# ***BlackHat*, an Automated Program for the Computation of One-Loop Amplitudes.**

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PHENO08

# NLO EW/QCD at LHC

- precise SM backgrounds to electroweak & QCD processes needed to identify and interpret anomalies in collider experiments
- aim for NLO corrections to high-multiplicity processes; relevant to decays of new particles with multi-body decays
- to date no complete NLO QCD computation with at least 4 final-state objects (in electroweak $e^+e^-$ to 4 fermions: *Denner, Dittmaier*)

## Bottleneck at NLO:

- LO information long available
- fully automated subtraction method (*Catani, Seymour*) available
- missing: IR-finite parts of one-loop virtual corrections

*Gleisberg, Krauss; Seymour, Tevlin; QCD/Jet physics session*

“... extremely time and theorist consuming... ” (*quote from Les-Houches Summary Report 2007*)

Les-Houches 2005

| process wanted at NLO ($V \in \{Z, W, \gamma\}$) | background to |
|---|---|
| 1. $pp \to VV +$ jet | $t\bar{t}H$, new physics |
| 2. $pp \to H + 2$ jets | $H$ production by vector boson fusion (VBF) |
| 3. $pp \to t\bar{t}b\bar{b}$ | $t\bar{t}H$ |
| 4. $pp \to t\bar{t} + 2$ jets | $t\bar{t}H$ |
| 5. $pp \to VVb\bar{b}$ | VBF $\to H \to VV$, $t\bar{t}H$, new physics |
| 6. $pp \to VV + 2$ jets | VBF $\to H \to VV$ |
| 7. $pp \to V + 3$ jets | new physics |
| 8. $pp \to VVV$ | SUSY trilepton |

*Dittmaier, Kallweit, Uwer; Campbell, Ellis, Zanderighi* (→ 1.)

*Campbell, Ellis, Zanderighi; Ciccolini, Denner, Dittmaier* (→ 2.)

*Lazopoulos, Melnikov, Petriello, Hankele, Zeppenfeld* (→ 8.)

... and of course there is more:

Run II Monte Carlo Workshop 2001

| Single boson | Diboson | Triboson | Heavy flavor |
|---|---|---|---|
| $W+\leq 5j$ | $WW+\leq 5j$ | $WWW+\leq 3j$ | $t\bar{t}+\leq 3j$ |
| $W+b\bar{b}+\leq 3j$ | $WW+b\bar{b}+\leq 3j$ | $WWW+b\bar{b}+\leq 3j$ | $t\bar{t}+\gamma+\leq 2j$ |
| $W+c\bar{c}+\leq 3j$ | $WW+c\bar{c}+\leq 3j$ | $WWW+\gamma\gamma+\leq 3j$ | $t\bar{t}+W+\leq 2j$ |
| $Z+\leq 5j$ | $ZZ+\leq 5j$ | $Z\gamma\gamma+\leq 3j$ | $t\bar{t}+Z+\leq 2j$ |
| $Z+b\bar{b}+\leq 3j$ | $ZZ+b\bar{b}+\leq 3j$ | $WZZ+\leq 3j$ | $t\bar{t}+H+\leq 2j$ |
| $Z+c\bar{c}+\leq 3j$ | $ZZ+c\bar{c}+\leq 3j$ | $ZZZ+\leq 3j$ | $t\bar{b}+\leq 2j$ |
| $\gamma+\leq 5j$ | $\gamma\gamma+\leq 5j$ | | $tb\bar{b}+\leq 3j$ |
| $\gamma+b\bar{b}+\leq 3j$ | $\gamma\gamma+b\bar{b}+\leq 3j$ | | |
| $\gamma+c\bar{c}+\leq 3j$ | $\gamma\gamma+c\bar{c}+\leq 3j$ | | |
| | $WZ+\leq 5j$ | | |
| | $WZ+b\bar{b}+\leq 3j$ | | |
| | $WZ+c\bar{c}+\leq 3j$ | | |
| | $W\gamma+\leq 3j$ | | |
| | $Z\gamma+\leq 3j$ | | |

need for automation!

