Next-to-Leading Order Tools for Colliders

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Lecture outline

Theory overview

- The simplest case: $e^+e^- \to 2$ jets
  - ⋆ what does NLO mean?
  - ⋆ ingredients for a NLO calculation
  - ⋆ sketch of the calculation
- Building a NLO program

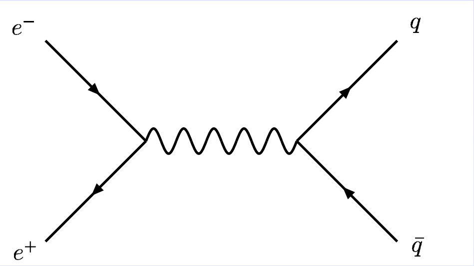
Phenomenology overview

- Current state of next-to-leading order QCD
  - ⋆ the calculational frontier
  - ⋆ survey of available tools for hadron colliders
- Shortcomings and future developments

The simplest case

- Let's make things easy for ourselves by considering 2 jet production at LEP, which can be represented by a single Feynman diagram at lowest order.

$$e^-(p_1) + e^+(p_2) \to q(q_1) + \bar{q}(q_2)$$

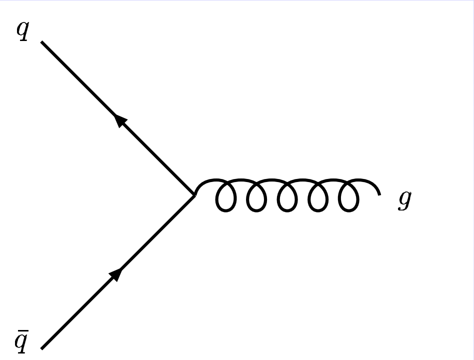


- We can simplify even further:
  - ⋆ let's assume all the particles are massless, $p_i^2 = q_i^2 = 0$
  - ⋆ forget about the Z for now, just imagine photon exchange

Gamma-matrix warmup exercise: show that the spin- and colour-summed squared matrix element is given by
$\sum |\mathcal{M}|^2 = 8Ne^4Q^2 \left(\frac{(p_1.q_1)^2 + (p_1.q_2)^2}{(p_1.p_2)^2} \right)$, where $Q =$ quark charge.

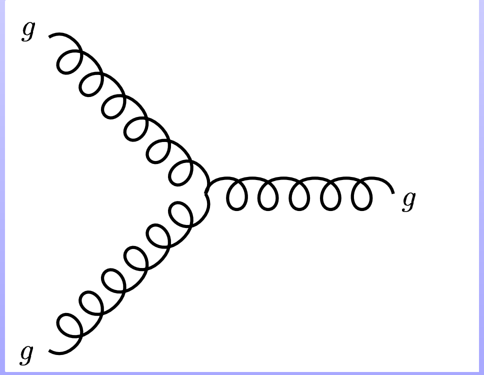
Adding QCD

- To calculate the effect of NLO QCD, we have to add contributions which are proportional to α_s. In other words, we need a total of two extra couplings of quarks to a gluon:

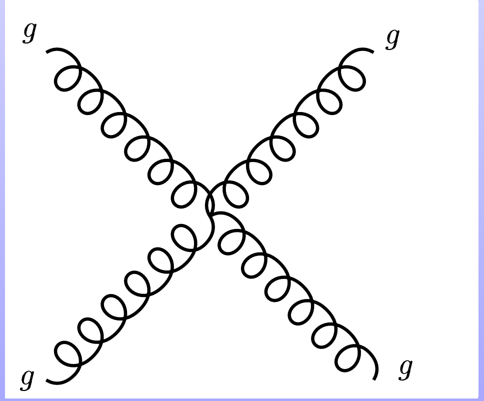


$\sim \quad g_s$

- In general, we can attach gluons in more complicated ways



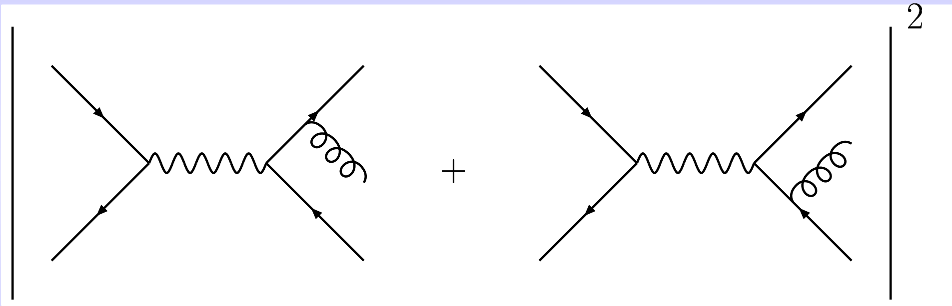
$\sim \quad g_s$



$\sim \quad g_s^2$

NLO diagrams: I

- One class of diagrams is immediate and corresponds to additional gluon radiation
- In our case, there are only two diagrams

