NLO/NNLO group

- Introduction — VDD
- A complete formalism for one-loop multileg amplitudes — G. Heinrich
- A method for the numerical evaluation of one-loop integrals — Z. Kunszt
- Status of GRACE — Y. Kurihara
- NLO corrections to (pseudoscalar) H t tbar — S. Dittmaier
- Progress on NNLO subtraction — VDD
- More progress on NNLO subtraction — M. Grazzini

Precision QCD

Precise determination of

- strong coupling constant α_s
- parton distributions
- electroweak parameters
- LHC parton luminosity

Precise prediction for

- Higgs production
- new physics processes
- their backgrounds

Desired NLO cross sections

Run II Monte Carlo Workshop, April 2001

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

NLO history

$e^+e^- \to 3$ jets	K. Ellis, D. Ross, A. Terrano 1981
$e^+e^- \to 4$ jets	Z. Bern et al., N. Glover et al., Z. Nagy Z. Trocsanyi 1996-97
$pp \to 1, 2$ jets	K. Ellis J. Sexton 1986, W. Giele N. Glover D. Kosower 1993
$pp \to 3$ jets	Z. Bern et al., Z. Kunszt et al. 1993-1995, Z. Nagy 2001
$pp \to V + 1$ jet	W. Giele N. Glover & D. Kosower1993
$pp \to V + 2$ jet	Bern et al., Glover et al. 1996-97, K. Ellis & Campbell 2003
$pp \to Vb\bar{b}$	K. Ellis & J. Campbell 2003
$pp \to Vb\bar{b} + 1$ jet	??
$pp \to VV$	Ohnemus & Owens, Baur et al.1991-96, Dixon et al. 2000
$pp \to VV + 1$ jet	??
$pp \to \gamma\gamma$	B. Bailey et al 1992, T. Binoth et al 1999
$pp \to \gamma\gamma + 1$ jet	Z. Bern et al. 1994, V. Del Duca et al. 2003
$pp \to Q\bar{Q}$	Dawson K. Ellis Nason 1989, Mangano Nason Ridolfi 1992
$pp \to Q\bar{Q} + 1$ jet	A. Brandenburg et al. 2005 ?

NLO production rates

Process-independent procedure devised in the 90's

- slicing — Giele Glover & Kosower
- subtraction — Frixione Kunszt & Signer; Nagy & Trocsanyi
  - dipole — Catani & Seymour
  - antenna — Kosower; Campbell Cullen & Glover

$$\sigma = \sigma^{\rm LO} + \sigma^{\rm NLO} = \int_m d\sigma^B_m \; J_m + \sigma^{\rm NLO}$$

$$\sigma^{\rm NLO} = \int_{m+1} d\sigma^{\rm R}_{m+1} J_{m+1} + \int_m d\sigma^{\rm V}_m J_m$$

the 2 terms on the rhs are divergent in d=4

use universal IR structure to subtract divergences

$$\sigma^{\rm NLO} = \int_{m+1} \left[d\sigma^{\rm R}_{m+1} J_{m+1} - d\sigma^{\rm R,A}_{m+1} J_m \right] + \int_m \left[d\sigma^{\rm V}_m + \int_1 d\sigma^{\rm R,A}_{m+1} \right] J_m$$

