N(N)LO TOOLS FOR THE LHC

Zoltán Trócsányi

University of Debrecen and Institute of Nuclear Research, Hungary

CERN MC workshop, July 7, 2003.

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SCIENCE AND FICTION IN NLO COMPUTATIONS

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- Science
  - jet cross sections at NLO, available tools
- Fiction (turning into science)
  - automatization
  - NLO with parton showers, NNLO

QCD tools

for the process

$$h_A(p_A) + h_B(p_B) \to H(Q, \{P, \ldots\}) + X$$

QCD TOOLS

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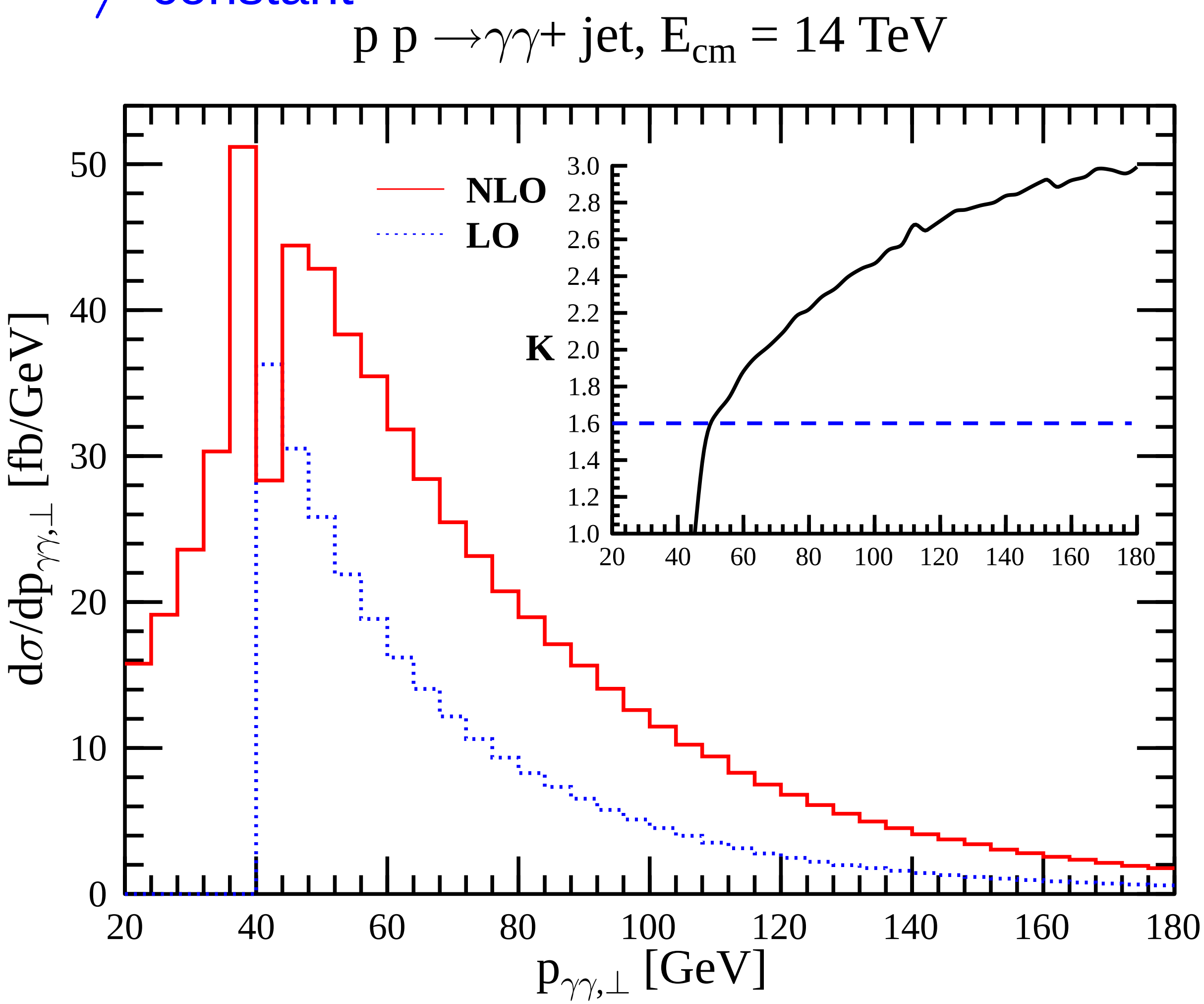
the factorization theorem:

$$\sigma_{AB}(p_A, p_B; Q, \{P, \ldots\}) =$$
$$\sum_{a,b} \int \mathrm{d}x_a \mathrm{d}x_b\, f_{a/A}(x_a, \mu_F^2)\, f_{b/B}(x_b, \mu_F^2)$$
$$\times \hat{\sigma}_{ab}(x_a p_A, x_b p_B, \mu_F^2, \alpha_s(Q), \{P, \ldots\})$$
$$+\mathrm{O}((\Lambda_{\mathrm{QCD}}/Q)^p)$$

perturbative → $\hat{\sigma}_{ab}$

QCD, hep-ph/0005025

$$K = \frac{\sigma^{LO} + \sigma^{NLO}}{\sigma^{LO}} \neq \text{constant}$$



V. Del Duca, F. Maltoni, Z. Nagy, Z.T.

JET CROSS SECTIONS AT NLO

$$\hat{\sigma} = \sigma^{\mathrm{LO}} + \sigma^{\mathrm{NLO}} = \int_m \mathrm{d}\sigma^{\mathrm{B}} + \sigma^{\mathrm{NLO}}$$

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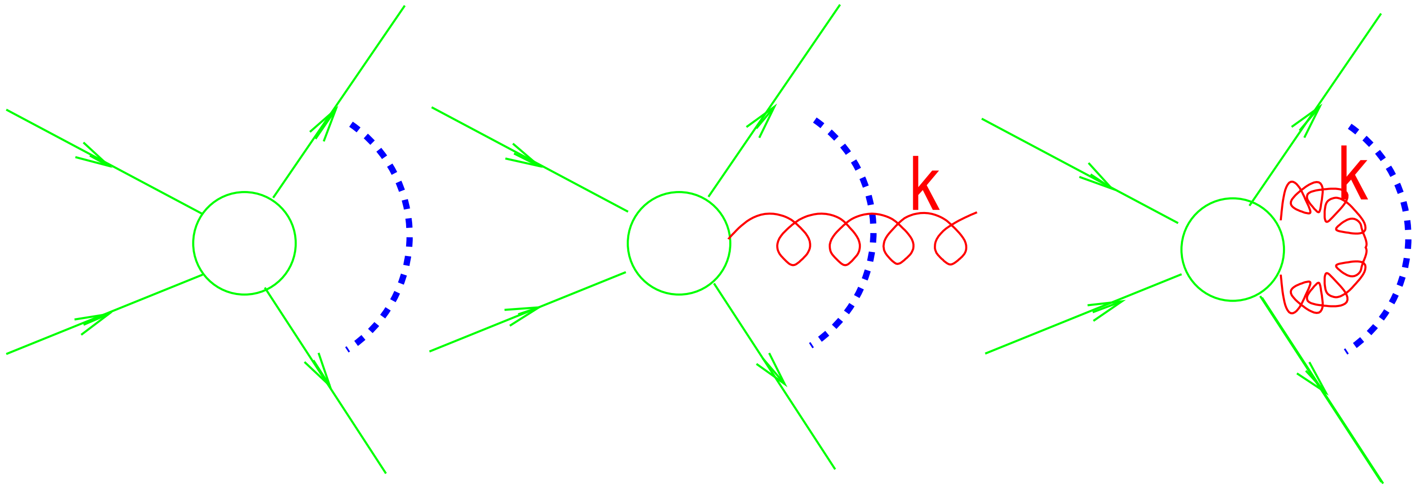