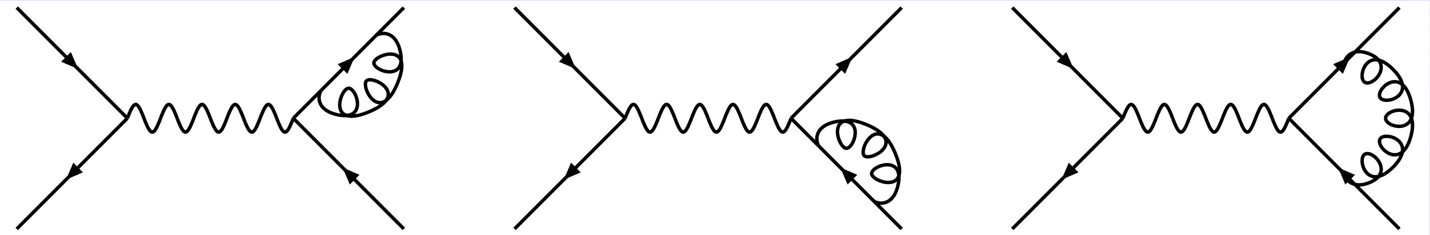


$$\sim \quad g_s \times g_s \quad \sim \quad \alpha_s$$

- These are referred to as the real radiation contribution and, on the surface, look like they should be easy to calculate since they are just the lowest order matrix elements for $e^+e^- \longrightarrow q\bar{q}g$
- There's another set of diagrams to consider though ...

NLO diagrams: II

- The other class of diagrams is referred to as the virtual corrections and involves emission of the gluon from a quark and reabsorption on the same, or a different, quark line
- For us, there are 3 diagrams: two self-energies ('bubbles') and one vertex correction ('triangle'):



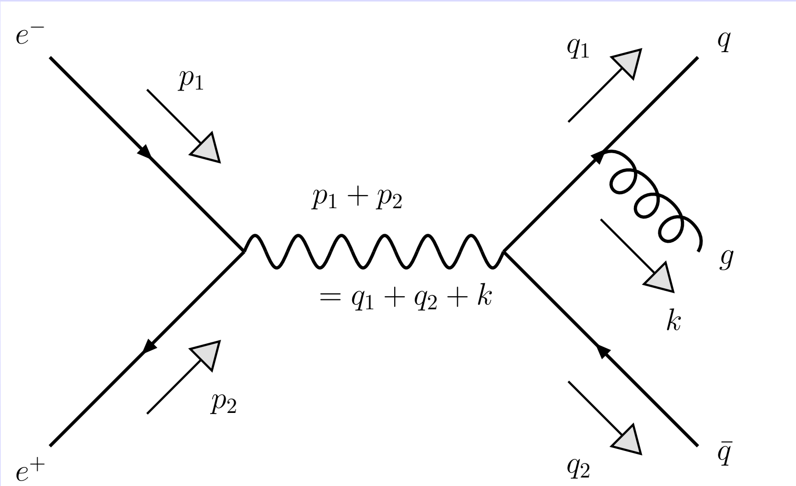
- These diagrams contribute as an interference with the lowest order diagram:

$$\mathcal{O}(1) \times \mathcal{O}(g_s^2) = \mathcal{O}(\alpha_s)$$

- One calculates the NLO cross-section by summing the real and virtual contributions

The 'easy' piece

- (In principle) we know how to calculate the real contribution
- Applying the Feynman rules and working through the algebra is fairly straightforward, but just from looking at the diagrams we can learn much immediately:



$$e^-(p_1) + e^+(p_2) \rightarrow q(q_1) + \bar{q}(q_2) + g(k)$$

- The intermediate quark propagator before the gluon emission contributes a factor of

$$\frac{1}{(q_1+k)^2} = \frac{1}{2q_1.k}, \qquad \text{since } q_1^2 = k^2 = 0.$$

A closer look ...

- Looking at the other diagram gives us another propagator to worry about: $\frac{1}{2q_2.k}$
- Since all our particles are massless, we can write their 4-vectors in the form:

$$q_1 = E_q(1, \vec{n}_q), \quad q_2 = E_{\bar{q}}(1, \vec{n}_{\bar{q}}), \quad k = E_g(1, \vec{n}_g)$$

  where n_i is a unit vector in the direction of particle i
- Our propagators are then given by

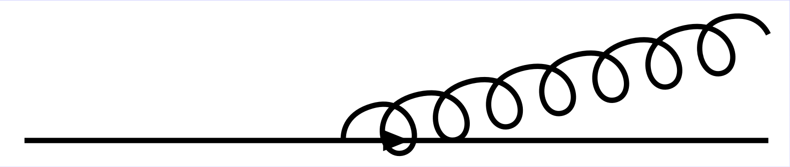
$$2q_1.k = 2E_qE_g(1 - \cos\theta_{qg}), \quad 2q_2.k = 2E_{\bar{q}}E_g(1 - \cos\theta_{\bar{q}g})$$

  where $\theta_{qg}(\theta_{\bar{q}g})$ is the angle between the gluon and the (anti-)quark.
- These propagators can clearly vanish in a number of cases

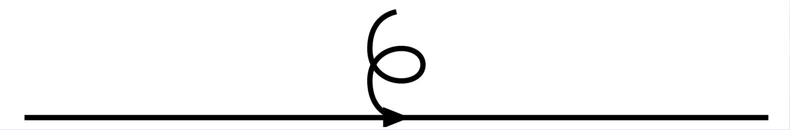
Vanishing propagators

$$2q_1.k = 2E_qE_g(1 - \cos\theta_{qg})$$

the gluon and a quark
are collinear, $\theta_{qg} \to 0$



the gluon is soft, $E_g \to 0$



- Note: we don't have to worry about a quark becoming soft. The kinematics make the available phase space vanish. It would require that the remaining anti-quark and gluon are back-to-back.
- Together, these two problems are called infrared singularities

Problems?

