn}	$\langle n_{conn}\rangle_{MC}$	Ratio
$gg \to b\bar{b}\,W^+W^-$	6	1.74	3.5
$gg \to t\bar{t}b\bar{b}$	24	3.04	7.9
$gg \to t\bar{t}gg$	120	6.27	19.1

HOW HELAC-NLO WORKS-VIRTUAL

Generate $w = 1$ events (Les Houches format) using HELAC at tree order. Information included: LH + color assignment, helicity. Optimization!

Calculate using `HELAC-1L` virtual part for each $w = 1$ event. Produce a new LH file including virtual corrections. Includes UV renormlization

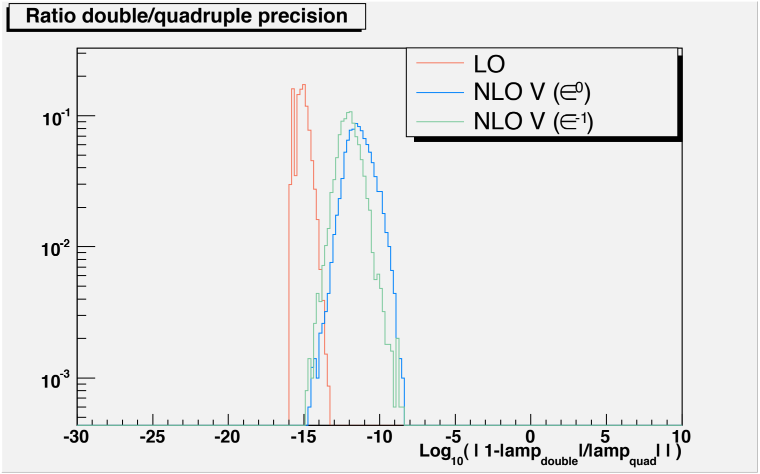
HOW HELAC-NLO WORKS-VIRTUAL

Generate $w = 1$ events (Les Houches format) using HELAC at tree order. Information included: LH + color assignment, helicity. Optimization!

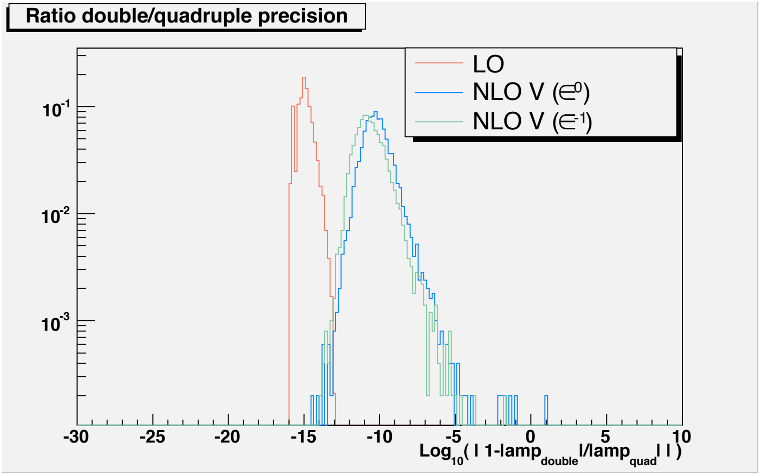
Calculate using `HELAC-1L` virtual part for each $w = 1$ event. Produce a new LH file including virtual corrections. Includes UV renormlization

The final LH file can now be used to produce any kinematical distribution !

HOW HELAC-NLO WORKS - STABILITY



HOW HELAC-NLO WORKS - STABILITY



HOW HELAC-NLO WORKS-REAL

`HELAC-DIPOLES`

Generate CS Dipoles and calculate $R - D$, jet-algorithm, histograms

HOW HELAC-NLO WORKS-REAL

HELAC-DIPOLES

Generate CS Dipoles and calculate $R - D$, jet-algorithm, histograms

Calculate I operator contributions, histograms

HOW HELAC-NLO WORKS-REAL

HELAC-DIPOLES

Generate CS Dipoles and calculate $R - D$, jet-algorithm, histograms

Calculate I operator contributions, histograms

Calculate KP operator contributions, histograms

$pp \to VVV$

T. Binoth, G. Ossola, C. G. Papadopoulos and R. Pittau, JHEP **0806** (2008) 082 [arXiv:0804.0350 [hep-ph]].

Process	scale μ	Born cross section [fb]	NLO cross section [fb]
ZZZ	$3M_Z$	9.7(1)	15.3(1)
WZZ	$2M_Z + M_W$	20.2(1)	40.4(2)
WWZ	$M_Z + 2M_W$	96.8(6)	181.7(8)
WWW	$3M_W$	82.5(5)	146.2(6)