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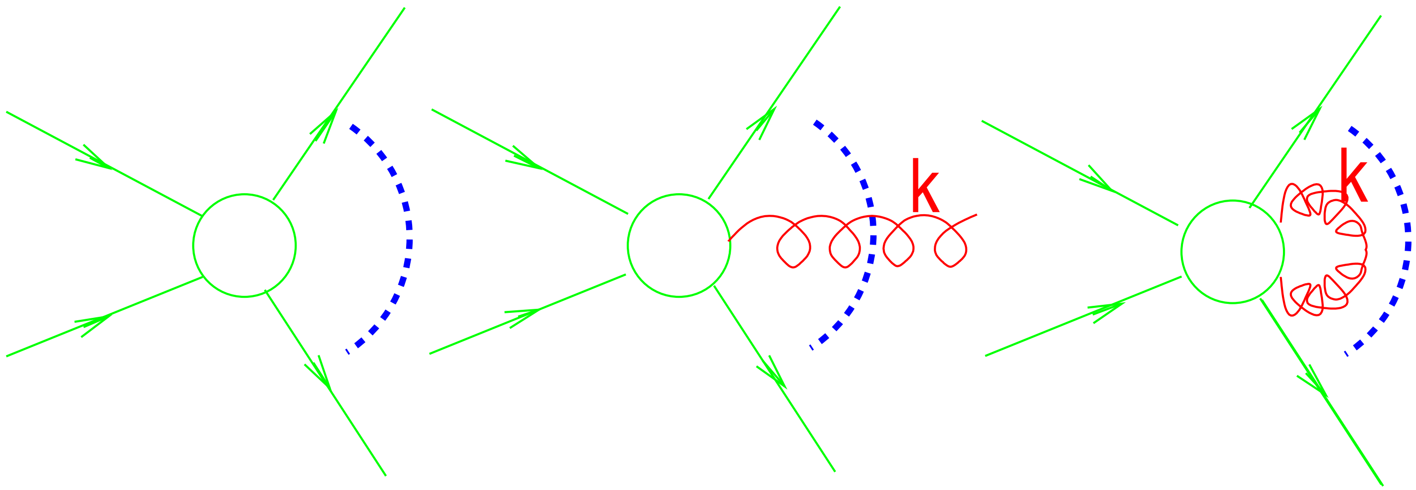

$$\underbrace{\int \mathrm{d}\Gamma(\mathrm{k}) \qquad\qquad \int \mathrm{d}^4\mathrm{k}}$$

finite

divergent in 4 dimensions

Jet cross sections at NLO

$$\hat{\sigma} = \sigma^{\mathrm{LO}} + \sigma^{\mathrm{NLO}} = \int_m \mathrm{d}\sigma^{\mathrm{B}} + \sigma^{\mathrm{NLO}}$$

$$\sigma^{\mathrm{NLO}} = \underbrace{\int_{m+1} \mathrm{d}\sigma^{\mathrm{R}} + \int_m \mathrm{d}\sigma^{\mathrm{V}}}_{\text{divergent in } d=4}$$

General solution:

$$\sigma^{\mathrm{NLO}} = \int_{m+1} \left[\left(\mathrm{d}\sigma^{\mathrm{R}} \right)_{\varepsilon=0} - \left(\mathrm{d}\sigma^{\mathrm{A}} \right)_{\varepsilon=0} \right] + \int_m \left[\mathrm{d}\sigma^{\mathrm{V}} + \int_1 \mathrm{d}\sigma^{\mathrm{A}} \right]_{\varepsilon=0}$$

$$\equiv \int_{m+1} \mathrm{d}\sigma^{\mathrm{NLO}}_{m+1} + \int_m \mathrm{d}\sigma^{\mathrm{NLO}}_m$$

AVAILABLE TECHNIQUES

Process independent methods: (1) slicing; (2) residue; (3) dipole

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vi) can be implemented in a fully process independent way: `MCFM`, `NLOJET++`.

PARTONIC MONTE CARLO PROGRAMS AT NLO FOR THE LHC

- **MCFM**: $pp(\text{or } \bar{p})$ J.M. Campbell, R.K. Ellis PRD60:011501, PRD62:114012
  - $\rightarrow$ V ($W^{\pm}$, or Z) + 0, 1 or 2 jets
  - $\rightarrow$ V ($W^{\pm}$, or Z) + g$^{*}(\rightarrow b\bar{b})$, massless/massive b-quarks
  - $\rightarrow$ $V + V'$ ($W^{+} + W^{-}$, $W^{\pm} + Z/\gamma^{*}$, $Z/\gamma^{*} + Z/\gamma^{*}$)
  - $\rightarrow$ H
  - $\rightarrow$ $H + V$ (W^{+} or Z)
  - $\rightarrow$ $H + b$
  - $\rightarrow$ $H+$ 1, or 2 jets
  - $\rightarrow$ $\tau^{+} + \tau^{-}$ (DY)