- These singularities are not physical and, in fact, we could have avoided them
- We treated all our particles as massless
  - ⋆ Adding a mass to the gluon, or putting the quarks slightly off-shell would turn these singularities into a logarithmic divergence
  - ⋆ Nothing wrong with this, perhaps even physically motivated
- However, introducing masses complicates the algebra and often makes the ensuing calculations intractable
  - ⋆ Most NLO calculations assume quark masses vanish whenever possible
- The most common trick for proceeding is to use dimensional regularization (DR):

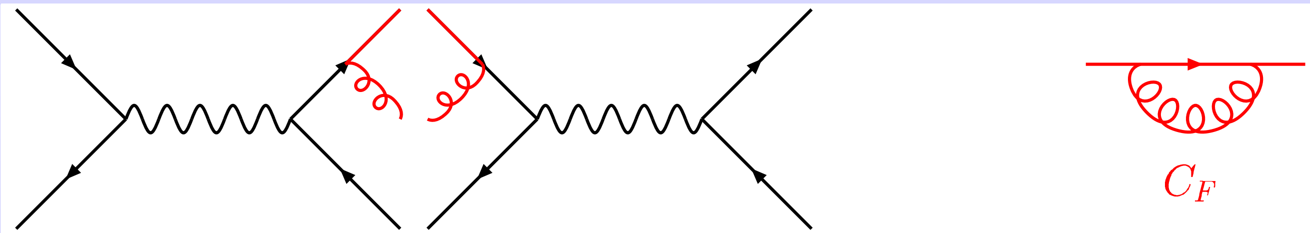
$$D = 4 \qquad \longrightarrow \qquad D = 4 - 2\epsilon$$

Extra dimensions

- All the singularities can now be controlled, manifesting themselves as factors of $\frac{1}{\epsilon}$
- Integrating our matrix elements poses no problems, with the result:

$$\sigma_{\rm real} \sim \frac{C_F \alpha_s}{2\pi} \left(\frac{2}{\epsilon^2} + \frac{3}{\epsilon} + \frac{19}{2} + \mathcal{O}(\epsilon) \right) \sigma_{\rm LO}$$

- We've used $(t^A t^A)_{ij} = C_F \delta_{ij}$ to obtain the colour factor C_F (= $4/3$)

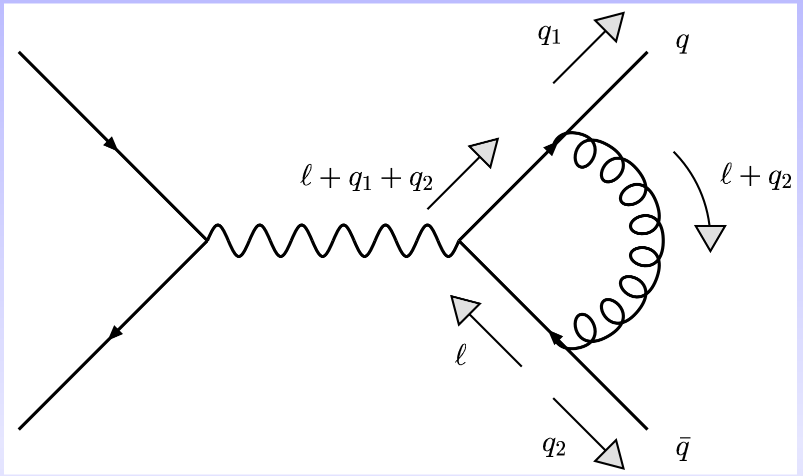


- This is a trick for now: in the end we want to take $\epsilon \to 0$ of course.
- Notice that, in particular, the ϵ poles are proportional to the lowest order result. This is a crucial observation - more on this later.

Virtual contribution

$$\frac{d^4\ell \quad \mathcal{N}}{\ell^2(\ell+q_2)^2(\ell+q_1+q_2)^2}$$

with $\mathcal{N} = \ldots(\hat{\ell} + \widehat{q_1} + \widehat{q_2})\gamma^\mu \hat{\ell} \ldots$



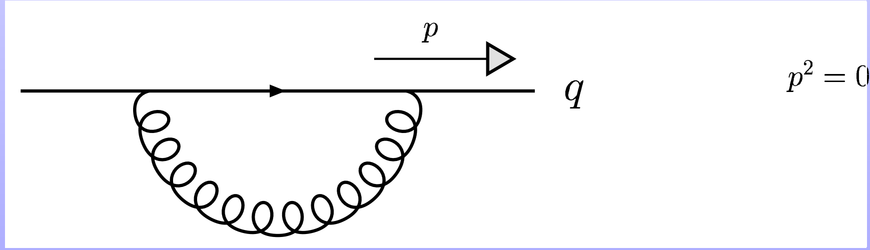
- This is not a back-of-the-envelope calculation, but again we don't have to go through all the details:
  - ⋆ We're integrating over all loop momenta: but what about the case $\ell = -q_2$? This is a soft singularity again.
  - ⋆ In fact, $\ell = xq_2$ for any value of x also makes two propagators vanish - another collinear singularity.
- Moreover, as $|\ell| \to \infty$, power counting makes some terms look logarithmically divergent, $\sim \int \frac{dy}{y}$ (ultraviolet divergence)