Table 1: Cross section for the four processes, corresponding to the distributions in Fig 4. Different values of the factorization(renormalization) scale are used for the different processes.

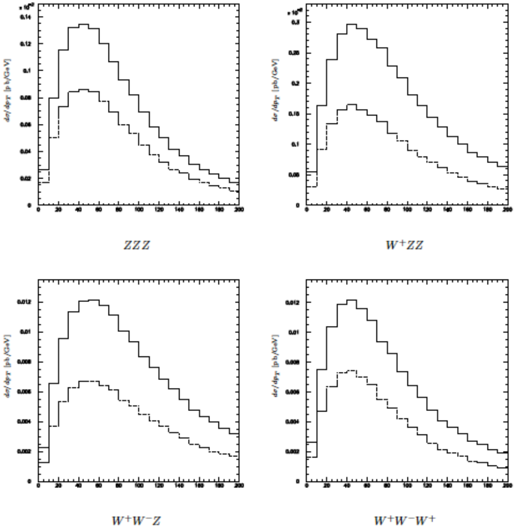


Figure 4: Transverse momentum distribution, as defined in the text, for the four processes $pp \to VVV$: NLO (solid line) compared with the LO contribution (dashed line).

G. Bevilacqua, M. Czakon, C. G. Papadopoulos, R. Pittau and M. Worek, JHEP **0909** (2009) 109 [arXiv:0907.4723 [hep-ph]].

Setup: $\sqrt{s} = 14$ TeV, $p_{T,b} > 20$ GeV, $\Delta R > 0.8$, $|y_b| < 2.5$
$\mu_R = \mu_F = m_t$

Process	$\sigma^{\rm LO}_{[23,24]}$ [fb]	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}_{[23,24]}$ [fb]	$\sigma^{\rm NLO}_{\alpha_{max}=1}$ [fb]	$\sigma^{\rm NLO}_{\alpha_{max}=0.01}$ [fb]
$q\bar{q} \to t\bar{t}b\bar{b}$	85.522(26)	85.489(46)	87.698(56)	87.545(91)	87.581(134)
$pp \to t\bar{t}b\bar{b}$	1488.8(1.2)	1489.2(0.9)	2638(6)	2642(3)	2636(3)

Table 1: *Cross sections for $pp \to t\bar{t}b\bar{b} + X$ at the LHC at LO and NLO for the scale choice $\mu_F = \mu_R = m_t$, in comparison with the results of Refs. [23, 24]. The statistical errors are quoted in parentheses.*

$$K = 1.77$$

$pp \to t\bar{t}b\bar{b}$

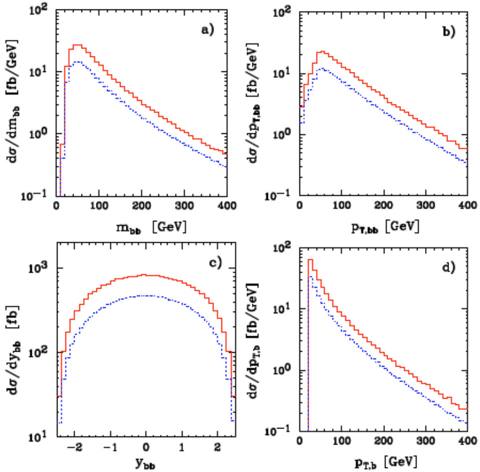


Figure 3: *Distribution of the invariant mass $m_{b\bar{b}}$ of the bottom-anti-bottom pair (a), distribution in the transverse momentum $p_{T_{b\bar{b}}}$ of the bottom-anti-bottom pair (b), distribution in the rapidity $y_{b\bar{b}}$ of the bottom-anti-bottom pair (c) and distribution in the transverse momentum p_{T_b} of the bottom quark (d) for $pp \to t\bar{t}b\bar{b} + X$ at the LHC at LO (blue dashed line) and NLO (red solid line). All distributions have been obtained with $\alpha_{max} = 0.01$.*

$pp \to t\bar{t}(H \to)b\bar{b}$

"The SM and NLO multileg working group: Summary report," arXiv:1003.1241 [hep-ph].

