HELAC-PHEGAS

The Swiss Army Knife
of Leading Order Parton Level MC Generators

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Outline

- General features of **HELAC-PHEGAS**
- Dyson-Schwinger Recursive Algorithm
- Colour structure
- Matching matrix elements to parton showers
- Results & Comparisons
- Performance
- Summary & Outlook
- Software & Support

Convolution with PDFs

Summation over subprocesses

Complete Standard Model

Matching to parton showers and hadronisation

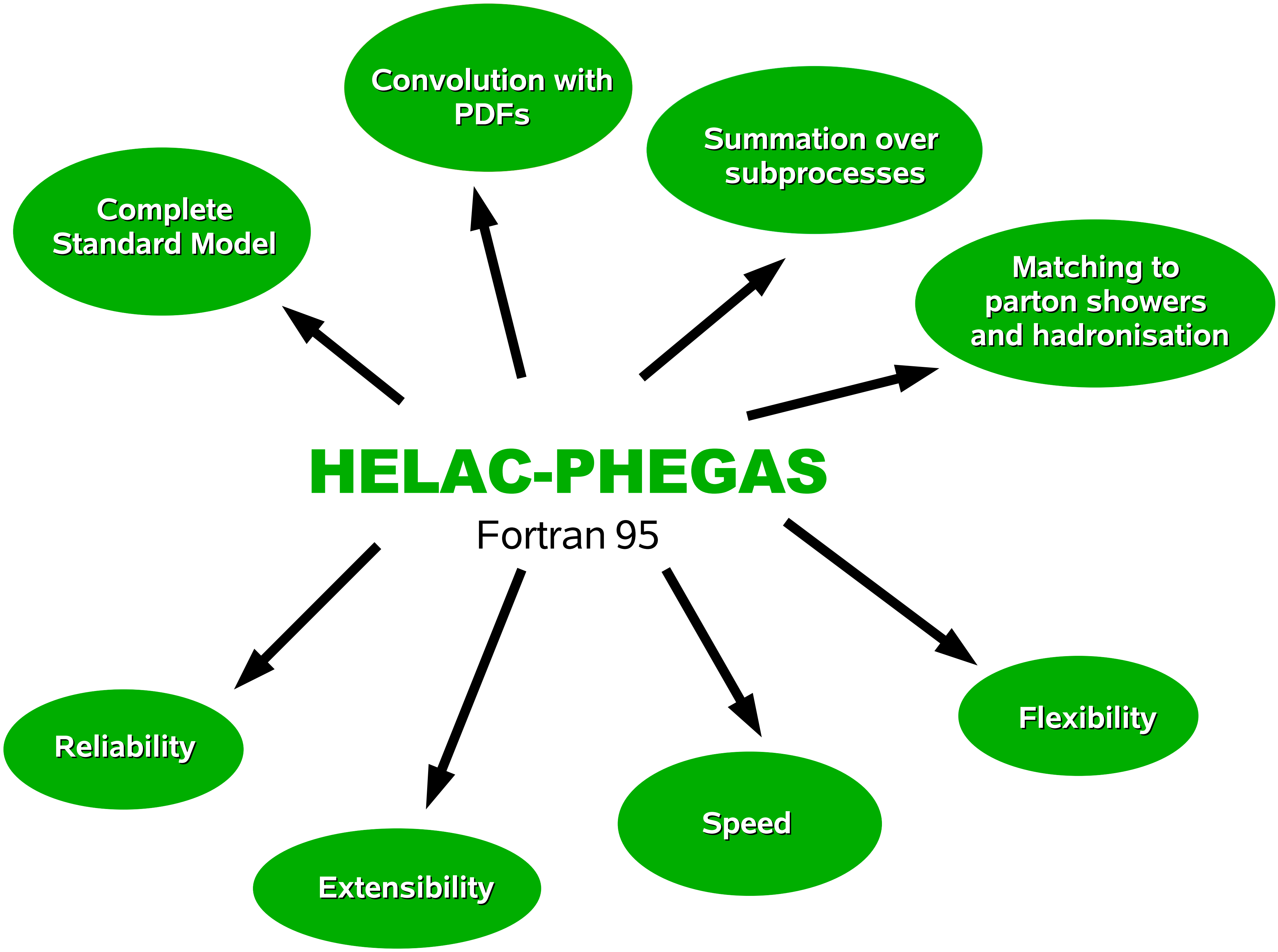
Features of a complete MC generator

Flexibility

Reliability

Speed

Extensibility



Convolution with PDFs
Summation over subprocesses
Complete Standard Model
Matching to parton showers and hadronisation
HELAC-PHEGAS
Fortran 95
Reliability
Extensibility
Speed
Flexibility

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Complete Standard Model

Matching to parton showers and hadronisation

Leading order without approximations

- Electroweak, QCD and mixed contributions
- Unitary and Feynman gauges
- Fixed width and complex mass schemes for unstable particles
- All correlations (colour, spin) taken into account naturally
- Non-zero fermion masses
- CKM matrix and Running couplings