Virtual result

- Using dimensional regularization again takes care of these problems - exposing both IR and UV poles
- In our case, the result is:

$$\sigma_{\text{virt}} \sim \frac{C_F \alpha_s}{2\pi} \left(-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} - 8 + \mathcal{O}(\epsilon) \right) \sigma_{\text{LO}}$$

- Note that DR makes the contribution from our bubble diagrams vanish. For this reason, sometimes the diagrams for self-energy corrections on massless external quarks are not even written down



NLO total

- All we need to do now is add up the two contributions:

$$\begin{array}{r|l} \sigma_{\text{real}} & \frac{C_F \alpha_s}{2\pi} \left(+ \frac{2}{\epsilon^2} + \frac{3}{\epsilon} + \frac{19}{2} \right) \sigma_{\text{LO}} \\ +\sigma_{\text{virt}} & \frac{C_F \alpha_s}{2\pi} \left(- \frac{2}{\epsilon^2} - \frac{3}{\epsilon} - 8 \right) \sigma_{\text{LO}} \\ =\sigma_{\text{NLO correction}} & \frac{C_F \alpha_s}{2\pi} \frac{3}{2} \sigma_{\text{LO}} \end{array}$$

- Plugging in the numbers gives the well-known result

$$\sigma_{\text{NLO}} = \left(1 + \frac{\alpha_s}{\pi} \right) \sigma_{\text{LO}}$$

- This correction $\sim 3\%$ agrees well with very precise data from LEP

NLO Monte Carlo's

- We've just been through a NLO calculation in a few slides. Can't we make every NLO prediction in this way?
  - ⋆ Unfortunately, the complexity of the matrix elements and the phase space for increasing particle multiplicity means that the integrals can only be performed in certain very simple cases
  - ⋆ For the result that I just showed, there were no constraints on any of the particles. This isn't realistic - when experimental cuts are enforced, the integrals become even harder
  - ⋆ Moreover, every new type of cut implies a new calculation
- For these reasons, flexible tools have been developed that perform the NLO calculation numerically and in a general manner, so that any desired experimental cuts can be applied
- A NLO Monte Carlo is so-called because of the integration technique that is used to evaluate the phase space integral over the appropriate matrix elements

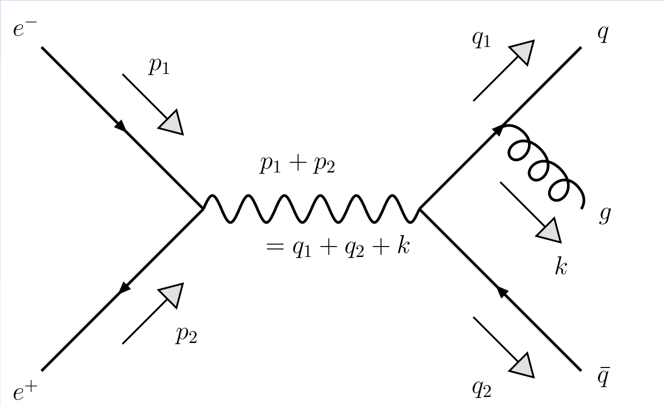
Building a NLO Monte Carlo

- Even though the procedure isn't quite as simple as for our toy example, the basic anatomy of the calculation is the same
  - ⋆ One has to calculate the virtual and real contributions and add them together
  - ⋆ Each contribution is separately divergent
- The divergence in the real contribution comes from the integration over the phase space of the additional particle
  (in particular, the soft and collinear regions)
- This doesn't bode well for a numerical procedure
- The solution is to render the integrations finite in some way. This is made possible by the factorization properties of QCD matrix elements in soft and collinear limits

Factorization

- Examine the matrix element for $e^+e^- \to q\bar{q}g$ again:

$$\sum |\mathcal{M}|^2 = 8NC_F e^4 Q^2 g^2 \times \frac{(p_1.q_1)^2 + (p_1.q_2)^2 + (p_2.q_1)^2 + (p_2.q_2)^2}{p_1.p_2 \; q_1.k \; q_2.k}$$



- What happens in the soft limit, $k \to 0$?
  - ⋆ Ignoring terms of $\mathcal{O}(k)$, $p_2.q_1 \to p_1.q_2$ and $p_2.q_2 \to p_1.q_1$
  - ⋆ Then we can write,

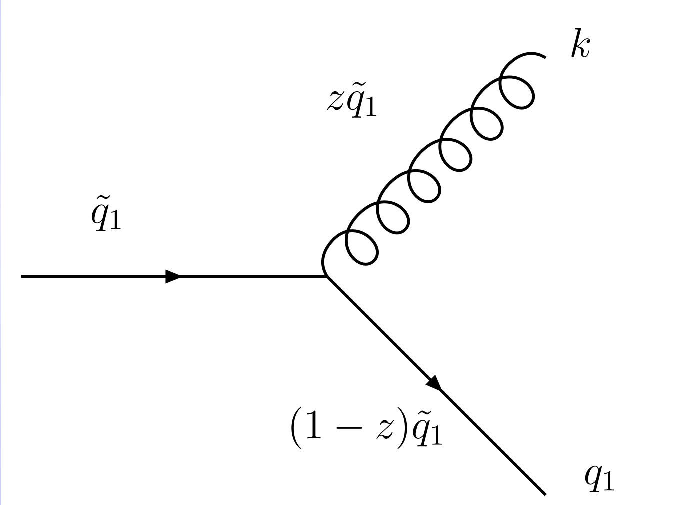
$$\sum |\mathcal{M}|^2 \to C_F g^2 \frac{2}{p_1.p_2 \; q_1.k \; q_2.k} 8Ne^4Q^2 \left((p_1.q_1)^2 + (p_1.q_2)^2 \right)$$