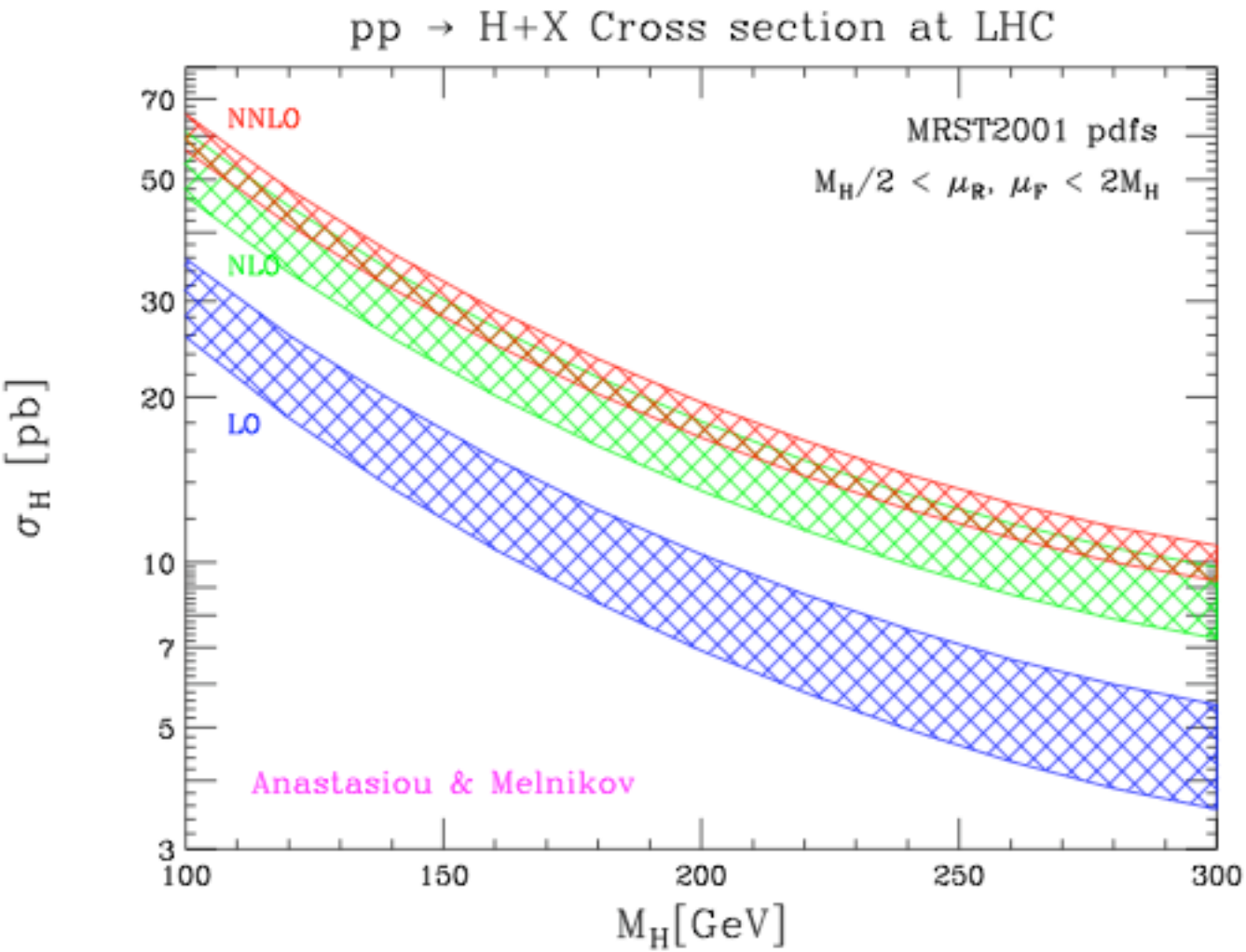
the 2 terms on the rhs are finite in d=4

NLO complications

- loop integrals are involved and process-dependent
- more particles ⇒ many scales ⇒ lenghty analytic expressions
  - even though it is known how to compute loop integrals with $2 \to n$ particles no integrals with $n > 4$ have been computed (either analytically or numerically)
- no numeric methods yet for hadron collisions
  - counterterms are subtracted analytically

Is NLO enough to describe data ?

Total cross section for inclusive Higgs production at LHC



contour bands are

lower

$\mu_R = 2M_H \quad \mu_F = M_H/2$

upper

$\mu_R = M_H/2 \quad \mu_F = 2M_H$

scale uncertainty is about 10%

NNLO prediction stabilises the perturbative series

NNLO state of the art

- Drell-Yan W, Z production
  - total cross section — Hamberg, van Neerven, Matsuura 1990; Harlander, Kilgore 2002
  - rapidity distribution — Anastasiou et al. 2003
- Higgs production
  - total cross section — Harlander, Kilgore; Anastasiou, Melnikov 2002
  - fully differential cross section — Anastasiou, Melnikov, Petriello 2004
- $e^+e^- \to 3$ jets
  - the C_F^2 term — the Gehrmanns, Glover 2004

NNLO cross sections

- Sector decomposition — Denner Roth 1996; Binoth Heinrich 2000; Anastasiou, Melnikov, Petriello 2003

  ↑ the only method which, so far, yields useful NNLO cross sections

  ↑ cancellation of divergences is performed numerically

  ↓ process dependent

- Subtraction

  ↑ process independent

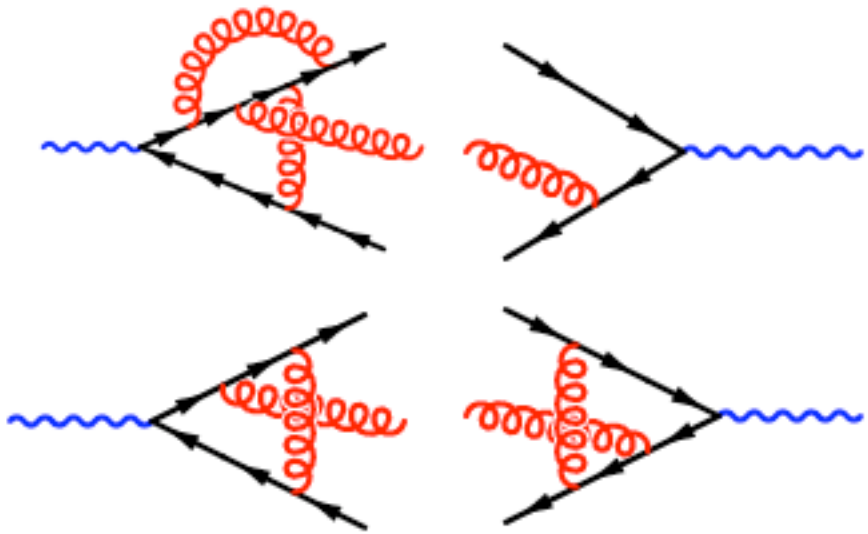
  ↓ cancellation of divergences is semi-analytic

