One-loop corrections to many-particle production

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Contents

Motivation

LHC: Multi-particle final states of major importance

number of jets	3	4	5	6	7
$\sigma/$nb	91.4	6.54	0.46	0.032	0.002

($p_T^{jet} > 60$ GeV, $\theta_{ij} > 30^0$, $|\eta^j| < 3$) [Draggiotis, Kleiss, C. Papadopoulos 02]

- Poor description by present event generators
- leading order:
  - large scale dependence
  - poor jet modelling
  - large sensitivity to cuts

need for NLO predictions

NLO: Ingredients

e.g. $2 \to N$ process

- Diagram Generation

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- ideally: combine with Parton Shower

Loop Diagram Generators

- FeynArts/LoopTools
- GRACE 1-loop
- QGRAF

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Real Radiation

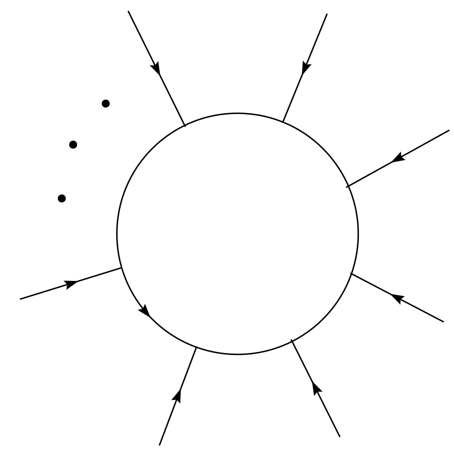
- Phase space slicing
- Subtraction

mature state

One-loop amplitudes

hard scattering

- $2 \to 2$: "state of the art"
- $2 \to 3$: only few results
- $2 \to 4$: frontier



Status NLO $2 \to 3$ (LHC)

$$pp \to 3\,jets$$
$$pp \to V\,j\,j \quad (V = \gamma, Z, W^{\pm})$$
$$pp \to \gamma\gamma j$$
$$pp \to V\,b\bar{b}$$
$$pp \to t\bar{t}H, b\bar{b}H$$
$$pp \to t\bar{t}\,j$$

Campbell, De Florian, Del Duca, R.K. Ellis, Giele, Glover, Kilgore, Kunszt, Maltoni, Miller, Nagy, Trocsanyi, Beenakker, Dittmaier, Plümper, Spira, Zerwas, Dawson, Orr, Reina, Wackeroth, Brandenburg, Uwer, Weinzierl, . . .

Status NLO $2 \to 3$ (ILC)

$$e^+e^- \to 4jets$$
$$e^+e^- \to \nu\bar{\nu}H$$
$$e^+e^- \to e^+e^-H$$
$$e^+e^- \to \nu\bar{\nu}\gamma$$
$$e^+e^- \to t\bar{t}H$$
$$e^+e^- \to ZHH$$
$$\gamma\gamma \to t\bar{t}H$$

Bern, Dixon, Kosower, Weinzierl, Kunszt, Frixione, Signer, Trocsanyi, Campbell, Cullen, Glover, Miller, Bélanger, Boudjema, Fujimoto, Ishikawa, Kaneko, Kato, Kurihara, Shimizu, Yasui, Jegerlehner, Tarasov, Denner, Dittmaier, Roth, Weber, Ren-You, Wen-Gan, Hui, Yan-Bin, Hong-Sheng, Pei-Yun,. . .

Status NLO $2 \rightarrow 4$

$e^+e^- \longrightarrow 4$ fermions :

Boudjema, Fujimoto, Ishikawa, Kaneko, Kato, Kurihara, Shimizu 07/04: progress report

Denner, Dittmaier, Roth, Wieders 02/05: complete electroweak $\mathcal{O}(\alpha)$ corrections

some unphysical results

6-gluon amplitudes for Super–Yang–Mills $\mathcal{N} = 4$

Bern, Dixon, Dunbar,Kosower 94

All non-MHV 7-gluon amplitudes for Super–Yang–Mills $\mathcal{N} = 4$

Bern, Del Duca, Dixon, Kosower 04

6-scalar amplitudes in the Yukawa model

T. Binoth, J.Ph. Guillet, GH, C. Schubert 01

2-photon 4-scalar amplitudes in the Yukawa model

T. Binoth 02

public programs: (hadron collider)