- Equivalently,

$$\sum |\mathcal{M}|^2 \to C_F g^2 \frac{2p_1.p_2}{q_1.k \; q_2.k} |\mathcal{M}_{\rm LO}|^2$$

More factorization

- We've seen that a cross-section factorizes when a gluon becomes soft
- What about the case when two partons are collinear?



$$k = z\tilde{q}_1 \quad , \quad q_1 = (1-z)\tilde{q}_1$$

so that the gluon and quark are collinear

- In this limit, we find that a similar (but more complicated) factorization occurs:

$$|\mathcal{M}_{q\bar{q}g}|^2 \longrightarrow 2g^2 C_F \, \frac{1}{2q_1.k} P_{qq}(z) \times |\mathcal{M}_{q\bar{q}}|^2$$

Splitting functions

- P_{qq} is the Altarelli-Parisi splitting function which describes the emission of a gluon of momentum fraction z from a quark
- There are other functions that represent the processes of gluon splitting into gluon pairs (P_{gg}) and quark-antiquark pairs (P_{gq}), e.g.

$$P_{gg} = \frac{z^2 + (1-z)^2}{z(1-z)}$$

Note the singularities both as $z \to 0$ and $z \to 1$, corresponding to each gluon becoming soft.

> Simple exercise: Using the matrix elements and the collinear momemtum substitution given on the previous slides, derive the splitting function P_{qq}

- These functions are universal – they are sufficient to describe the soft and collinear behaviour of all QCD matrix elements

First steps towards a Monte Carlo

- Since we now know the behaviour of our matrix elements in the singular regions, it's easy to envisage a generic method for generating a finite real contribution:
  - ⋆ Calculate the real diagrams
  - ⋆ Identify all the soft and collinear divergences
  - ⋆ Construct terms that contain the same divergences and subtract them:

$$\int dPS_{\mathrm{LO}+1}\left[|\mathcal{M}_{\mathrm{real}}|^2 - \left(\sum \mathrm{counter}-\mathrm{terms}\right)\times|\mathcal{M}_{\mathrm{LO}}|^2\right]$$

    where the integral is over the phase space corresponding to the lowest order process, plus one extra parton

- The integral should now be perfectly well-defined and suitable for numerical integration

Virtual terms

- We've dealt with the real diagrams, but what happens to the divergences in the virtual contribution?

$$2\mathcal{M}_{\rm virt}\,\mathcal{M}_{\rm LO}^\dagger \sim \left(-\frac{2}{\epsilon^2}-\frac{3}{\epsilon}+A\right)|\mathcal{M}_{\rm LO}|^2+F$$

- Clearly we must add back on the counter-terms that we just subtracted from the real contribution:

$$\int dPS_{\rm LO+1}\left(\sum {\rm counter-terms}\right)\times|\mathcal{M}_{\rm LO}|^2$$

- By choosing a good parametrization, it is possible to factor the phase-space into the lowest order phase space multiplied by a region that represents the emission of an additional gluon:

$$dPS_{\rm LO+1} \quad\longrightarrow\quad dPS_{\rm LO}\times dPS_{\rm gluon}$$

Virtual result

- With this factorization, we can now integrate the counter-terms over this reduced phase-space:

$$\int dPS_{\mathrm{gluon}}\,(\mathrm{counter}-\mathrm{terms}) \;\sim\; \left(+\frac{2}{\epsilon^2}+\frac{3}{\epsilon}+B\right)$$

- The poles clearly cancel as before and we are left with a simple finite integral over the lowest-order phase-space:

$$\int dPS_{\mathrm{LO}}\Big((A+B)|\mathcal{M}_{\mathrm{LO}}|^2+F\Big)$$

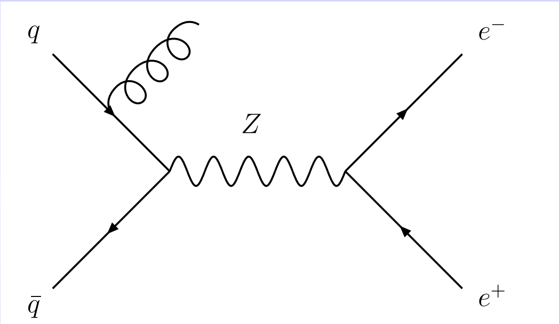
- What is remarkable is that the subtraction terms can be chosen such that they are both completely general (QCD factorization) and integrable (smart choices)

