BERGISCHE UNIVERSITÄT WUPPERTAL

LO and NLO calculations with HELAC-PHEGAS

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

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Outline of the Talk

- Introduction & Motivation
- Main Obstacles and Computational Complexity for multi-leg processes
- Leading Order level MC Programs: **HELAC-PHEGAS**
- Matching to Parton Shower
- Main Features & Numerical Results
- Next-To-Leading Order level MC Programs: **HELAC-DIPOLES, HELAC-1LOOP, CUTTOOLS**
- Summary & Outlook

In collaboration with: M. Czakon (RWTH Aachen)
C. G. Papadopoulos (INP Athens)

Monte Carlo Generators

- Physics program of two main **LHC** experiments **ATLAS** and **CMS**:
  - Discovery of **Higgs boson(s)**
  - Search for signal of new physics beyond the **SM**
  - Remember: **Present day signals = Tomorrow backgrounds**

- Signal events dug out from a bulk of background events
- Backgrounds due to **SM** processes
- Mostly **QCD** processes, accompanied by additional electroweak bosons
- Final state - high number of jets or identified particles
- Reliable predictions for multi-particle final states needed !
- All this can be described by **Monte Carlo generators**

Benchmarking against real data turns MC simulation into powerful tool !

Biggest Obstacles

- Complexity of calculation based on Feynman diagrams **~ n!**
- Flavours of partons never detected (b-tagging)
- For given jet configuration very many contributing subprocesses
- Neither the colour nor the spin of any parton is observed
- Amplitude with p quark and q gluons $(2\times3)^p(2\times8)^q$ contributions
- Amplitude peaks in complicated ways inside the momentum phase space
- Straightforward integration is impractical

Automated calculation of the ME based on recursive equations

MC summation over helicity and colour as well as over flavour

Search for efficient mappings - importance and stratified sampling

Tools @ LHC

- Standard Model and beyond tools @ tree level
- Parton-level tools which are completely self-contained and automated and provide amplitudes and integrators on their own

AlpGen, AMEGIC++/Sherpa, COMIX/Sherpa, Helac-Phegas, MadGraph/MadEvent, O'Mega/WHIZARD, ...

- General purpose Monte Carlo programs (parton shower, hadronisation, multiple interactions, hadrons decays, ...)

Herwig, Herwig++, Pythia 6.4, Pythia 8, Sherpa, ...

Generators are not perfect ! Shop around and compare several approaches before drawing conclusions. Blind usage of a generator is not encouraged !

T. Sjöstrand

Features of a MC generator

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

Convolution with PDFs

Summation over subprocesses

Complete Standard Model

Matching to parton showers and hadronisation

HELAC-PHEGAS

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

Cafarella, Papadopoulos, Worek '09

Flexibility

Reliability

Speed

Extensibility

Convolution with PDFs

Summation over subprocesses

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

Summation over subprocesses

Complete Standard Model

Matching to parton showers and hadronisation

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

Flexibility

Reliability

Speed

Extensibility

Convolution with PDFs

Summation over subprocesses

Complete Standard Model

Matching to parton showers and hadronisation

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

$$p_{T\ i} > 60\ GeV, \quad \theta_{ij} > 30^o \quad |\eta_i| < 3$$

# 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

Flexibility

Reliability

Speed

Extensibility

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
- Also will be possible via CKKW scheme - **HERWIG++**
- LHA files and interfacing routines