Flexibility

Reliability

Speed

Extensibility

Convolution with PDFs

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Complete Standard Model

Matching to parton showers and hadronisation

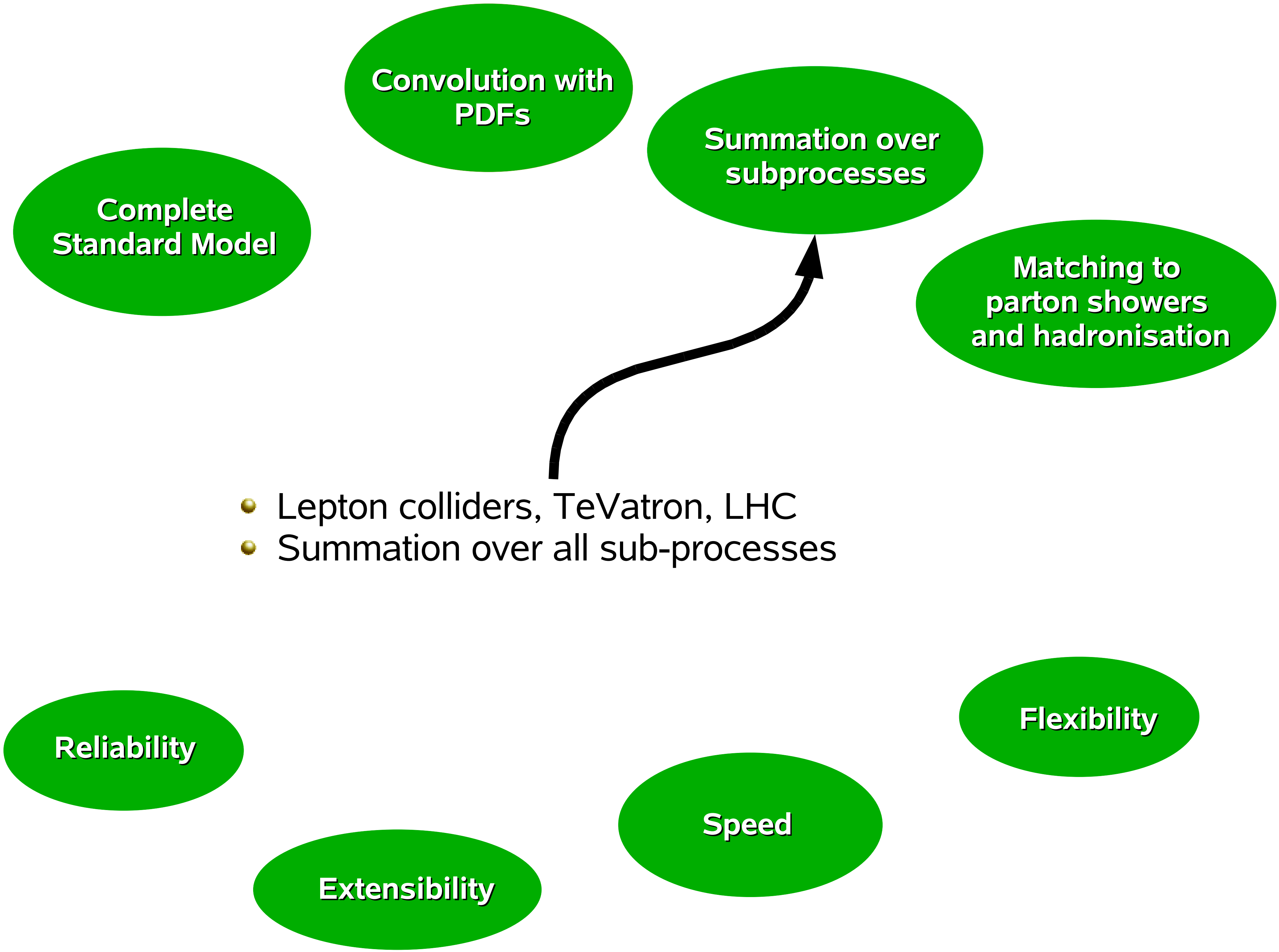
- Standalone version with build-in CTEQ6L1
- Interface to the LHAPDF

Reliability

Flexibility

Speed

Extensibility



- Lepton colliders, TeVatron, LHC
- Summation over all sub-processes

Convolution with PDFs

Summation over subprocesses

Complete Standard Model

Matching to parton showers and hadronisation

- Parton level weighted/unweigted events
- Parton shower and hadronisation via interface to PYTHIA
- Merging parton showers and matrix elements via MLM scheme
- LHA files and interfacing routines

Reliability

Flexibility

Speed

Extensibility

Convolution with PDFs

Summation over subprocesses

Complete Standard Model

Matching to parton showers and hadronisation

PHEGAS – phase space generator

- Automatic multi-channel phase-space mapping
- Self-adapting procedure to reshape the generated phase space density
- For example: per mille level $t\bar{t}$ + 0,1,2 jets (6,7,8 final states) with full off-shell and finite width effects

Reliability

Flexibility

Speed

Extensibility

Convolution with PDFs

Summation over subprocesses

Complete Standard Model

Matching to parton showers and hadronisation

- Straightforward inclusion of new physics effects
- New models: for example MSSM (under way)
- New couplings: for example effective Hγγ and Hgg couplings (completed, available in the next version)

Reliability

Flexibility

Speed

Extensibility

Convolution with PDFs

Summation over subprocesses

Complete Standard Model

Matching to parton showers and hadronisation

- 3^n complexity due to the Dyson-Schwinger recursive algorithm
- Monte Carlo summation over:
  - helicity configurations
  - color configurations (completed, available in the next version)
  - subprocesses (under way)
- Trivial parallelization over clusters