With realistic cuts on $b\bar{b}$

$\mu_R = \mu_F = m_t + m_H/2$

$$\sigma^{\rm S}_{\rm LO} = (150.375 \pm 0.077)\ {\rm fb}\,.$$

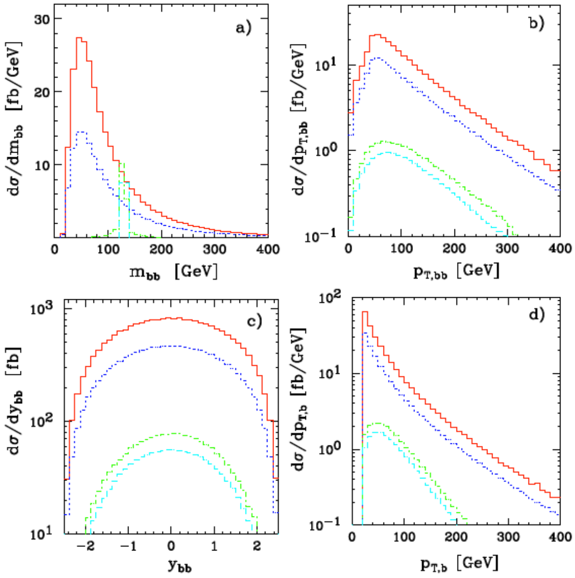
At the NLO we obtain

$$\sigma^{\rm S}_{\rm NLO} = (207.473 \pm 0.232)\ {\rm fb} \quad {\rm for}\ \ \alpha_{\rm max} = 0.01\,,$$

$$\sigma^{\rm S}_{\rm NLO} = (207.268 \pm 0.150)\ {\rm fb} \quad {\rm for}\ \ \alpha_{\rm max} = 1$$

$K = 1.38$

$pp \to t\bar{t}(H \to)b\bar{b}$



G. Bevilacqua, M. Czakon, C. G. Papadopoulos and M. Worek, arXiv:1002.4009 [hep-ph].

Setup: $\sqrt{s} = 14$ TeV, $p_{T,j} > 20$ GeV, $\Delta R > 1$, $|y_j| < 4.5$

$$\sigma_{t\bar{t}jj}^{NLO} = (106.94 \pm 0.17)\text{pb} \quad K = 0.89$$

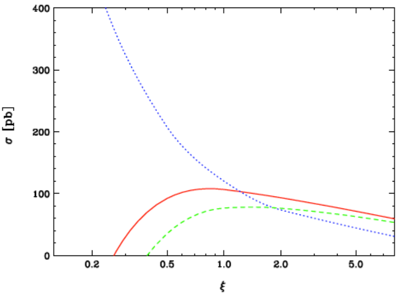
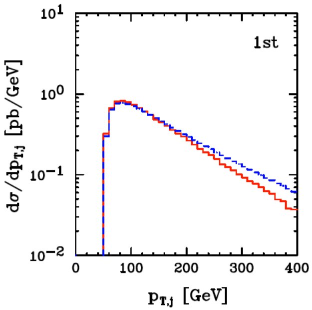
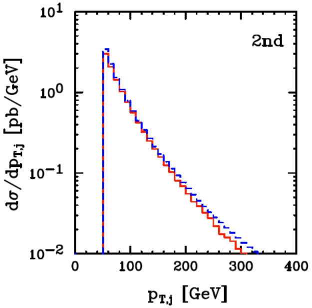


FIG. 2: Scale dependence of the total cross section for $pp \to t\bar{t}jj + X$ at the LHC with $\mu_R = \mu_F = \xi \cdot \mu_0$ where $\mu_0 = m_t$. The blue dotted curve corresponds to the LO, the red solid to the NLO result whereas the green dashed to the NLO result with a jet veto of 50 GeV.