J. Alwall et al. '07

Flexibility

Reliability

Speed

Extensibility

Complete Standard Model

Convolution with PDFs

Summation over subprocesses

Matching to parton showers and hadronisation

PHEGAS – phase space generator

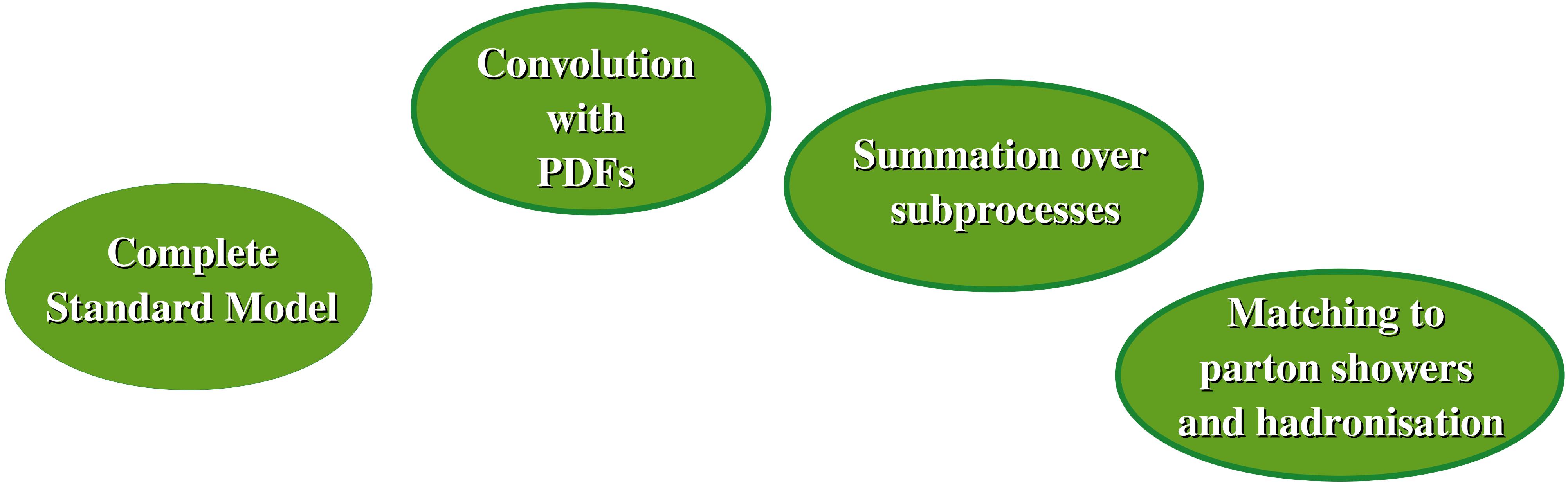
- Automatic multi-channel phase-space mapping
- Self-adapting procedure to reshape the generated phase space density
- For example: per mille level tt + 0,1,2 jets (6,7,8 final states) with full off-shell and finite width effects