Reliability

Flexibility

Speed

Extensibility

Convolution with PDFs

Summation over subprocesses

Complete Standard Model

Matching to parton showers and hadronisation

- Arbitrary cuts, distributions and scale choices
- Configuration via scripts
- Compilers: Lahey Fujitsu, Intel, GNU gfortran/g95
- Multiprecision numerics

Flexibility

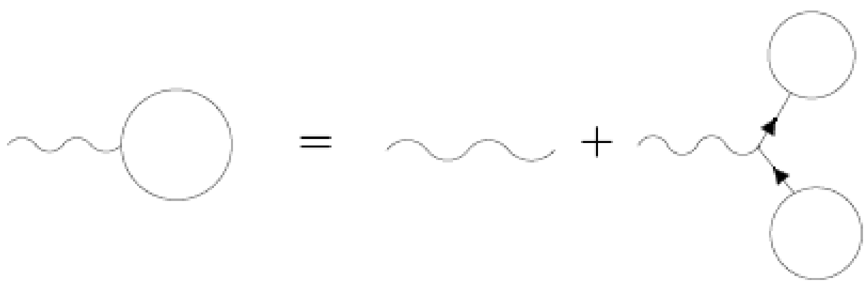
Reliability

Speed

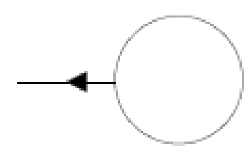
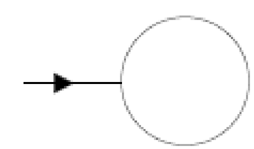
Extensibility

Dyson-Schwinger Recursion

- Alternative to Feynman Diagrams representation
- Express n-point Green's functions in terms of 1-, 2-,... (n-1)-point functions
- Diagrammatic representation, e.g. QED-like theory
- Interaction of a spinor field to a gauge boson



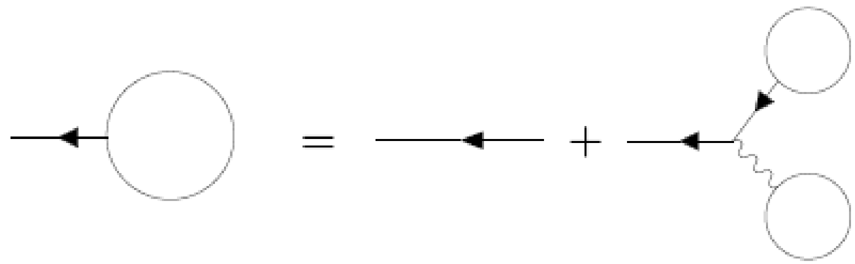
$$b^\mu(P) \;=\; \sum_{i=1}^{n} \delta_{P=p_i} b^\mu(p_i) + \sum_{P=P_1+P_2} (ig)\, \Pi^\mu_\nu\, \bar{\psi}(P_2)\gamma^\nu \psi(P_1)\epsilon(P_1,P_2)$$

$b_\mu(P) \;=$  $\psi(P) \;=$  $\bar{\psi}(P) \;=$ 

- Sub-amplitude with off-shell boson of momentum P
- Blobs denote sub-amplitude with the same structure

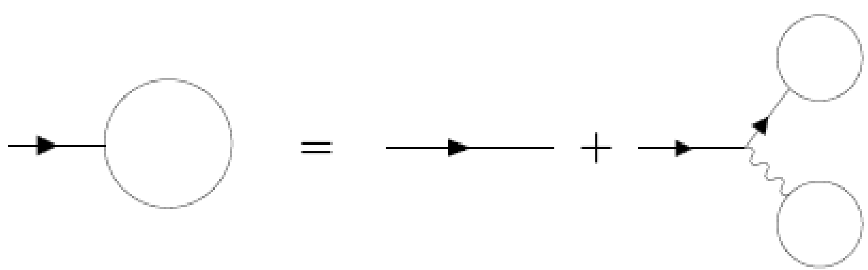
Dyson-Schwinger Recursion

- For fermion with momentum P



$$\psi(P) = \sum_{i=1}^{n} \delta_{P=p_i}\psi(p_i) + \sum_{P=P_1+P_2} (ig)\mathcal{P}\,\not{b}(P_2)\psi(P_1)\,\epsilon(P_1,P_2)$$

- For antifermion with momentum P



$$\bar{\psi}(P) = \sum_{i=1}^{n} \delta_{P=p_i}\bar{\psi}(p_i) + \sum_{P=P_1+P_2} (ig)\bar{\psi}(P_1)\not{b}(P_2)\bar{\mathcal{P}}\,\epsilon(P_1,P_2)$$

Example $e^+e^- \rightarrow \mu^+\mu^-\gamma$

- Binary representation of the particles momenta
- External momenta p_i where $i = 1, \ldots, n \rightarrow m_i = 2^{i-1}$
- Ordering of the integers relies on level defined as $l = \sum_{i=1}^{n} m_i$
- External momenta – level 1
- Total amplitude – level 2^{n-1}

$$
\begin{aligned}
b_\mu(12) &= (ig)\Pi^{\nu}_{12\mu}\bar{\psi}(4)\gamma_\nu\psi(8) \\
\bar{\psi}(18) &= (ig)\bar{\psi}(2)\not{b}(16)\bar{\mathcal{P}}_{18} \\
\bar{\psi}(20) &= (ig)\bar{\psi}(4)\not{b}(16)\bar{\mathcal{P}}_{20} \\
\psi(24) &= (ig)\mathcal{P}_{24}\not{b}(16)\psi(8)
\end{aligned}
$$