Partonic Monte Carlo programs at NLO for the LHC

- MCFM mcfm.fnal.gov
- NLOJET++: $pp($or $\bar{p})$ Z. Nagy, Z.T. PRL88:122003

$\longrightarrow$ inclusive jet, 2 and 3 jets

$\longrightarrow$ (direct) $\gamma + \gamma$ + 1 jet

PARTONIC MONTE CARLO PROGRAMS AT NLO FOR THE LHC

- MCFM mcfm.fnal.gov
- NLOJET++ www.cpt.dur.ac.uk/∼nagyz/nlo++/
- HVQMNR M. Mangano, P. Nason, G. Ridolfi NP B373, 295.
  - total cross section and distributions/correlations of heavy quark production

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- MCFM — mcfm.fnal.gov
- NLOJET++ — www.cpt.dur.ac.uk/∼nagyz/nlo++/
- HVQMNR — www.ge.infn.it/∼ridolfi/hvqlibx.tgz
- Isolated photon(s)
  - ☛ PHONLL: γ + jet — M. Werlen
  - ☛ DIPHOX: $\gamma\gamma$ — T. Binoth, J.Ph. Guillet, E. Pilon and M. Werlen

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- Isolated photon(s) monicaw.home.cern.ch/monicaw/phonll.html

  wwwlapp.in2p3.fr/lapth/PHOX_FAMILY/diphox.html
- H and sparticle production people.web.psi.ch/spira/proglist.html

Contents of many other codes are included in the above

NLO COMPUTATIONS WITH MASSIVE PARTONS

At the LHC processes involving massive partons will be very important

Finite mass M of the QCD partons

- is essential if M sets the hard scale of the cross section (e.g. total cross section for heavy quark hadroproduction). The massless limit is IR unstable

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$\Rightarrow$Extensions of known methods to jet cross sections involving massive partons with smooth massless limit is needed (also for MC@NLO)

S. Catani, S. Dittamier, M.H. Seymour and Z.T. NP B627 189 (Dipole)

Ingredients of computing QCD cross sections at NLO

☛ the Born contribution, $\mathrm{d}\sigma^{\mathrm{B}}$ in 4 dimensions

INGREDIENTS OF COMPUTING QCD CROSS SECTIONS AT NLO

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- the Born contribution, $\mathrm{d}\sigma^{\mathrm{B}}$ in 4 dimensions
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- a set of independent colour projections of the matrix element squared at the Born level, summed over parton polarizations, in 4 dimensions (for constructing $\mathrm{d}\sigma^{\mathrm{A}}$)
- the one-loop contribution, $\mathrm{d}\sigma^{\mathrm{V}}$ in d dimensions
- an additional projection of the Born level matrix element over the helicity of each external gluon in 4 dimensions

Automatization of computing $d\sigma_m^{LO}$ and $d\sigma_{m+1}^{NLO}$

- Several programs can generate QCD partonic cross sections at tree level (needed for $d\sigma^{B}$ and $d\sigma^{R}$)

☛ CompHEP/LanHEP: theory.sinp.msu.ru/comphep/

A. Pukhov et al, A. Semenov

☛ GRACE: minami-home.kek.jp Minami-Tateya Collaboration

☛ MADGRAPH/MADEVENT: madgraph.physics.uiuc.edu

F. Maltoni, T. Stelzer

☛ AMEGIC++ F. Krauss et al, JETL C.G. Papadopoulos et al

See talks by T. Stelzer and F. Krauss on Wednesday and by Y. Kurihara on Thursday

Comparison of these is necessary

Automatization of computing $\mathrm{d}\sigma_m^{\mathrm{LO}}$ and $\mathrm{d}\sigma_{m+1}^{\mathrm{NLO}}$

- Several programs can generate QCD partonic cross sections at tree level (needed for $\mathrm{d}\sigma^{\mathrm{B}}$ and $\mathrm{d}\sigma^{\mathrm{R}}$)
- Generation of colour-connected Born squared matrix element is conceptually not more complicated than that of the tree matrix elements