  ↓ despite a great deal of efforts, it's not there yet

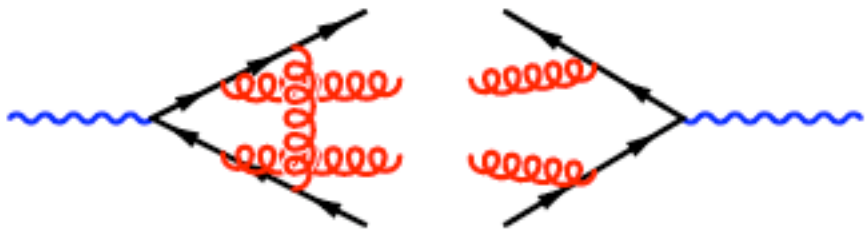
NNLO assembly kit

$e^+e^- \to 3$ jets

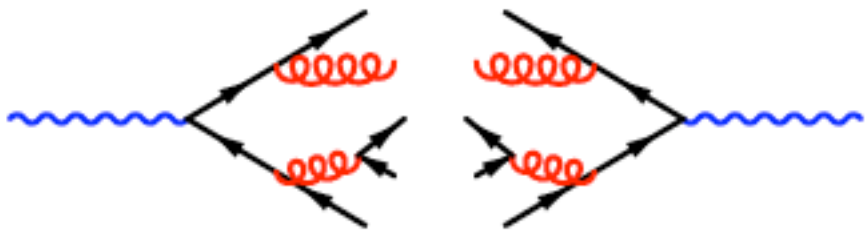
double virtual



real-virtual



double real



Two-loop matrix elements

- two-jet production $qq' \to qq',\ q\bar{q} \to q\bar{q},\ q\bar{q} \to gg,\ gg \to gg$

  C. Anastasiou N. Glover C. Oleari M. Tejeda-Yeomans 2000-01

  Z. Bern A. De Freitas L. Dixon 2002

- photon-pair production $q\bar{q} \to \gamma\gamma,\ gg \to \gamma\gamma$

  C. Anastasiou N. Glover M. Tejeda-Yeomans 2002

  Z. Bern A. De Freitas L. Dixon 2002

- $e^+e^- \to 3$ jets $\qquad \gamma^* \to q\bar{q}g$

  L. Garland T. Gehrmann N. Glover A. Koukoutsakis E. Remiddi 2002

- $V + 1$ jet production $q\bar{q} \to Vg$

  T. Gehrmann E. Remiddi 2002

- Drell-Yan V production $q\bar{q} \to V$

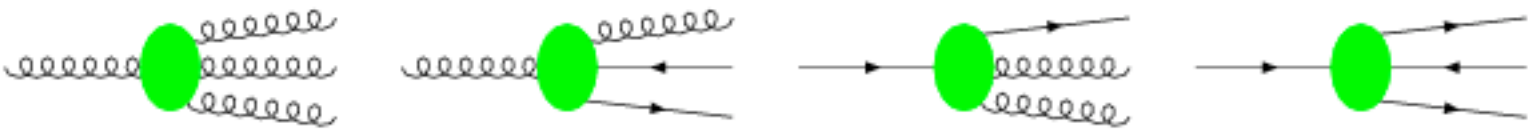
  R. Hamberg W. van Neerven T. Matsuura 1991

- Higgs production $gg \to H$ (in the $m_t \to \infty$ limit)

  R. Harlander W. Kilgore; C. Anastasiou K. Melnikov 2002

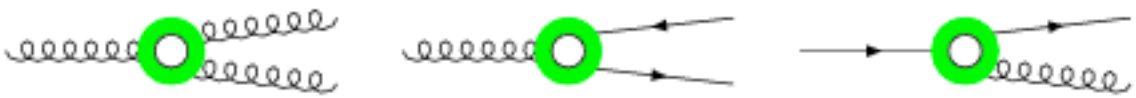
NNLO cross sections: subtraction

- universal IR structure ⇒ process-independent procedure
- universal collinear and soft currents
  - 3-parton tree splitting functions



J. Campbell N. Glover 1997; S. Catani M. Grazzini 1998; A. Frizzo F. Maltoni VDD 1999; D. Kosower 2002

  - 2-parton one-loop splitting functions



Z. Bern W. Kilgore C. Schmidt VDD 1998-99; D. Kosower P. Uwer 1999; D. Kosower 2003

- universal subtraction counterterms
  - several ideas and works in progress
    but so far not yet completely figured out

D. Kosower; S. Weinzierl; the Gehrmanns & G. Heinrich 2003
S. Frixione M. Grazzini 2004; G. Somogyi Z. Trocsanyi VDD 2005
the Gehrmanns & N. Glover 2004-5