$pp \to t\bar{t}+2$ JETS





HELAC-NLO

- Complete software for NLO-QCD at LHC:
  LO (lhc)+ Virtual(lhc) + Real(lhc ?)
  lhc=Les Houches Compatible

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- Speed, stability, efficiency issues under control
  Improvements in PS for real corrections

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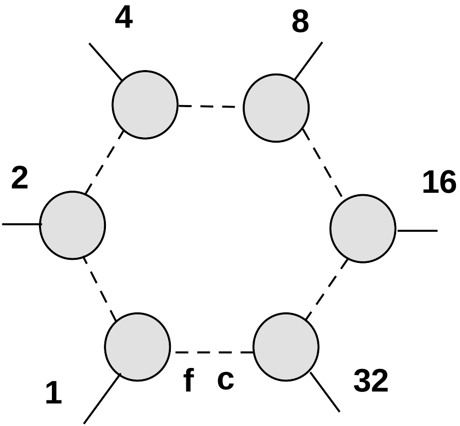
- Complete software for NLO-QCD at LHC:
  LO (lhc)+ Virtual(lhc) + Real(lhc ?)
  lhc=Les Houches Compatible

- Speed, stability, efficiency issues under control
  Improvements in PS for real corrections

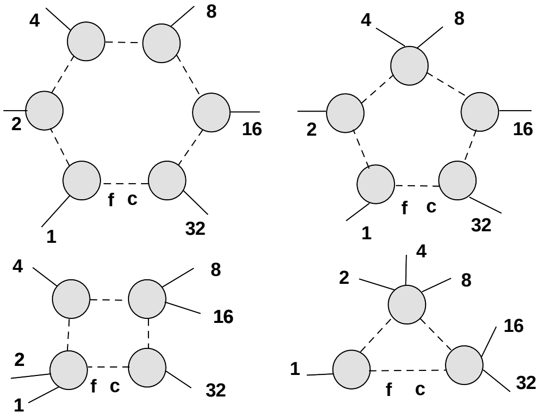
- Provide NLO calculator for all processes $2 \to n$, where 4(5) out of n, i.e. 6(7) particles attached to the loop
  MCFM-type approach ?

For those who are interested in more details

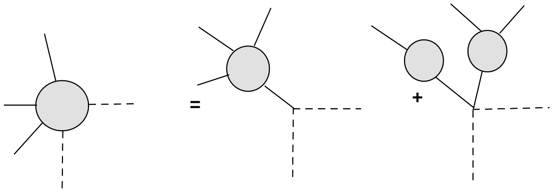
HELAC 1-LOOP



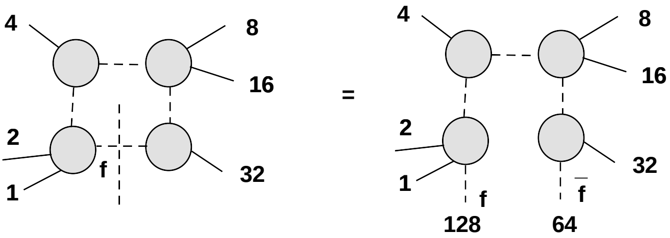
HELAC 1-LOOP



HELAC 1-LOOP



HELAC 1-LOOP



$$\mathcal{M}^{a_1,i_2,\ldots,i_k}_{j_2,\ldots,j_k} t^{a_1}_{i_1 j_1} \to \mathcal{M}^{i_1,i_2,\ldots,i_k}_{j_1,j_2,\ldots,j_k}$$

$$\mathcal{M}^{i_1,i_2,\ldots,i_k}_{j_1,j_2,\ldots,j_k} = \sum_{\sigma} \delta_{i_{\sigma_1},j_1} \delta_{i_{\sigma_2},j_2} \ldots \delta_{i_{\sigma_k},j_k} A_\sigma$$