# Computational Challenges

- traditional approach: large number of Feynman diagrams:
  - e.g.: 2 $\longrightarrow$ 6 jets: $10^6$ diagrams and about $10^{10}$ terms before integration
- redundant information: cancellations between gauge non-invariant parts
- numerical reduction of tensor integrals unstable

experience: simple answers in the right language; source of progress:

on-shell technology

many contributed to recent (string inspired) progress: *Anastasiou, Badger, Berger, Bern, Britto, Bjerrum-Bohr, Brandhuber, Cachazo, Del Duca, Dixon, Dunbar, Feng, Forde, Febres Cordero, Giele, Glover, Kosower, Kunszt, Mastrolia, McNamara, Melnikov, Ossola, Papadopoulos, Perkins, Pittau, Risager, Spence, Travaglini, Witten, ...*

# BlackHat

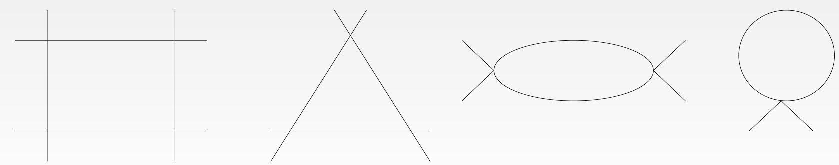
*C.F. Berger, Z. Bern, L.J. Dixon, F. Febres Cordero, D. Forde, HI, D.A. Kosower, D. Maitre; T. Gleisberg*

- Framework for automated NLO computations
- C++ implementation
- Library of functions: spinor-helicity formalism, computation of hard scattering amplitudes, factorisation, residue extraction...
- Input Libraries: tree-amplitudes, spectrum
- Caching and assembly

will be released publicly usable as black box in about 1 year

# On-Shell Methods for One-Loop Amplitudes

known basis of scalar integrals:



$$A^{\text{1-loop}} = \sum_i C_i \, Int_i + R$$

- split amplitude into sum of scalar integrals and rational remainder
- rational integral coefficients computed via generalized unitarity
- purely rational part from on-shell recursions & “cut-completion”
- related approach by other groups: *Ossola, Papadopoulos, Pittau; Ellis, Giele, Kunszt, Melnikov; Anastasiou, Britto, Feng, Mastrolia*

*Bern, Dixon, Kosower; Britto, Cachazo, Feng*

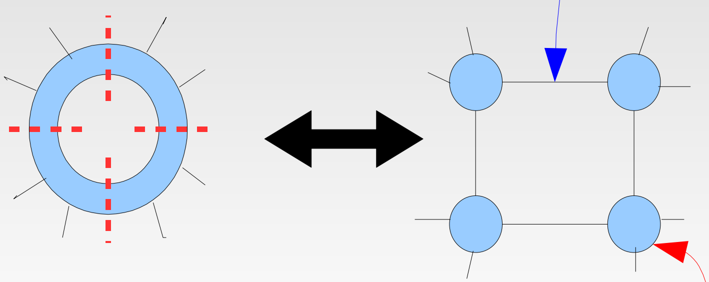
*Britto, Cachazo, Feng, Witten; Berger, Bern, Dixon, Forde; Bern, Bjerrum-Bohr, Dunbar, HI*

# Generalized Unitarity

# On-Shell Recursion

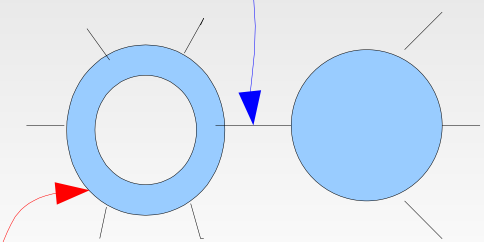
*Bern, Dixon, Kosower;*
*Britto, Cachazo, Feng;*

*Bern, Dixon, Kosower;*
*Bern, Bjerrum-Bohr, HI, Dunbar;*
*Berger, Bern, Dixon, Forde, Kosower*



on-shell states

on-shell amplitudes



*also: Ossola, Papadopoulos, Pittau; Forde;*

- unitarity allows to use optical theorem to trade logs for on-shell condition in loops

- universal factorization properties can be inverted

- tree-like computations: sewing on-shell amplitudes to get full amplitude
- tricks: use complex momenta, suitable parametrizations, discrete Fourier projection