Reliability

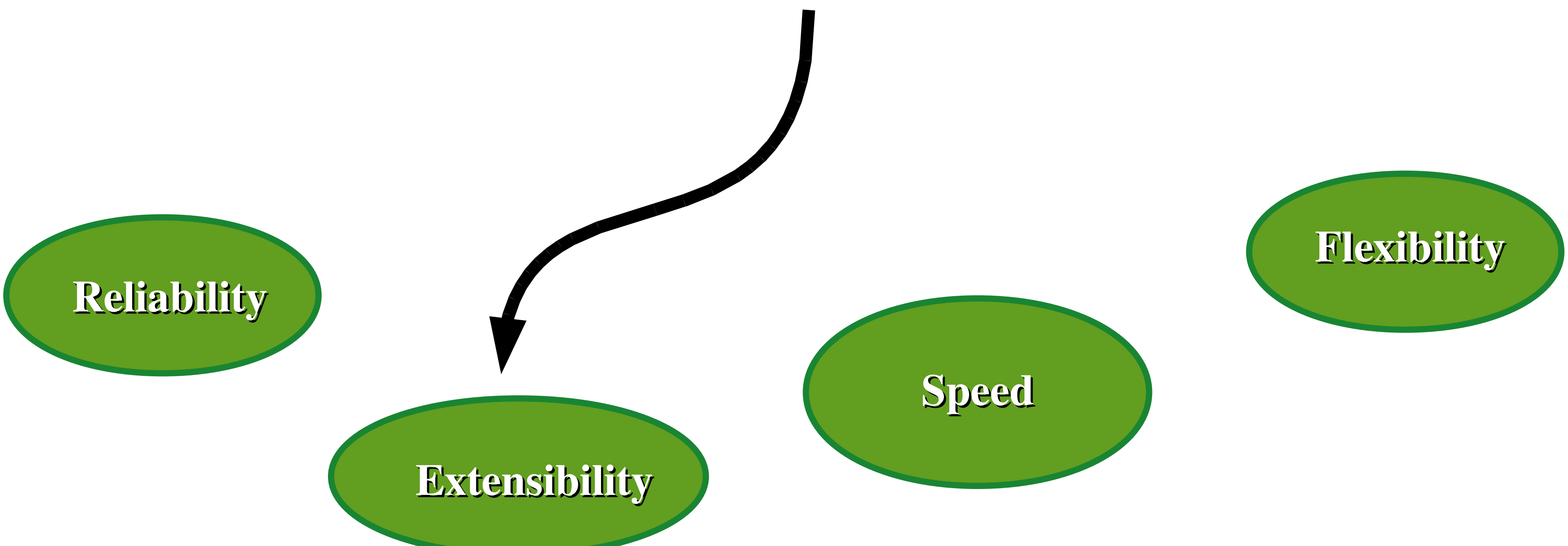
Extensibility

Speed

Flexibility



- Straightforward inclusion of new physics effects
- New models: for example MSSM
- New couplings: for example effective Hγγ and Hgg couplings



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 (completed)
  - color configurations (completed)
  - subprocesses
- Trivial parallelization over clusters (LSF at CERN)

Flexibility

Reliability

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 Fortran**, **GNU gfortran/g95**
- Multiprecision numerics

Flexibility

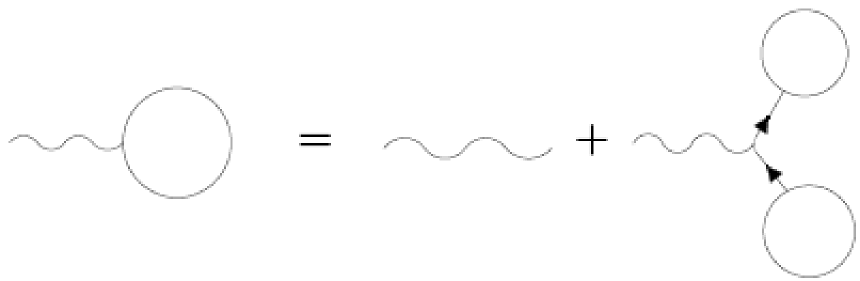
Reliability

Speed

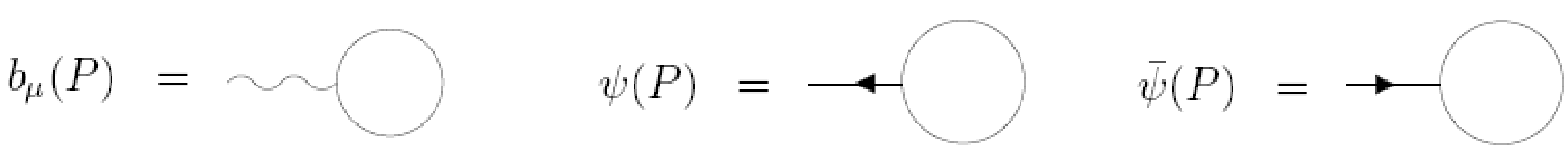
Extensibility

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



$$b^{\mu}(P) = \sum_{n=1}^{n} \delta(P=P_i)\, b^{\nu}(P_i) + \sum_{P=P_1+P_2} (ig)\, \Pi^{\mu}_{\nu}\, \bar{\psi}(P_2)\, \gamma^{\nu}\, \psi(P_1)\, \epsilon(P_1, P_2)$$

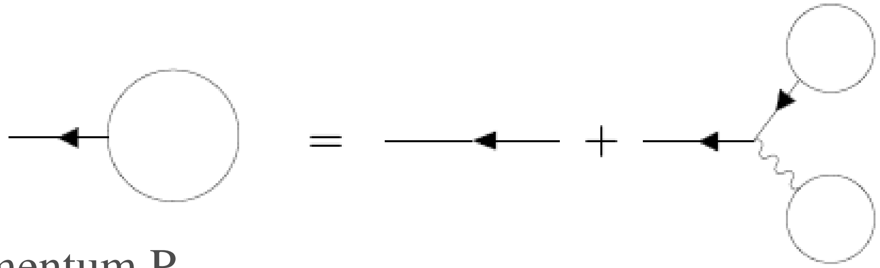


- Sub-amplitude with off-shell boson of momentum P
- Blobs denote sub-amplitude with the same structure