$$\sum_{\{i\},\{j\}} |\mathcal{M}^{i_1,i_2,\ldots,i_k}_{j_1,j_2,\ldots,j_k}|^2$$

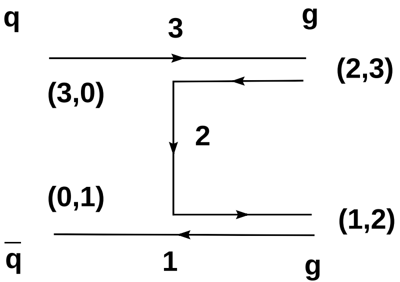
$$\sum_{\sigma,\sigma'} A^*_\sigma \mathcal{C}_{\sigma,\sigma'} A_{\sigma'}$$

$$\mathcal{C}_{\sigma,\sigma'} \equiv \sum_{\{i\},\{j\}} \delta_{i_{\sigma_1},j_1} \delta_{i_{\sigma_2},j_2} \ldots \delta_{i_{\sigma_k},j_k} \delta_{i_{\sigma'_1},j_1} \delta_{i_{\sigma'_2},j_2} \ldots \delta_{i_{\sigma'_k},j_k}$$

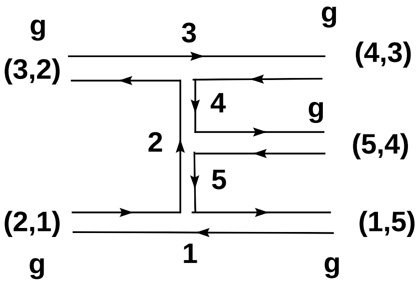
HELAC Color treatment

$$(x_1, y_1) \dots (x_n, y_n)$$

where y_i take the values $\{1, 2, \dots, n_l\}$ if i is a gluon or an outgoing quark (incoming anti-quark) otherwise $y_i = 0$, whereas x_i take the values $\{\sigma_1, \sigma_2, \dots, \sigma_{n_l}\}$ if i is a gluon or an incoming quark (outgoing anti-quark) otherwise $x_i = 0$. So for instance for a $q\bar{q} \to gg$ process, $n_l = 3$ and a possible color connection is given by $(3, 0)(0, 1)(1, 2)(2, 3)$



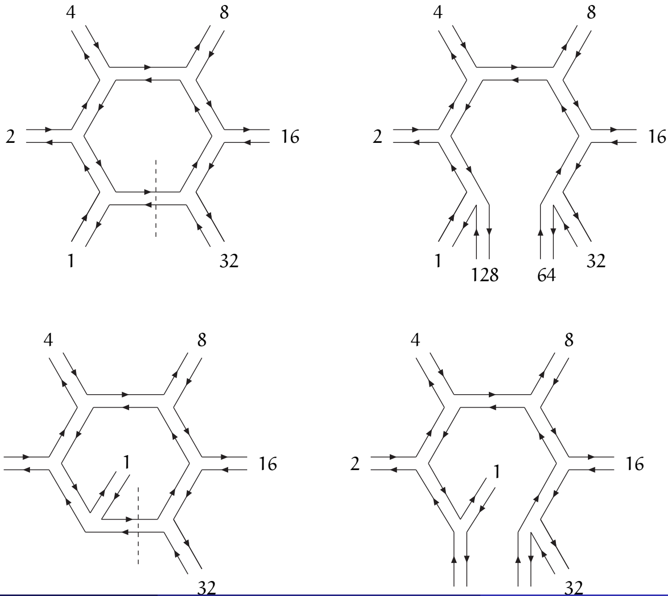
whereas for $gg \to ggg$, $n_l = 5$ and a possible color connection is given by $(2,1)(3,2)(4,3)(5,4)(1,5)$

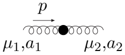


$$\mathcal{C}_{\sigma,\sigma'} = N_c^{m(\sigma,\sigma')}$$

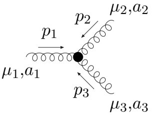
where $m(\sigma,\sigma')$ count the number of common cycles of the two permutations.