NLO techniques

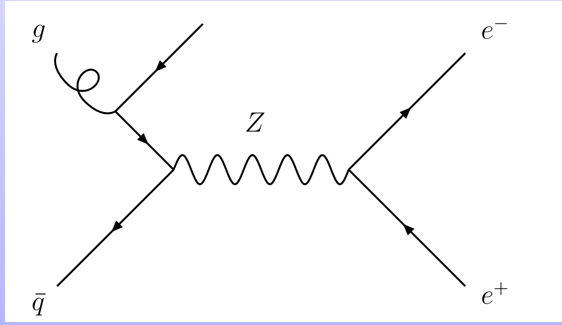
- This isn't the only way to do a NLO calculation - it's an outline of one technique, called the subtraction method
- A popular modern variant of this is called dipole subtraction.
  - ⋆ It corresponds to a clever choice of the subtraction terms so that this method can be applied to any QCD process, with a basic set of integrals that can be recycled
  - ⋆ The subtraction terms are chosen with different kinematics in each singular region in order to optimize cancellation
- The other popular method is referred to as phase-space slicing.
  - ⋆ Rather than subtracting counter-terms, it approximates the matrix elements in the soft and collinear region. An arbitrary small parameter δ is introduced that specifies the extent of the singular regions
  - ⋆ δ-dependence vanishes (numerically) in the final result
- We will see examples of both of these techniques shortly

What's left to know?

- So far we've only examined NLO corrections at an e^+e^- collider
- At a hadron collider, the situation becomes more complicated. For instance, consider the crossing-related process, Drell-Yan



initial state radiation $\sim -\frac{1}{\epsilon} P_{qq}$ absorbed into redefinition of the PDF's at NLO



additional processes enter – this cross-section now becomes sensitive to the gluon PDF

- However, much of the machinery carries through as before

What do we gain from NLO?

We expect to see many benefits when performing a NLO calculation (examples coming soon):

- Less sensitivity to unphysical input scales
  - ⋆ first predictive normalization of observables at NLO
  - ⋆ more accurate estimates of backgrounds for new physics searches and (hopefully) interpretation
  - ⋆ confidence that cross-sections are under control for precision measurements
- More physics
  - ⋆ jet merging
  - ⋆ initial state radiation
  - ⋆ more parton fluxes
- It represents the first step for a plethora of other techniques
  - ⋆ matching with resummed calculations, NLO parton showers

NLO status

Given all the advantages of performing a NLO calculation, are the theoretical advances keeping up with the pace of progress in Run II at the Tevatron and construction at the LHC?

- What's the current state-of-the-art?
- Why are we lacking NLO predictions for many interesting processes that could be crucial to new physics discoveries in the near future?
  - ⋆ traditional methods
  - ⋆ where the difficulties lie
- What's being done about it?
  - ⋆ promising new approaches
- Survey of available NLO tools for hadron colliders

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

Theoretical status

Single boson	Diboson	Triboson	Heavy flavour
$W+\leq 2j$	$WW+\leq 0j$	$WWW+\leq 3j$	$t\bar{t}+\leq 0j$
$W+b\bar{b}+\leq 0j$	$WW+b\bar{b}+\leq 3j$	$WWW+b\bar{b}+\leq 3j$	$t\bar{t}+\gamma+\leq 2j$
$W+c\bar{c}+\leq 0j$	$WW+c\bar{c}+\leq 3j$	$WWW+\gamma\gamma+\leq 3j$	$t\bar{t}+W+\leq 2j$
$Z+\leq 2j$	$ZZ+\leq 0j$	$Z\gamma\gamma+\leq 3j$	$t\bar{t}+Z+\leq 2j$
$Z+b\bar{b}+\leq 0j$	$ZZ+b\bar{b}+\leq 3j$	$WZZ+\leq 3j$	$t\bar{t}+H+\leq 0j$
$Z+c\bar{c}+\leq 0j$	$ZZ+c\bar{c}+\leq 3j$	$ZZZ+\leq 3j$	$t\bar{b}+\leq 0j$
$\gamma+\leq 1j$	$\gamma\gamma+\leq 1j$		$b\bar{b}+\leq 0j$
$\gamma+b\bar{b}+\leq 3j$	$\gamma\gamma+b\bar{b}+\leq 3j$		
$\gamma+c\bar{c}+\leq 3j$	$\gamma\gamma+c\bar{c}+\leq 3j$		
	$WZ+\leq 0j$		
	$WZ+b\bar{b}+\leq 3j$		
	$WZ+c\bar{c}+\leq 3j$		
	$W\gamma+\leq 0j$		
	$Z\gamma+\leq 0j$		

Slow progress

- Why has progress been so slow?