$$
\begin{aligned}
\bar{\psi}(14) &= (ig)\bar{\psi}(2)\not{b}(12)\bar{\mathcal{P}}_{14} \\
b_\mu(28) &= (ig)\Pi^{\nu}_{28\mu}\left(\bar{\psi}(20)\gamma_\nu\psi(8) + \bar{\psi}(4)\gamma_\nu\psi(24)\right)
\end{aligned}
$$

$$
\bar{\psi}_0(30) = (ig)\left(\bar{\psi}(2)\not{b}(28) + \bar{\psi}(14)\not{b}(16) + \bar{\psi}(18)\not{b}(12)\right)
$$

$$
\mathcal{A} = \bar{\psi}_0(30)\psi(1)
$$

Colour Structure

- DS equations both for: full and colour ordered amplitudes
- Colour ordered - ordinary approach SU(N) algebra
- Quarks and gluons treated differently

$$M(\{p_i\}_1^n;\{\varepsilon_i\}_1^n;\{a_i\}_1^n) = \sum_{I\in P(2,\dots,n)} Tr(t^{a_{\sigma_I(1)}} t^{a_{\sigma_I(2)}} \dots t^{a_{\sigma_I(n)}}) A_I(\{p_i\}_1^n;\{\varepsilon_i\}_1^n)$$

$$\sum_{\{\varepsilon_i\}_1^n;\{a_i\}_1^n} |M(\{p_i\}_1^n;\{\varepsilon_i\}_1^n;\{a_i\}_1^n)|^2 = \sum_{\varepsilon}\sum_{IJ} A_I C_{IJ} A_J^*$$

$$C_{IJ} = \sum_{IJ} Tr(t^{a_1} t^{a_{\sigma_I(2)}} \dots t^{a_{\sigma_I(n)}}) Tr(t^{a_1} t^{a_{\sigma_J(2)}} \dots t^{a_{\sigma_J(n)}})^*$$

Colour Structure

- U(N) type colour algebra, gluon = $q\bar{q}$ pair
- Each colour amplitude proportional to D_I
- σ_I - I-th permutation of the set 1,2,...,n

$$M(\{p_i\}_1^n;\{\varepsilon_i\}_1^n;\{a_i\}_1^n) = \sum_{I\in P(2,\ldots,n)} D_I A_I(\{p_i\}_1^n;\{\varepsilon_i\}_1^n)$$

$$D_I=\delta_{1\sigma_I(1)}\delta_{2\sigma_I(2)}\ldots\delta_{n\sigma_I(n)}$$

$$C_{IJ} = \sum_{IJ} D_I D_J = N_C^{\alpha}, \quad \alpha=\langle\sigma_{1,}\sigma_2\rangle$$

- Exact colour treatment for low colour charge
- Incoherent sum over colour performed via MC over “real” colour (completed, available in the next version)