HELAC Color treatment - 1 loop

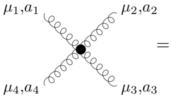




$$= \frac{ig^2 N_{col}}{48\pi^2}\,\delta_{a_1 a_2}\left[\frac{p^2}{2} g_{\mu_1\mu_2} + \lambda_{HV}\left(g_{\mu_1\mu_2}p^2 - p_{\mu_1}p_{\mu_2}\right) + \frac{N_f}{N_{col}}\,(p^2 - 6\,m_q^2)\,g_{\mu_1\mu_2}\right]$$

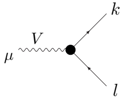


$$= -\frac{g^3 N_{col}}{48\pi^2}\left(\frac{7}{4} + \lambda_{HV} + 2\frac{N_f}{N_{col}}\right) f^{a_1 a_2 a_3}\, V_{\mu_1\mu_2\mu_3}(p_1, p_2, p_3)$$

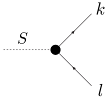


$$= -\frac{ig^4 N_{col}}{96\pi^2}\sum_{P(234)}\left\{\left[\frac{\delta_{a_1a_2}\delta_{a_3a_4} + \delta_{a_1a_3}\delta_{a_4a_2} + \delta_{a_1a_4}\delta_{a_2a_3}}{N_{col}} + 4\,Tr(t^{a_1}t^{a_3}t^{a_2}t^{a_4} + t^{a_1}t^{a_4}t^{a_2}t^{a_3})\,(3+\lambda_{HV}) - Tr(\{t^{a_1}t^{a_2}\}\{t^{a_3}t^{a_4}\})\,(5+2\lambda_{HV})\right] g_{\mu_1\mu_2}g_{\mu_3\mu_4} + 12\frac{N_f}{N_{col}}Tr(t^{a_1}t^{a_2}t^{a_3}t^{a_4})\left(\frac{5}{3}g_{\mu_1\mu_3}g_{\mu_2\mu_4} - g_{\mu_1\mu_2}g_{\mu_3\mu_4} - g_{\mu_2\mu_3}g_{\mu_1\mu_4}\right)\right\}$$

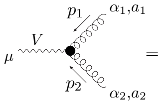
HELAC R2 TERMS



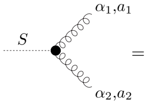
$$= -\frac{g^2}{16\pi^2}\frac{N_{col}^2-1}{2N_{col}}\,\delta_{kl}\gamma_\mu\,(v+a\gamma_5)\,(1+\lambda_{HV})$$



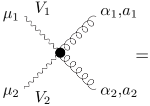
$$= -\frac{g^2}{8\pi^2}\frac{N_{col}^2-1}{2N_{col}}\,\delta_{kl}\,(c+d\gamma_5)\,(1+\lambda_{HV})$$



$$= a\,\frac{ig^2}{12\pi^2}\,\delta_{a_1a_2}\epsilon_{\mu\alpha_1\alpha_2\beta}\,(p_1-p_2)^\beta$$