Dyson-Schwinger Recursion

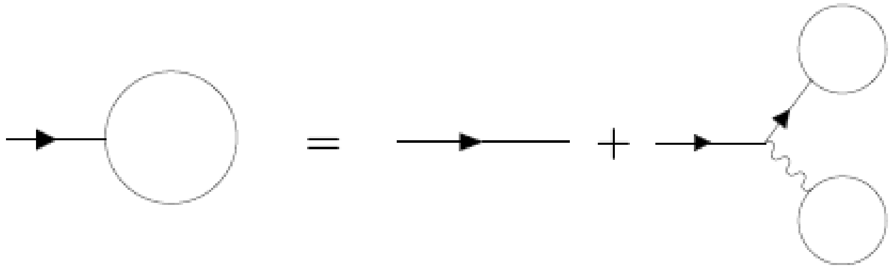
- Fermion with momentum P

$$\psi(P) = \sum_{n=1}^{n} \delta(P=P_i)\psi(P_i) + \sum_{P=P_1+P_2} (ig) P\, b_\mu(P_2)\gamma^\mu \psi(P_1)\epsilon(P_1, P_2)$$



- Antifermion with momentum P

$$\bar{\psi}(P) = \sum_{n=1}^{n} \delta(P=P_i)\bar{\psi}(P_i) + \sum_{P=P_1+P_2} (ig)\bar{\psi}(P_1) b_\mu(P_2)\gamma^\mu \bar{P}\epsilon(P_1, P_2)$$



Building Amplitude

- Off-shell fields – building blocks of any process
- Used iteratively, at each step two (three) momenta are combined
- Initial conditions for the external particles:

$$
\begin{aligned}
b^\mu(p_i) &= \epsilon^\mu_\lambda(p_i), \lambda = \pm 1, 0 \\
\psi(p_i) &= \begin{cases} u_\lambda(p_i) & \text{if } p_i^0 \geq 0 \\ v_\lambda(-p_i) & \text{if } p_i^0 \leq 0 \end{cases} \\
\bar{\psi}(p_i) &= \begin{cases} \bar{u}_\lambda(p_i) & \text{if } p_i^0 \geq 0 \\ \bar{v}_\lambda(-p_i) & \text{if } p_i^0 \leq 0 \end{cases}
\end{aligned}
$$

- Amplitude can be calculated by any of the following relations:

$$
\mathcal{A}(p_1, \ldots, p_n) = \begin{cases} b_0^\mu(P_i) b_\mu(p_i) \\ \bar{\psi}_0(P_i)\psi(p_i) \\ \bar{\psi}(p_i)\psi_0(P_i) \end{cases}
$$

Combining ME & PS

Goal:

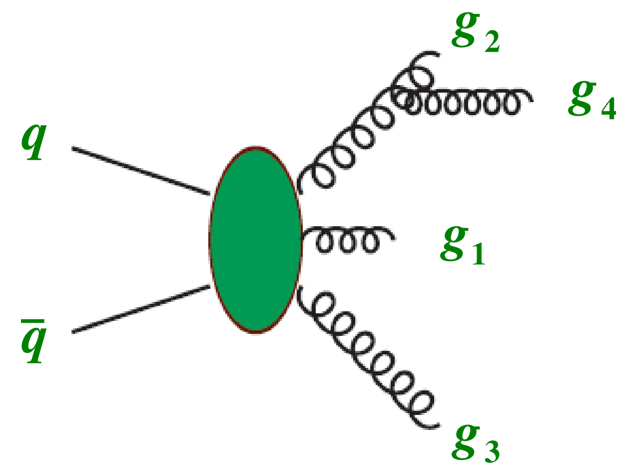
- All jet emissions correct at tree level + LL
- Soft emission correctly resumed in PS

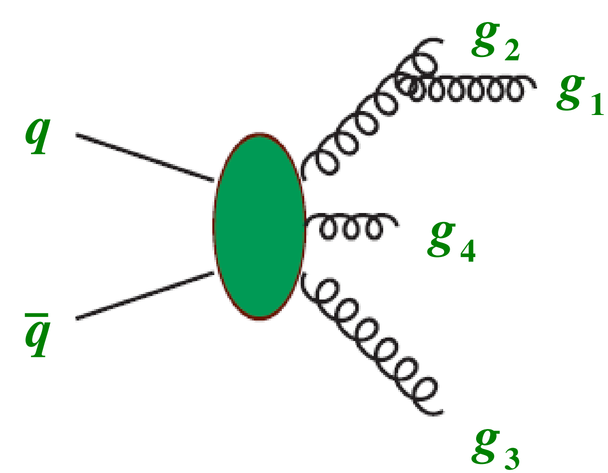
Problem:

- **Double Counting** - jet can appear both from relatively hard emission during shower evolution and from inclusion of higher order ME

Solution:

- Matching algorithm - separate jet production/evolution by $Q_{jet} = k_T$ jet measure





$$p_{T_1} \ll p_{T_4} \ll p_{T_2},\ p_{T_3}$$

Main Differences

Catani, Krauss, Khun, Webber '01
Lonnblad '02
Krauss '02
Mangano, Moretti, Pittau '02
Mangano, Moretti, Piccinini, Treccani '07

A few algorithms along these lines:

- **CKKW-L** – for e+e- dependence on the resolution parameter is shifted beyond NLL accuracy, proposal to extend procedure to hadronic collisions but no proof of NLL accuracy
- **MLM** - alternative proposal, LL accuracy

Differ mainly:

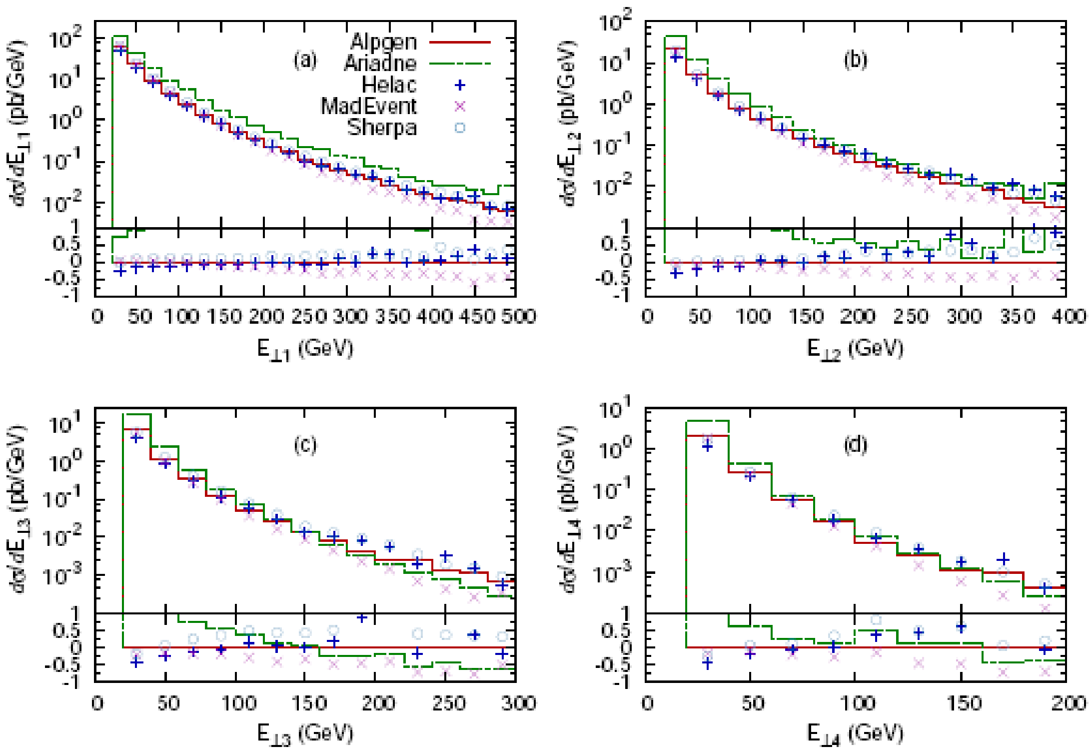
- Jet definition used for the ME evaluation
- Way the ME rejection weights are constructed
- Details concerning starting conditions of jet vetoing inside PS

Have similar systematics:

- Residual dependence on the phase space separation cut Q_{jet}
- Variations with the number of ME legs
- Dependencies on the internal jet algorithm

pp → W + jets @ LHC

Inclusive E_T spectra of leading 4 jets



J. Alwall et al. '08

ALPGEN – angular-ordered PS in HERWIG with MLM matching

ARIADNE – matrix elements MadGraph, p_T ordered dipole PS with CKKW-L, PYTHIA

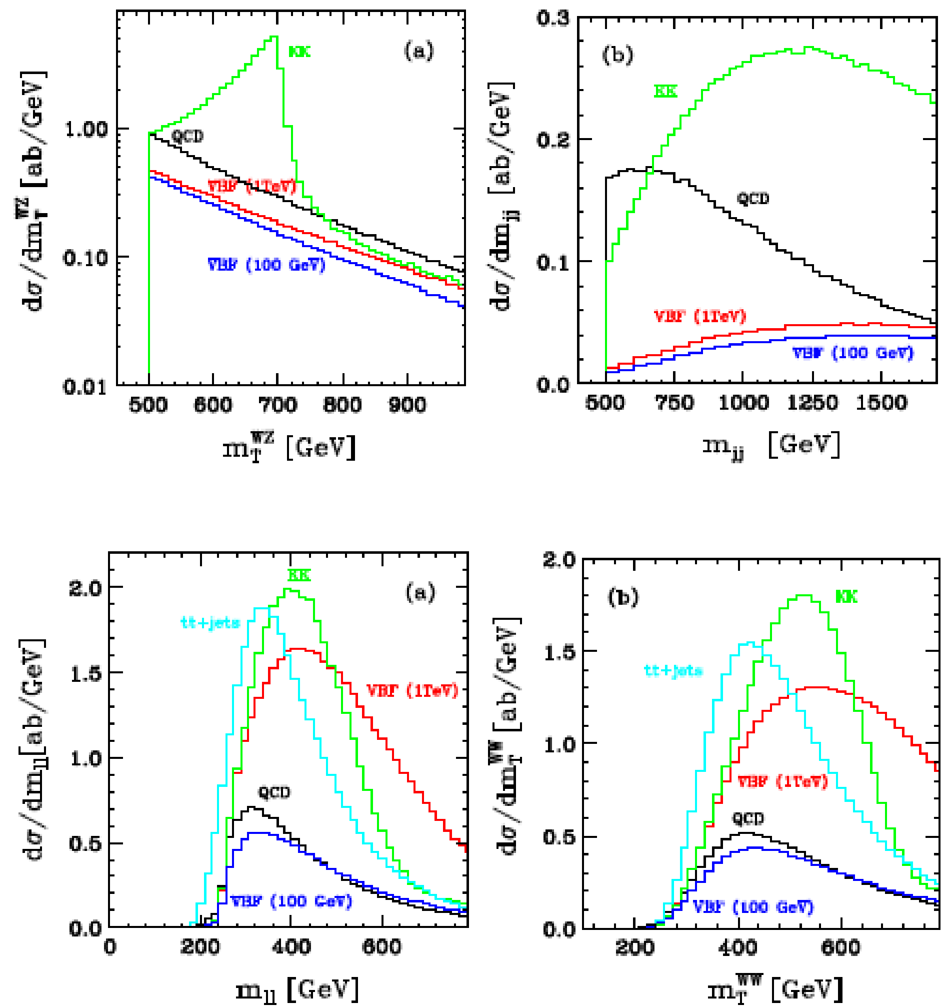
HELAC – mass-ordered PS in PYTHIA with MLM matching

MADEVENT – mass-ordered PS in PYTHIA with MLM matching

SHERPA – mass-ordered PS with CKKW matching, PYTHIA

Background Studies

- $qq \to W^+ W^- qq\,,\quad qq \to W^+ Z qq$
- **VBFNLO** - Warped Higgsless Kaluza-Klein model of narrow spin1 resonances
- **HELAC-PHEGAS** - Most prominent background processes
- Full off-shell and finite width effects for final states with two tagging jets and four leptons
- Double forward jet-tagging techniques
- Dedicated cuts on the observable jets and charged leptons
- Substantial sensitivity to strong interactions in EWSB sector



VBFNLO
K. Arnold et al. '09
http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb/

Englert, Jager, Worek, Zeppenfeld '09

Real radiation

HELAC-DIPOLES

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

- Complete, publicly available automatic implementation of Catani-Seymour dipole subtraction
  - ⇒ phase space integration of subtracted real radiation and integrated dipoles in both massless and massive cases — Catani, Seymour '97 & Catani, Dittmaier, Seymour, Trocsanyi '02