  $e^+e^- \longrightarrow 3$ jets c. 1980

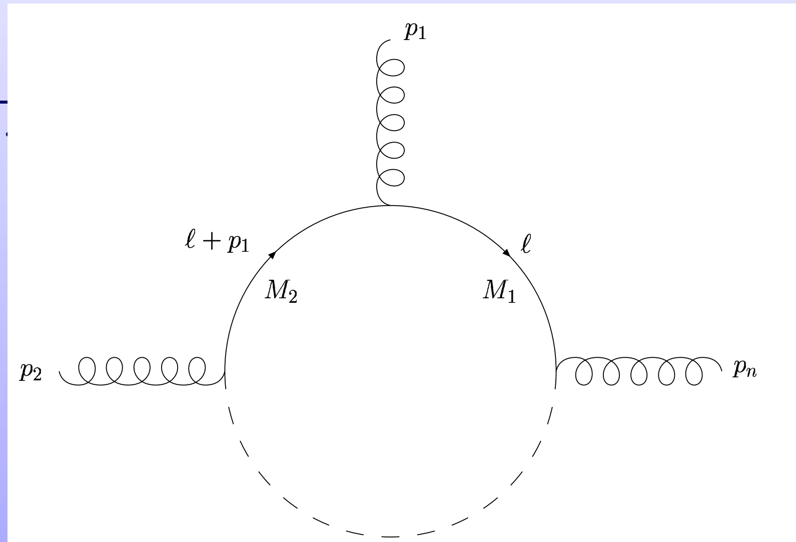
  R. K. Ellis et al., 1981

  $e^+e^- \longrightarrow 4$ jets c. 2000

  Bern et al., Glover et al., 1996-7

- More particles → many scales → lengthy analytic expressions
- Integrals are complicated and process-specific:

$$\int d^{4-2\epsilon}\ell \, \frac{1}{(\ell^2 - M_1^2)((\ell+p_1)^2 - M_2^2)\ldots}$$



- different for:

$p_i^2 \neq 0$ W, Z, H

$M_i^2 \neq 0$ $t, b, \ldots$

Complications

- Fermions and non-Abelian couplings lead to more complicated tensor integrals:

$$\int d^{4-2\epsilon}\ell \, \frac{\ell^\mu}{(\ell^2 - M_1^2)((\ell + p_1)^2 - M_2^2)\ldots}$$

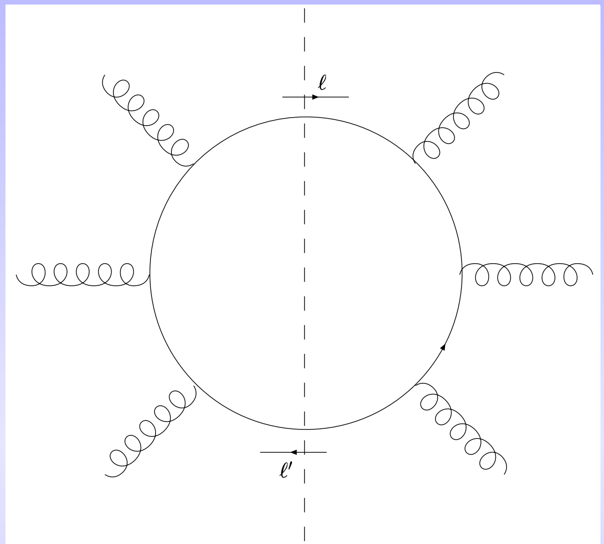
- Passarino-Veltman reduction in terms of scalar integrals:

$$\longrightarrow c_1 p_1^\mu + \ldots c_{n-1} p_{n-1}^\mu$$

  where the c_i are given by the solutions of $(n-1)$ equations

- This gives rise to the $(n-1) \times (n-1)$ Gram determinant, $\Delta = \det(2p_i \cdot p_j)$.
  - ⋆ large intermediate expressions
  - ⋆ spurious singularities

Unitarity technique



$\mathcal{M}_{tree}$ $\mathcal{M}'_{tree}$

$$= \int dPS(\ell, \ell')\, \mathcal{M}_{tree} \times \mathcal{M}'_{tree}$$

- Standard tree-level tricks can be used to simplify amplitudes, yielding compact results

  e.g. Dixon, hep-ph/9601359

- Rational functions of invariants cannot be obtained easily with this method
- Not easy to generalize and automate, simplification by hand

Numerical approach

- If all IR and UV singularities can be subtracted, perhaps loop integrals can be done numerically
- This method has many advantages:
  - ⋆ a general solution for many processes, regardless of internal and external masses
  - ⋆ extension to large final-state multiplicites limited only by CPU power
  - ⋆ presence of masses in general should simplify the procedure (less singularities) rather than requiring much more work (cf. analytical approach)
- Several algorithms laid out, but no practical implementation so far

  Nagy and Soper, hep-ph/0308127

  Giele and Glover, hep-ph/0402152
- Exciting prospect for the future, but probably not until the LHC