$$= c\,\frac{g^2}{8\pi^2}\,\delta_{a_1a_2}g_{\alpha_1\alpha_2}\,m_q$$



$$= -\frac{ig^2}{24\pi^2}\,\delta_{a_1a_2}(v_1v_2+a_1a_2)\,(g_{\mu_1\mu_2}g_{\alpha_1\alpha_2}+g_{\mu_1\alpha_1}g_{\mu_2\alpha_2}+g_{\mu_1\alpha_2}g_{\mu_2\alpha_1})$$

```
 kmax,ncc,nmax [illegible] 24 [illegible] 10
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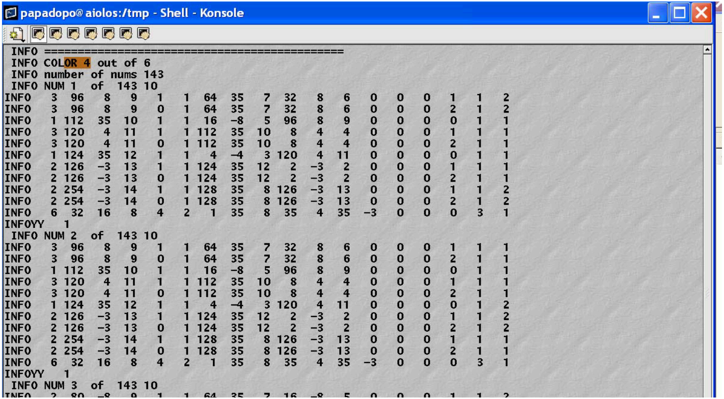
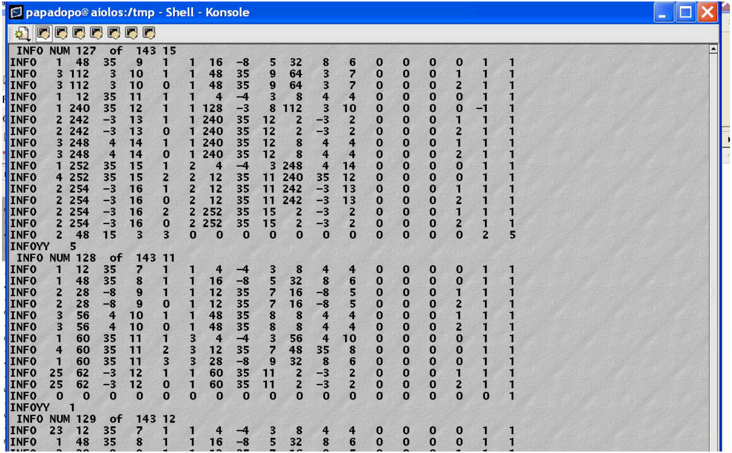
INFO    2  62  -3  16   1   3  12  35   7  50  -3  12   0   0   0   1   1   2
INFO    2  62  -3  16   0   3  12  35   7  50  -3  12   0   0   0   2   1   2
INFO    2  62  -3  16   2   3  48  35   8  14  -3   9   0   0   0   1   1   2
INFO    2  62  -3  16   0   3  48  35   8  14  -3   9   0   0   0   2   1   2
INFO    2  62  -3  16   3   3  60  35  15   2  -3   2   0   0   0   1   1   2
INFO    2  62  -3  16   0   3  60  35  15   2  -3   2   0   0   0   2   1   2
 INFO ================================================
 INFO COLOR 2 out of 6
INFO    1  12  35   7   1   1   4  -4   3   8   4   4   0   0   0   0   1   1
INFO    1  48  35   8   1   1  16  -8   5  32   8   6   0   0   0   0   1   1
```


papadopo@aiolos:/tmp - Shell - Konsole
INFO ==
INFO COLOR 4 out of 6
INFO number of nums 143
INFO NUM 1 of 143 10
INFO 3 96 8 9 1 1 64 35 7 32 8 6 0 0 0 1 1 2
INFO 3 96 8 9 0 1 64 35 7 32 8 6 0 0 0 2 1 2
INFO 1 112 35 10 1 1 16 -8 5 96 8 9 0 0 0 0 1 1
INFO 3 120 4 11 1 1 112 35 10 8 4 4 0 0 0 1 1 1
INFO 3 120 4 11 0 1 112 35 10 8 4 4 0 0 0 2 1 1
INFO 1 124 35 12 1 1 4 -4 3 120 4 11 0 0 0 0 1 1
INFO 2 126 -3 13 1 1 124 35 12 2 -3 2 0 0 0 1 1 1
INFO 2 126 -3 13 0 1 124 35 12 2 -3 2 0 0 0 2 1 1
INFO 2 254 -3 14 1 1 128 35 8 126 -3 13 0 0 0 1 1 2
INFO 2 254 -3 14 0 1 128 35 8 126 -3 13 0 0 0 2 1 2
INFO 6 32 16 8 4 2 1 35 8 35 4 35 -3 0 0 0 3 1
INFOYY 1
INFO NUM 2 of 143 10
INFO 3 96 8 9 1 1 64 35 7 32 8 6 0 0 0 1 1 1
INFO 3 96 8 9 0 1 64 35 7 32 8 6 0 0 0 2 1 1
INFO 1 112 35 10 1 1 16 -8 5 96 8 9 0 0 0 0 1 1
INFO 3 120 4 11 1 1 112 35 10 8 4 4 0 0 0 1 1 1
INFO 3 120 4 11 0 1 112 35 10 8 4 4 0 0 0 2 1 1
INFO 1 124 35 12 1 1 4 -4 3 120 4 11 0 0 0 0 1 2
INFO 2 126 -3 13 1 1 124 35 12 2 -3 2 0 0 0 1 1 2
INFO 2 126 -3 13 0 1 124 35 12 2 -3 2 0 0 0 2 1 2
INFO 2 254 -3 14 1 1 128 35 8 126 -3 13 0 0 0 1 1 1
INFO 2 254 -3 14 0 1 128 35 8 126 -3 13 0 0 0 2 1 1
INFO 6 32 16 8 4 2 1 35 8 35 4 35 -3 0 0 0 3 1
INFOYY 1
INFO NUM 3 of 143 10