Total rates pp$\rightarrow$ ng   n=2,...,9

- Total cross sections for processes with gluons

LHC

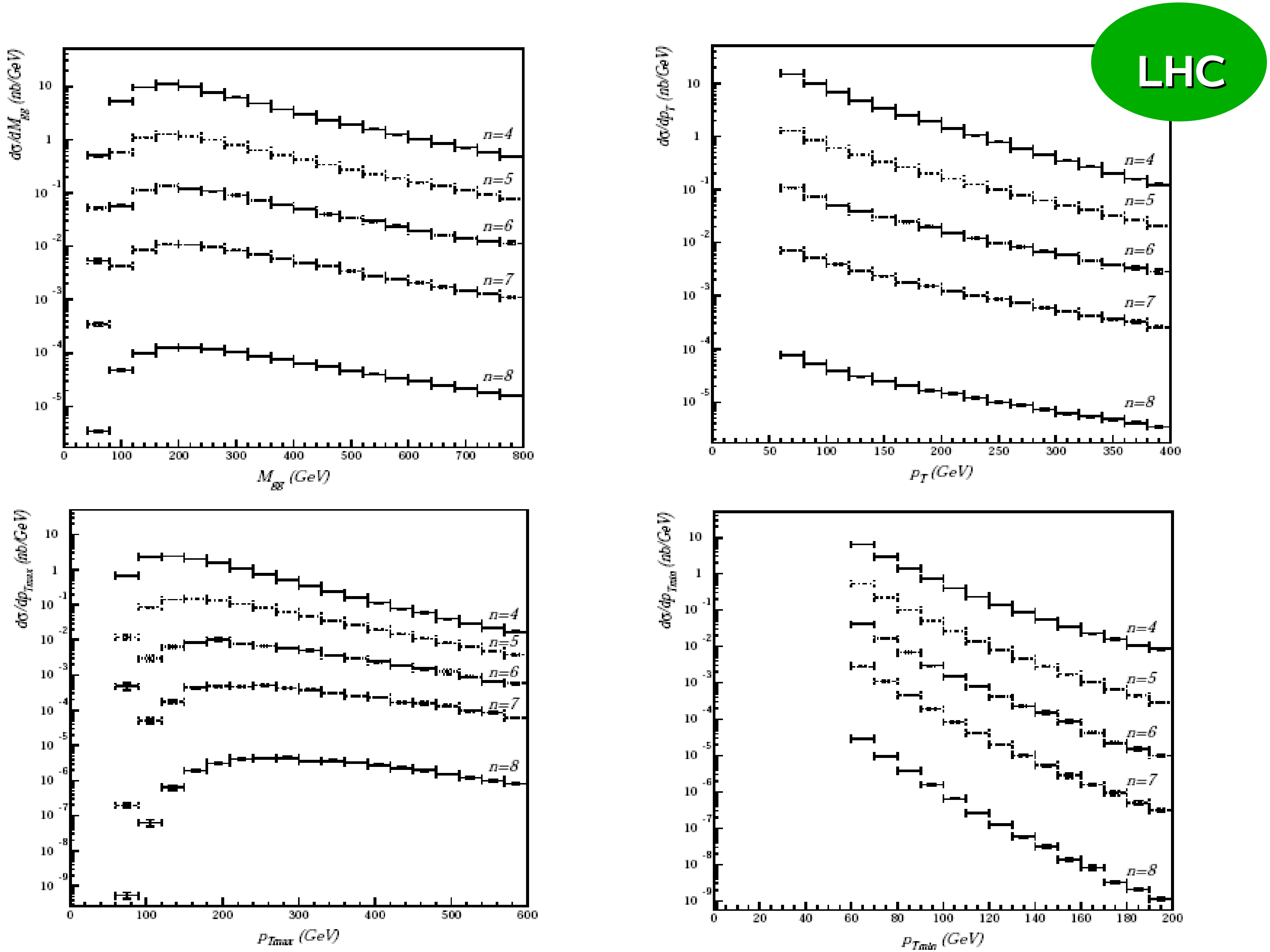
Process	$\sigma_{\text{EXACT}} \pm \varepsilon$ (nb)	ε (%)	$\sigma_{\text{MC}} \pm \varepsilon$ (nb)	ε (%)
$gg \rightarrow 2g$	$(0.46572 \pm 0.00258)\times 10^4$	0.5	$(0.46849 \pm 0.00308)\times 10^4$	0.6
$gg \rightarrow 3g$	$(0.15040 \pm 0.00159)\times 10^3$	1.0	$(0.15127 \pm 0.00110)\times 10^3$	0.7
$gg \rightarrow 4g$	$(0.11873 \pm 0.00224)\times 10^2$	1.9	$(0.12116 \pm 0.00134)\times 10^2$	1.1
$gg \rightarrow 5g$	$(0.10082 \pm 0.00198)\times 10^1$	1.9	$(0.09719 \pm 0.00142)\times 10^1$	1.5
$gg \rightarrow 6g$	$(0.74717 \pm 0.01490)\times 10^{-1}$	2.0	$(0.76652 \pm 0.01862)\times 10^{-1}$	2.4

- Comparison of the computational time

Process	$\sigma_{\text{MC}} \pm \varepsilon$ (nb)	ε (%)
$gg \rightarrow 7g$	$(0.53185 \pm 0.01149)\times 10^{-2}$	2.1
$gg \rightarrow 8g$	$(0.33330 \pm 0.00804)\times 10^{-3}$	2.4
$gg \rightarrow 9g$	$(0.13875 \pm 0.00430)\times 10^{-4}$	3.1

Process	$t^{\text{CF}}_{\text{EXACT}}$	t_{MC}	$t_{\text{EXACT}}/t_{\text{MC}}$
$gg \rightarrow 2g$	0.315×10^0	0.554×10^0	0.57
$gg \rightarrow 3g$	0.329×10^1	0.143×10^1	2.30
$gg \rightarrow 4g$	0.383×10^2	0.372×10^1	10.29
$gg \rightarrow 5g$	0.517×10^3	0.105×10^2	49.24
$gg \rightarrow 6g$	0.987×10^4	0.362×10^2	272.65

Distributions pp $\to$ ng n=4,...,8



Summation over Sub-processes

Multi-jet rates:

# jets	3	4	5	6	7	8
$\sigma(nb)$	91.41	6.54	0.458	$2.97\ \times 10^{-2}$	$2.21\ \times 10^{-3}$	$2.12\ \times 10^{-4}$
% Gluon	45.7	39.2	35.7	35.1	33.8	26.6

- Quark processes relevant
- $gg \longrightarrow ng$ not a good approximation

Multi-jet final state

How to simulate hard processes with additional hard radiation

- **Matrix element:**
  - Exact at some given order in α_s - all interferences are included
  - High energetic and well separated partons
  - Soft/Collinear regions are not adequately described – luck of multiple unresolved gluon emission
  - Difficult to match to hadronisation models

- **Parton Showers:**
  - Include logarithmically enhanced soft and collinear contributions of parton emissions
  - Able to connect both hard and fragmentation scales
  - Not enough high energetic gluons are emitted that have large angle from the shower initiator

Clearly two descriptions complement each other !