$\Rightarrow$

automatization is possible, but not done

Automatization of computing $\mathrm{d}\sigma_m^{\mathrm{NLO}}$

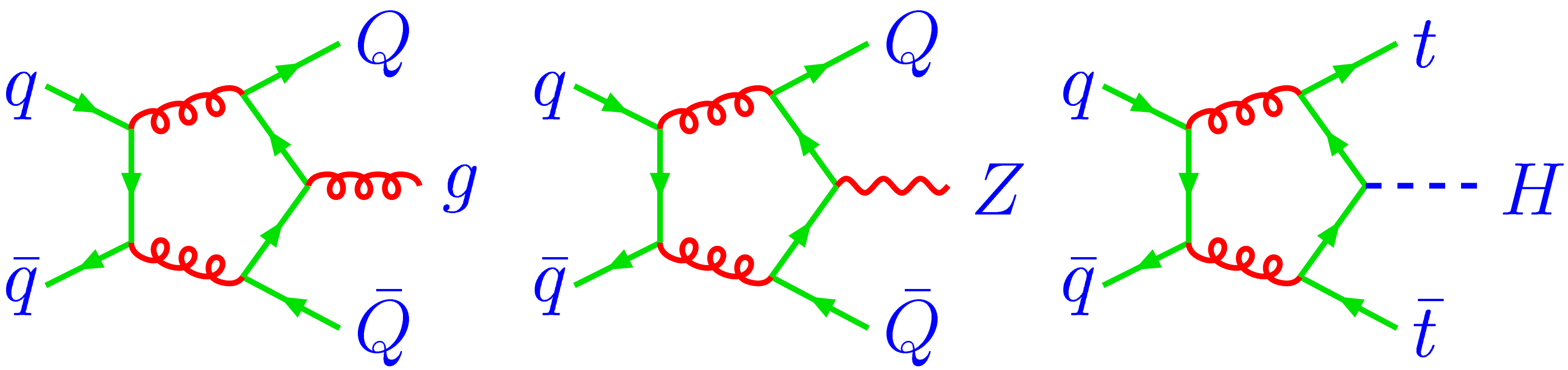
$$\int_m \mathrm{d}\sigma_m^{\mathrm{NLO}} = \int_m \left[\mathrm{d}\sigma^{\mathrm{V}} + \int_1 \mathrm{d}\sigma^{\mathrm{A}}\right]_{\varepsilon=0}$$

State of the art computation of $\mathrm{d}\sigma^{\mathrm{V}}$ is

art of analytic computations

$\Rightarrow$ brute force automatization is not feasible

Record:



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Yes: want analytic cancellation of ϵ poles

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Do we really need complicated analytic expressions for $\mathrm{d}\sigma^{\mathrm{V}}$?

Yes: want analytic cancellation of ϵ poles

No: want to evaluate complicated integrals numerically

AUTOMATIZATION OF COMPUTING $\sigma_m^{\rm NLO}$

'Purely' numerical computation of $\mathrm{d}\sigma^{\rm V}$ T. Binoth and G. Heinrich

is sufficient because the universal form of singular terms is

known analytically, but S. Catani, S. Dittmaier and Z.T.

the method follows the path of analytic computations

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☛ full automatization is cumbersome (many steps between diagrams and numerical integration)

☛ analytic continuation to the physical region is non-trivial

see T. Binoth's talk on Thursday

AUTOMATIZATION OF COMPUTING σ_m^{NLO}

Reconcile Yes and No: define local subtraction term for σ^{V}

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AUTOMATIZATION OF COMPUTING $\sigma_m^{\rm NLO}$

Reconcile Yes and No: define local subtraction term for $\sigma^{\rm V}$

- Not possible for the loop integral of the total amplitude
- may be possible for individual graphs Z. Nagy's talk on Thursday

  by localizing the origin of soft and collinear poles in loop integrals

The general structure

$$\sigma^{\rm NLO} = \int_{m+1}\Big[\Big(\mathrm{d}\sigma^{\rm R}\Big)_{\varepsilon=0} - \Big(\mathrm{d}\sigma^{\rm A_R}\Big)_{\varepsilon=0}\Big] + \sum_{\mathcal{G}}\int_m \int \mathrm{d}^4\ell\,\Big[\Big(\mathcal{G}^{\rm V}\Big)_{\varepsilon=0} - \Big(\mathcal{G}^{\rm A_V}\Big)_{\varepsilon=0}\Big] + \int_m \left[\int \mathrm{d}^d\ell\,\sum_{\mathcal{G}}\mathcal{G}^{\rm A_V} + \int_1 \mathrm{d}\sigma^{\rm A}\right]_{\varepsilon=0}$$

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- complicated integrals can be performed numerically
- cancellation of ϵ poles can be achieved analytically

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- cancellation of ϵ poles can be achieved analytically
- has the right form for starting a MC@NLO

CONCLUSIONS

☛ NLO computations are established, codes are available for $2 \to 2,\ 3$ processes

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- Automatization needs
  - generation of colour-connected amplitudes
  - better understanding of soft and collinear poles in loop integrals
  - the right solution should match the need of MC@NLO