HELAC 1-LOOP

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 INFO NUM 127  of  143 15
INFO   1  48  35   9   1   1  16  -8   5  32   8   6   0   0   0   0   1   1
INFO   3 112   3  10   1   1  48  35   9  64   3   7   0   0   0   1   1   1
INFO   3 112   3  10   0   1  48  35   9  64   3   7   0   0   0   2   1   1
INFO   1  12  35  11   1   1   4  -4   3   8   4   4   0   0   0   0   1   1
INFO   1 240  35  12   1   1 128  -3   8 112   3  10   0   0   0   0  -1   1
INFO   2 242  -3  13   1   1 240  35  12   2  -3   2   0   0   0   1   1   1
INFO   2 242  -3  13   0   1 240  35  12   2  -3   2   0   0   0   2   1   1
INFO   3 248   4  14   1   1 240  35  12   8   4   4   0   0   0   1   1   1
INFO   3 248   4  14   0   1 240  35  12   8   4   4   0   0   0   2   1   1
INFO   1 252  35  15   1   2   4  -4   3 248   4  14   0   0   0   0   1   1
INFO   4 252  35  15   2   2  12  35  11 240  35  12   0   0   0   0   1   1
INFO   2 254  -3  16   1   2  12  35  11 242  -3  13   0   0   0   1   1   1
INFO   2 254  -3  16   0   2  12  35  11 242  -3  13   0   0   0   2   1   1
INFO   2 254  -3  16   2   2 252  35  15   2  -3   2   0   0   0   1   1   1
INFO   2 254  -3  16   0   2 252  35  15   2  -3   2   0   0   0   2   1   1
INFO   2  48  15   3   3   0   0   0   0   0   0   0   0   0   0   0   2   5
INFOYY    5
 INFO NUM 128  of  143 11
INFO   1  12  35   7   1   1   4  -4   3   8   4   4   0   0   0   0   1   1
INFO   1  48  35   8   1   1  16  -8   5  32   8   6   0   0   0   0   1   1
INFO   2  28  -8   9   1   1  12  35   7  16  -8   5   0   0   0   1   1   1
INFO   2  28  -8   9   0   1  12  35   7  16  -8   5   0   0   0   2   1   1
INFO   3  56   4  10   1   1  48  35   8   8   4   4   0   0   0   1   1   1
INFO   3  56   4  10   0   1  48  35   8   8   4   4   0   0   0   2   1   1
INFO   1  60  35  11   1   3   4  -4   3  56   4  10   0   0   0   0   1   1
INFO   4  60  35  11   2   3  12  35   7  48  35   8   0   0   0   0   1   1
INFO   1  60  35  11   3   3  28  -8   9  32   8   6   0   0   0   0   1   1
INFO  25  62  -3  12   1   1  60  35  11   2  -3   2   0   0   0   1   1   1
INFO  25  62  -3  12   0   1  60  35  11   2  -3   2   0   0   0   2   1   1
INFO   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1
INFOYY    1
 INFO NUM 129  of  143 12
INFO  23  12  35   7   1   1   4  -4   3   8   4   4   0   0   0   0   1   1
INFO   1  48  35   8   1   1  16  -8   5  32   8   6   0   0   0   0   1   1
```