# Numerical Stability

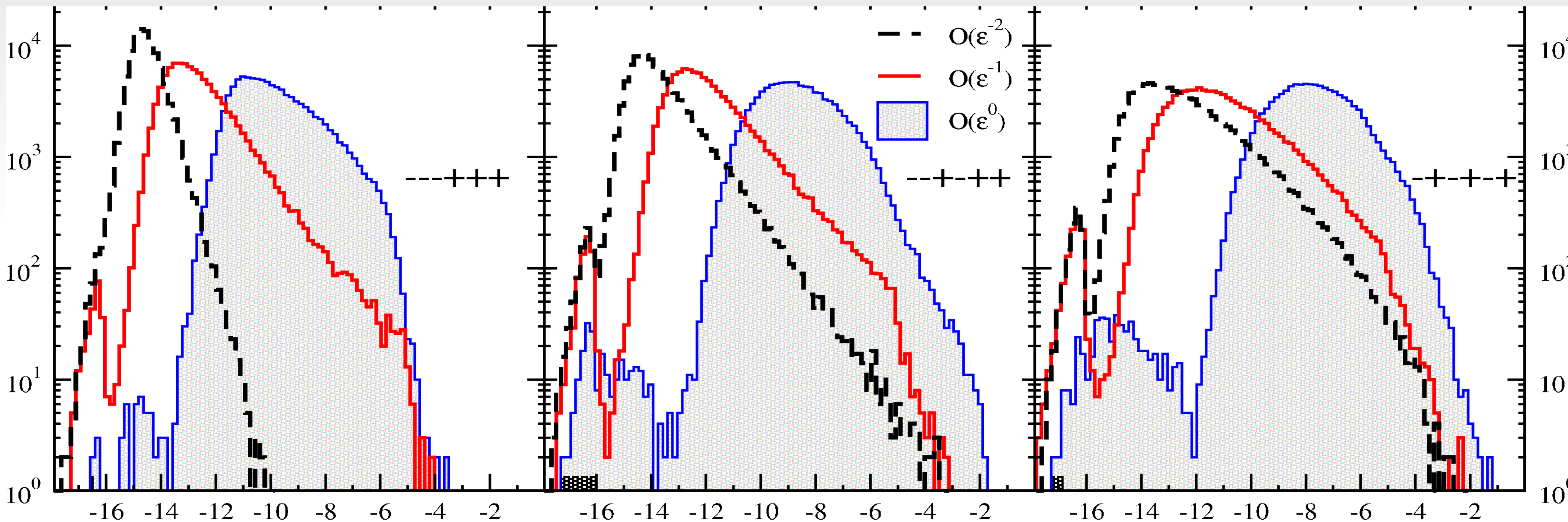
$$A_n^{1-loop} =_{1/\epsilon,\, non-log} \frac{1}{\epsilon} \sum_{j \in bubbles} C_j = -[\frac{1}{\epsilon}(\frac{11}{3} - \frac{2}{3}\frac{n_f}{N_c})] A_n^{tree}$$

- to test for loss of precision:
  - compare non-logarithmic $1/\epsilon$ singularities to tree amplitude
  - cancelling of spurious poles in $1/\epsilon$ singularity
- rescue strategy: recompute at higher precision: 16 to 32 (to 64) digits
  - local calls e.g. for the extraction of a single residue of cut-completion
  - robust to the source, simple to implement

- we do much better than needed for phenomenological studies, but demonstrates control over instabilities with almost no extra cost in computer time

# Precision Study

$$\log_{10}\left|\frac{A_n^{num}-A_n^{target}}{A_n^{target}}\right|$$




100 000 PS points, $E_T>0.01\ s^{(1/2)}$, pseudo-rapidity<3, separation cut >0.4

# Efficiency

pure gluon scattering

scaling with number of partons:

| | |
|---|---|
| 6 pt MHV | 8 ms |
| 7 pt MHV | 14 ms |
| 8 pt MHV | 34 ms |

scaling with complexity of helicity structure:

| | |
|---|---|
| ( - + - + + + ) | 24 ms |
| ( - + + - + + ) | 76 ms |
| ( - - - + + +) | 16 ms |
| ( - - + - + +) | 48 ms |
| ( - + - + - +) | 80 ms |

# Conclusions

- presented first results from BlackHat, an automated implementation of on-shell methods
- on-shell algorithms efficient and numerical stability
- moderate scaling of computer time with complexity or number of partons

# Tasks

- variety of computations inaccessible by traditional means are work in progress: external fermions, massive quarks & vector bosons
- towards cross sections: + automation of Catani-Seymour (*Gleisberg, Krauss*)
- BlackHat publicly available in about one year