- Extended for arbitrary polarizations — Czakon, Papadopoulos, Worek '09
  - ⇒ Monte Carlo over polarization states of external particles

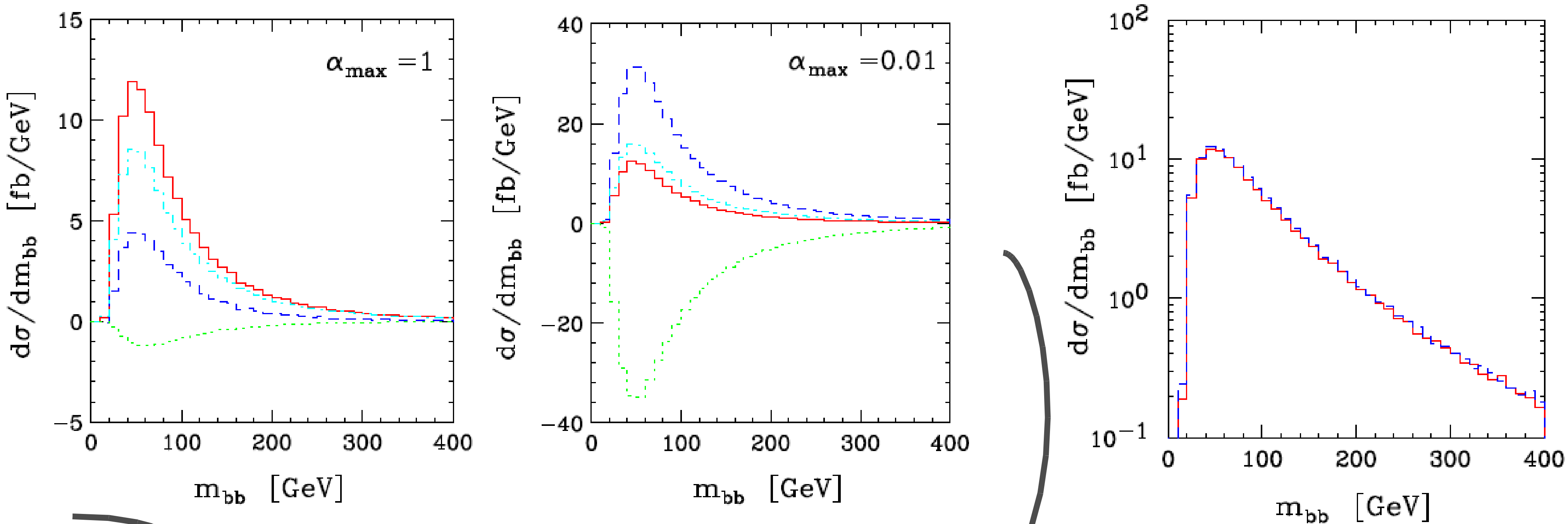
- Phase space restriction on the dipole phase space $\alpha_{max} \in \,]0,1]$

  Nagy, Trocsanyi '99 & Nagy '02
  Campbell, Ellis, Tramontano '04
  Campbell, Tramontano '05
  Czakon, Worek, Papadopoulos '09

  - ⇒ Cuts off dipole function for phase space regions away from singularity
  - ⇒ Less dipoles subtraction terms needed per event
  - ⇒ Increased numerical stability by decreasing size of dipole phase space
  - ⇒ Reduced missed binning problem
  - ⇒ Large cancellations between dipoles subtracted real radiation and integrated dipoles

Cutoff Dependence

Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09



Full result

Dipole subtracted real emission

K + P operators

I operator

$$pp \rightarrow t\,\bar{t}\,b\,\bar{b} + X$$

Summary & Outlook

- **HELAC–PHEGAS:** Framework for high energy phenomenology at LO + LL

- Automated approaches for NLO build around **HELAC-PHEGAS** **HELAC-1LOOP**, **CUTTOOLS** and **HELAC-DIPOLES**, **ONELOOP**

- Contribute to **ATLAS** and **CMS** generator groups in all stages (interfacing, validation, tuning, installation, configuration, user help, **physical analysis**...)

- Make **HELAC-PHEGAS** an option for the **LHC** !