Matching ME to PS

Goal

- LL accuracy in the prediction of final state with varying number of extra jets

Solution

- Matching algorithm

Recipe

- Cross section for each multiplicity N are calculating using LO ME for N partons
- Followed by full shower evolution
- Removal of double counting via inclusion of Sudakov form factors in the LO ME
- Vetoing shower evolutions leading to multiparton final state already described
- Double counting – jet can appear both from hard emission during shower evolution and from inclusion of higher order ME
- Phase space is split into two pieces – one covered by PS and the other by ME

Matching ME to PS

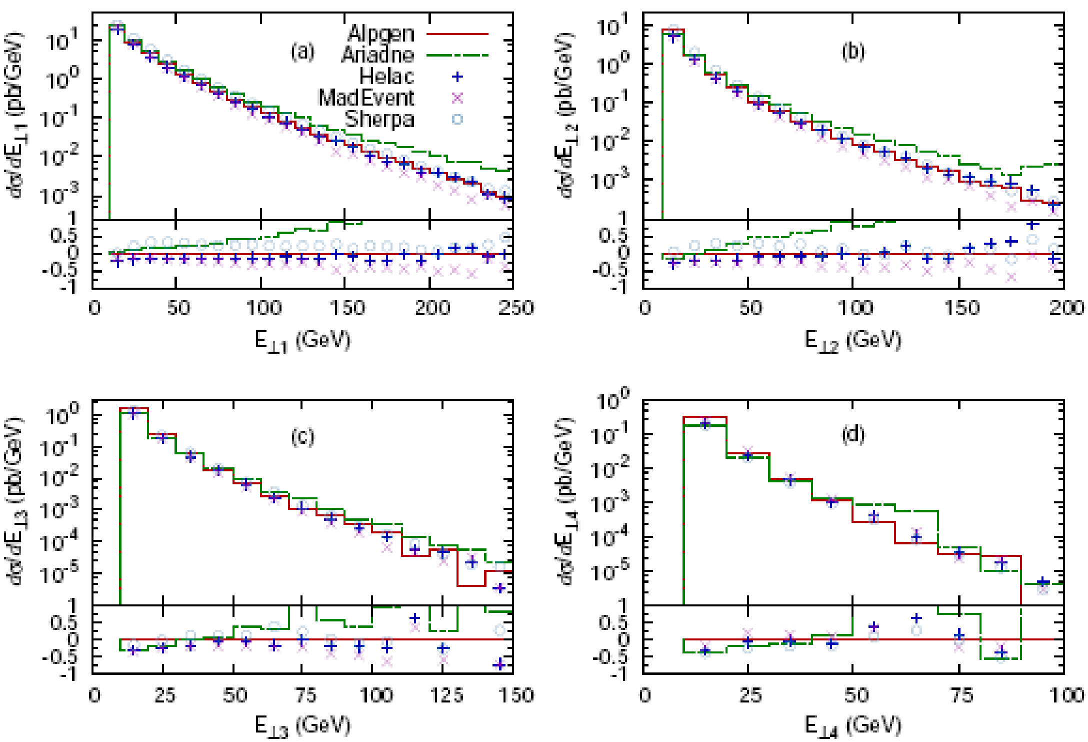
- A few algorithms along these lines: **CKKW-L, MLM**
- **Differ mainly:**
  - Jet definition used for the ME evaluation
  - Way the ME rejection weights are constructed
  - Details concerning starting conditions of jet vetoing inside PS
- **Have similar systematics:**
  - Residual dependence on the phase space separation cut Q_{cut}
  - Variations with the number of ME legs
  - Dependencies on the internal jet algorithm

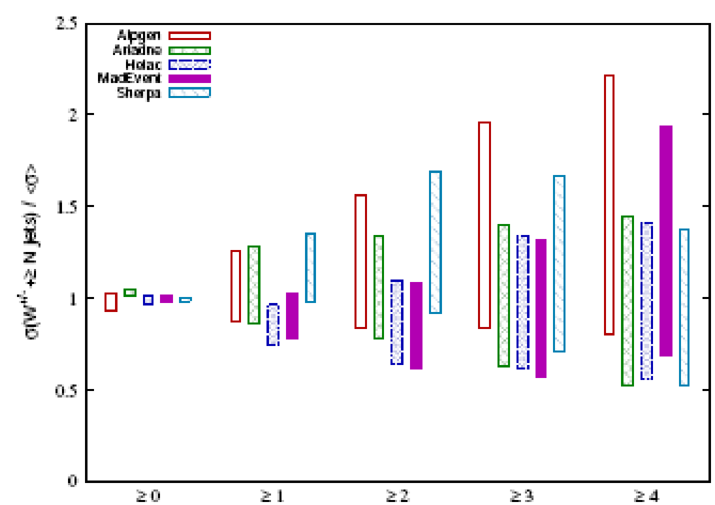
Example $p\bar{p} \rightarrow W$ + jets

TeVatron

- Cross sections in pb for inclusive jet rates
- Range of variation normalized to the average value
- Inclusive E_T spectra of leading 4 jets

Code	σ[tot]	$\sigma[\geq 1$ jet]	$\sigma[\geq 2$ jet]	$\sigma[\geq 3$ jet]	$\sigma[\geq 4$ jet]
ALPGEN, def	1933	444	97.1	18.9	3.2
ALpt20	1988	482	87.2	15.5	2.8
ALpt30	2000	491	82.9	12.8	2.1
ALscL	2035	540	135	29.7	5.5
ALscH	1860	377	72.6	12.7	2.0
ARIADNE, def	2066	477	87.3	13.9	2.0
ARpt20	2038	459	76.6	12.8	1.9
ARpt30	2023	446	67.9	11.3	1.7
ARscL	2087	553	116	21.2	3.6
ARscH	2051	419	67.8	9.5	1.3
ARs	2073	372	80.6	13.2	2.0
HELAC, def	1960	356	70.8	13.6	2.4
HELpt30	1993	373	68.0	12.5	2.4
HELscL	2028	416	95.0	20.2	3.5
HELscH	1925	324	55.1	9.4	1.4
MADEVENT, def	2013	381	69.2	12.6	2.8
MEkt20	2018	375	66.7	13.3	2.7
MEkt30	2017	361	64.8	11.1	2.0
MEscL	2013	444	93.6	20.0	4.8
MEscH	1944	336	53.2	8.6	1.7
SHERPA, def	1987	494	107	16.6	2.0
SHkt20	1968	465	85.1	12.4	1.5
SHkt30	1982	461	79.2	10.8	1.3
SHscL	1957	584	146	25.2	3.4
SHscH	2008	422	79.8	11.2	1.3