- $pp \to 1,2\, jets$ Ellis, Kunszt, Soper ; Frixione
- JETRAD, DYRAD $pp \to 1,2\, jets$, $pp \to V + jet$
  Giele, Glover, Kosower
- AYLEN/EMILIA $pp \to VV', pp \to V\gamma$
  De Florian, Dixon, Kunszt, Signer
- HVQMNR heavy quark production
  Mangano, Nason, Ridolfi, Frixione
- DIPHOX, JETPHOX $pp \to \gamma\gamma, pp \to \gamma\, jet$
  Aurenche, Binoth, Fontannaz, Guillet, Pilon, Werlen
- $pp \to \gamma\, jet$ Gordon, Vogelsang ; Frixione

[public] programs: (hadron collider)

- $pp \longrightarrow 3\,jets$ Giele, Kilgore
- NLOJET++ $pp \longrightarrow \leq\ 3\,jets$ Z. Nagy
- MCFM $pp \longrightarrow V + \leq 2\,jets\,(V = W, Z), pp \longrightarrow V + b\bar{b}$
  J. Campbell, R.K. Ellis, D. Rainwater
- GRACE/1-LOOP
  Bélanger, Boudjema, Fujimoto, Ishikawa, Kaneko, Kato, Shimizu
- $pp \longrightarrow t\bar{t}H, b\bar{b}H$
  Beenakker, Dittmaier, Plümper, Spira, Zerwas
  Dawson, Orr, Reina, Wackeroth

Combination with parton shower

- Collins, Zu 00
- Frixione, Nason, Webber (MC@NLO) 02
- Kurihara, Fujimoto, Ishikawa, Kato, Kawabata, Munehisa, Tanaka 02
- Krämer, Soper 03
- Nagy, Soper 05

An experimenter's wishlist

- Hadron collider cross-sections one would like to know at NLO

Run II Monte Carlo Workshop, April 2001

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

J. Campbell
Collider Physics Workshop 04

Calculation of one-loop amplitudes: methods

- fully numerical: sum over all cuts of the graphs before numerical integration over the loop momenta
  D.Soper
- algebraic/semi-numerical: separation into real and virtual contributions $\longrightarrow$ infrared poles $\longrightarrow$ subtraction
  - Ferroglia, Passera, Passarino, Uccirati
  - Kurihara, Kaneko
  - Nagy, Soper
  - Binoth, GH, Kauer

Methods

- algebraic reduction:
  - Bern, Dixon, Kosower massless
  - Fleischer, Jegerlehner, Tarasov massive
  - Denner, Dittmaier massive and massless
  - Duplancic, Nizic massless
  - Giele, Glover, Zanderighi massless
  - Del Aguila, Pittau massless, based on spinor helicity
  - Van Hameren, Vollinga, Weinzierl massless, spinor helicity
  - Binoth, Guillet, GH, Pilon, Schubert massless and massive

Methods

- unitarity-based methods
  (sewing together tree amplitudes)

  new insights from twistor space

  Bern, Del Duca, Dixon, Kosower,

  Badger, Glover, Khoze, Svrcek,

  Britto, Buchbinder, Cachazo, Feng,

  Bedford, Brandhuber, Spence, Travglini, Witten, . . .

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  - if algebraic tensor reduction is performed:
    inverse Gram determinants should be avoided

hep-ph/0504267 [Binoth, Guillet, GH, Pilon, Schubert]

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- valid for an arbitrary number of external legs
- valid for massless and massive particles
  (uses dimensional regularisation for IR poles)
- algebraic tensor reduction stops before purely scalar integrals are reached
  $\longrightarrow$ convenient set of basis integrals, same for every process
  $\longrightarrow$ easy to automate

basis integrals:

$I_2^n(\ldots j_2)$, $I_3^n(\ldots j_3)$, $I_3^{n+2}(1, j_1)$ $I_4^{n+2}(\ldots j_3)$, $I_4^{n+4}(1, j_1)$

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- efficient numerical evaluation of parameter integrals by contour deformation $\rightarrow$ robust
- further algebraic reduction possible, to be used in "safe" phase space regions $\rightarrow$ fast

feasible (?) until LHC starts (SM):

list to be discussed/modified/completed !

- $2 \to 3$
  - $pp \to V\,V\,jet$
  - $pp \to V\,V\,V$
- $2 \to 4$
  - $pp \to 4\,jets$
  - $pp \to t\bar{t}\,b\bar{b}$, $pp \to t\bar{t} + 2\,jets$,
  - $pp \to t\bar{t}\,H + jet$
  - $pp \to V + 3\,jets$
  - $pp \to V\,V + 2\,jets$
  - $pp \to V\,V\,V + jet$

calculations/collaborations to be started at Les Houches

Summary and Outlook

- Rapid development of various theoretical tools recently
- Results for $2 \to 4$ processes at NLO feasible until LHC starts taking data
- Still lengthy individual calculations, no largely automated multi-purpose program available yet
- Focus on crucial processes
- Work on automatisation