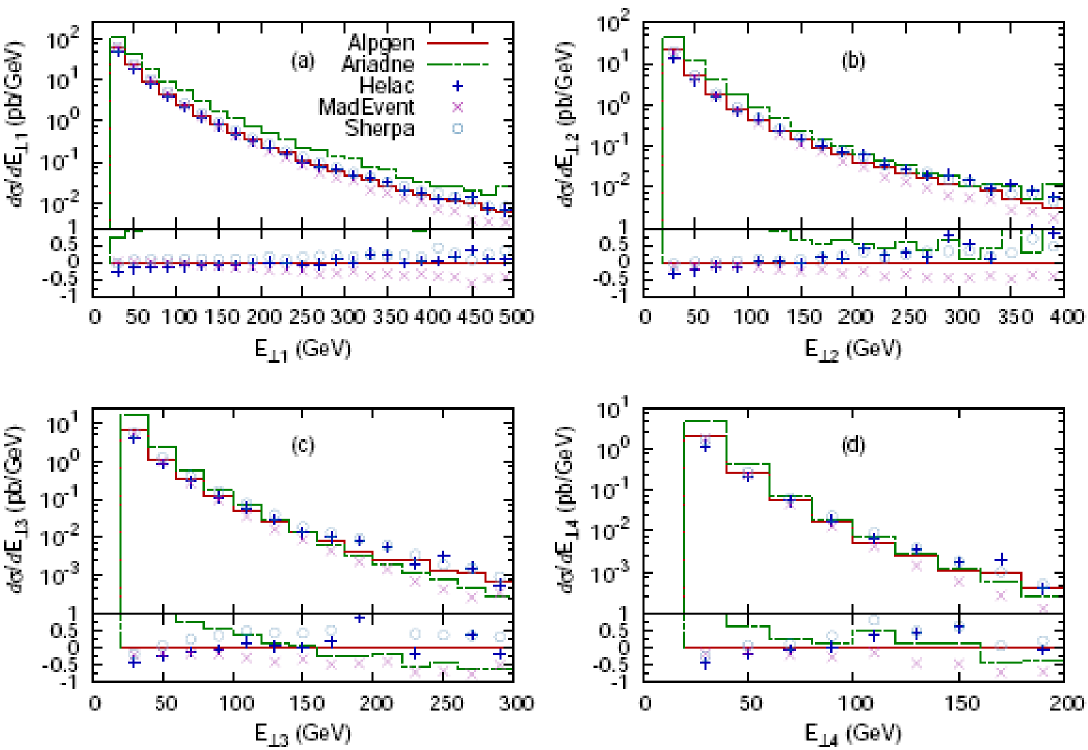




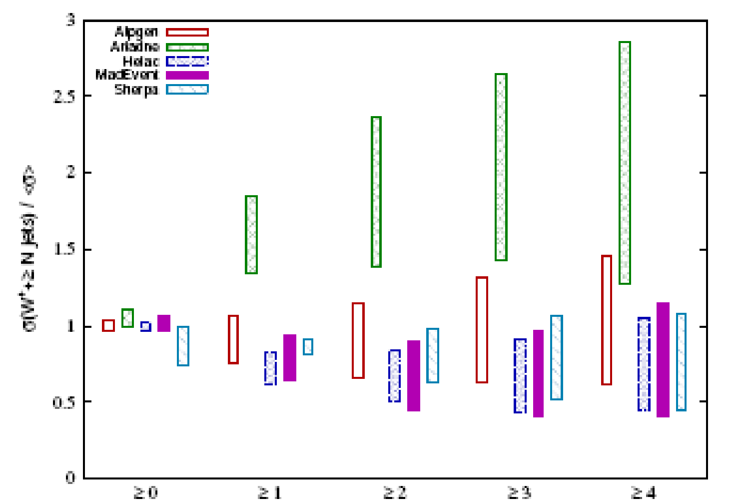
Example pp → W + jets

LHC

- Cross sections in pb for inclusive jet rates
- Range of variation normalized to the average value
- Inclusive E_T spectra of leading 4 jets



Code	σ[tot]	$\sigma[\geq 1$ jet]	$\sigma[\geq 2$ jet]	$\sigma[\geq 3$ jet]	$\sigma[\geq 4$ jet]
ALPGEN, def	10170	2100	590	171	50
ALpt30	10290	2200	555	155	46
ALpt40	10280	2190	513	136	41
ALscL	10590	2520	790	252	79
ALscH	9870	1810	455	121	33
ARIADNE, def	10890	3840	1330	384	101
ARpt30	10340	3400	1124	327	88
ARpt40	10090	3180	958	292	83
ARscL	11250	4390	1635	507	154
ARscH	10620	3380	1071	275	69
ARs	11200	3440	1398	438	130
HELAC, def	10050	1680	442	118	36
HELpt40	10150	1760	412	116	37
HELscL	10340	1980	585	174	57
HELscH	9820	1470	347	84	24
MADEVENT, def	10830	2120	519	137	42
MEkt30	10080	1750	402	111	37
MEkt40	9840	1540	311	78.6	22
MEscL	10130	2220	618	186	62
MEscH	10300	1760	384	91.8	27
SHERPA, def	8800	2130	574	151	41
SHkt30	8970	2020	481	120	32
SHkt40	9200	1940	436	98.5	24
SHscL	7480	2150	675	205	58
SHscH	10110	2080	489	118	30



Performance tt+jet Production

Intel Pentium 1.7 GHz
Intel Fortran

$pp \rightarrow t\,\bar{t}$

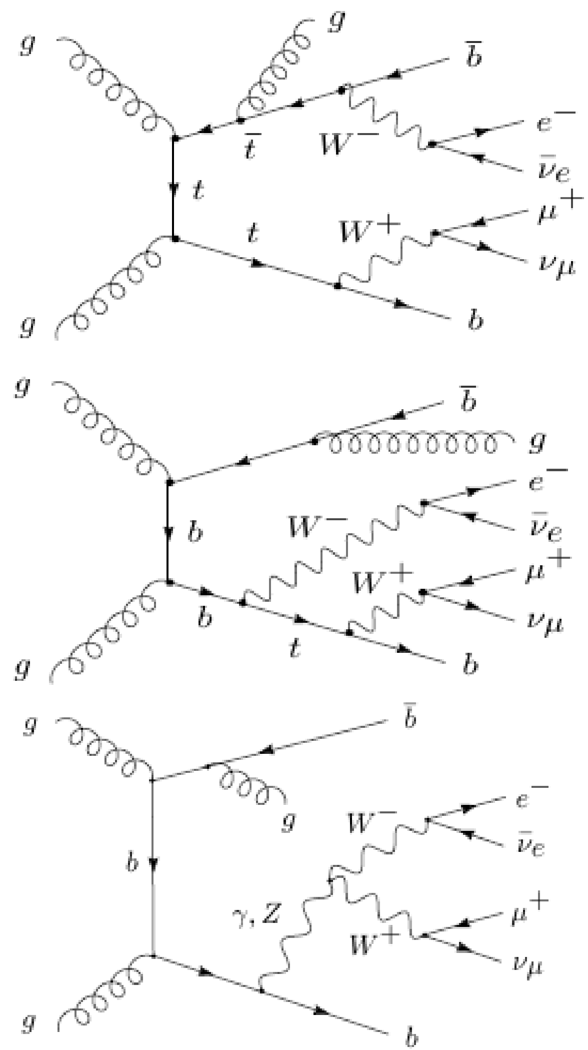
- 87 (3) graphs gg, 40 (1) graph qq
- Higgs on, b-quark off
- 9 subprocesses
- $\alpha_S^{\,2}\alpha_{EW}^{\,4}$

Time: ‰ ~ 10 (4) min.

$pp \rightarrow t\,\bar{t} + 1\text{jet}$

- 558 (16) graphs gg
- 246 (5) qq, gq, qg
- Higgs on, b-quark off
- 25 subprocesses
- $\alpha_S^{\,3}\alpha_{EW}^{\,4}$

Time: ‰ ~ 106 (34) min.



Code Structure

Main Files:

- **main_mc.f** $\longrightarrow$ main file
- **intpar.f** $\longrightarrow$ integer arithmetic
- **master_new.f** $\longrightarrow$ master file for DS solution
- **pan1.f** $\longrightarrow$ non-dressed vertices and amplitude calculation
- **pan2.f** $\longrightarrow$ dressed vertices
- **physics.f** $\longrightarrow$ all couplings

Main common blocks:

- **common_int.h** $\longrightarrow$ common/helac_int/n,io(20),ifl(20)
- **common_helc.h** $\longrightarrow$ common/helac_helc/ipol(20),icol(20,2)
- **common_phegas_mom.h** $\longrightarrow$ common/phegas_mom/pmom(20,5)

How to use HELAC

- Edit once for all the file **myenv**
  - **FC** = Fortran compiler
  - **FORTRAN_LIBRARIES** = path to your Fortran libraries
  - **LHAPDFLIB** = path to Les Houches Accord PDF's libraries
  - **LHAPDFSETS** = path to PDF sets

- User interface
  - **run.sh** – shell script that reads input files compiles and runs HELAC
  - **default.inp** – default values (can not be modified)
  - **user.inp** – select process, collider, energy, modify default values
  - **getqcdscale.h** – define QCD scale to be used by PDF and α_S

```
. run.sh user.inp
./run.sh user.inp myenv-xxx
```

Summary & Outlook

- **HELAC–PHEGAS** - Framework for high energy phenomenology
- **HELAC 1.0.0**
  - Standard Model fully included
  - Tested
  - Ready to be used for LHC, TeVatron, ILC
- **HELAC 2.0.0**
  - High colour charge processes
  - Multijet production
  - Testing phase
  - To be available very soon
- **HELAC MSSM**
  - Development phase

Summary & Outlook

- We are looking forward to contribute to **ATLAS** and **CMS** generator groups in all stages:

  - **interface**
  - **validation**
  - **tuning**

- We would like to make **HELAC-PHEGAS** an option !

- We also invite members of **ATLAS** and **CMS** to join us ! We are ready to collaborate for specific contributions !

- Small scale workshops may also be financed by **HEPTOOLS** !

Software & Support

Available from:

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

Installation/Configuration/Use help provided by:

Malgorzata Worek

arXiv:0710.2427 [hep-ph]