NLOJET++

Author(s): Z. Nagy

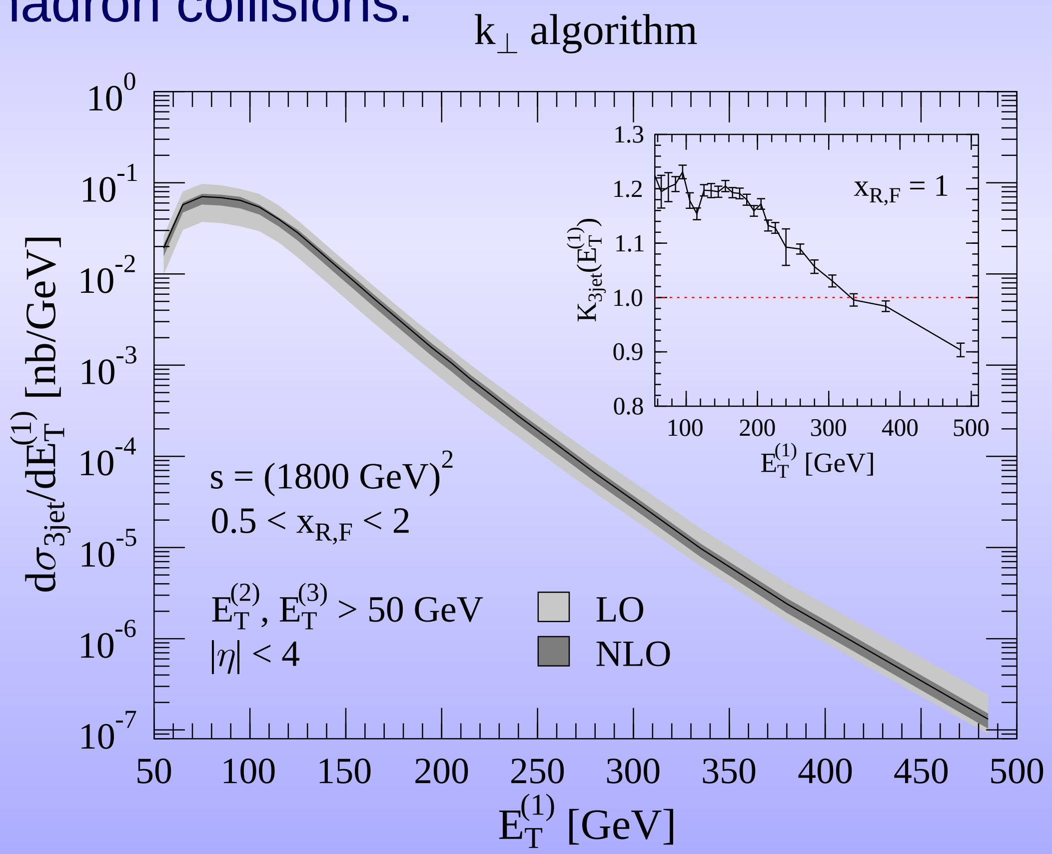
http://www.ippp.dur.ac.uk/~nagyz/nlo++.html

Multi-purpose C++ library for calculating jet cross-sections in e^+e^- annihilation, DIS and hadron-hadron collisions.

$e^+e^- \longrightarrow\ \leq 4$ jets

$ep \longrightarrow (\leq 3+1)$ jets

$p\bar{p} \longrightarrow\ \leq 3$ jets



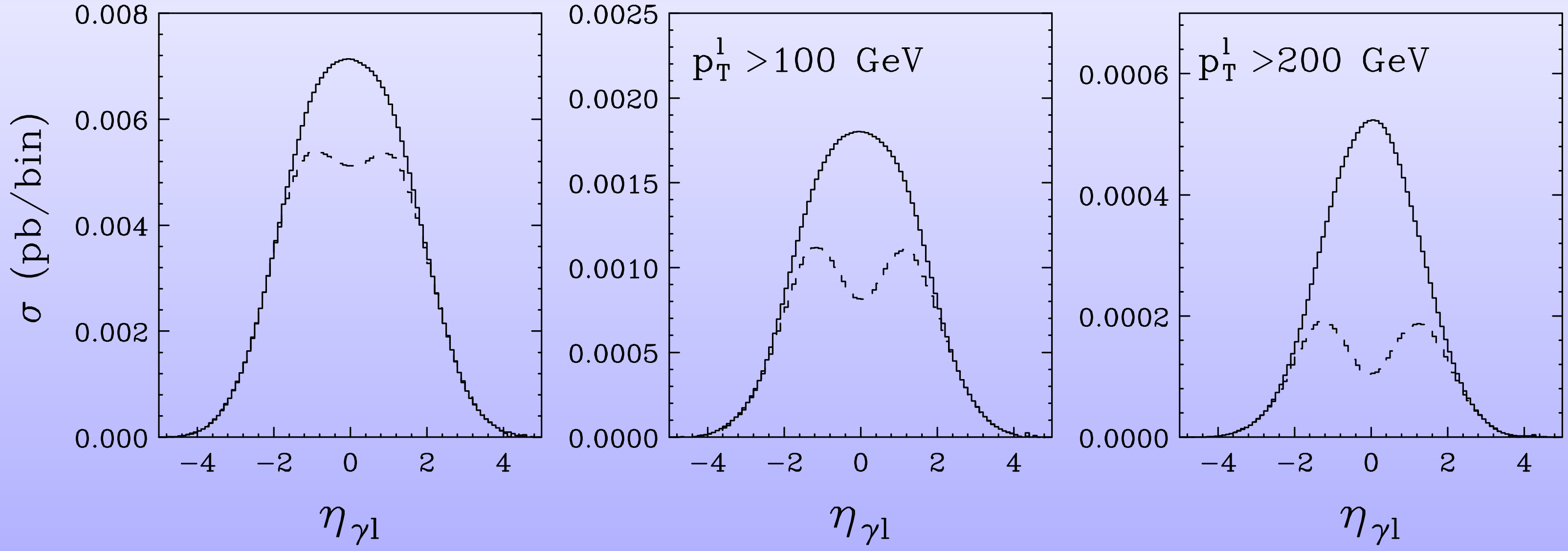
hep-ph/0110315

AYLEN/EMILIA

Author(s): L. Dixon, Z. Kunszt, A.Signer, D. de Florian
`http://www.itp.phys.ethz.ch/staff/dflorian/codes.html`
Fortran implementation of gauge boson pair production at hadron colliders, including full spin and decay angle correlations.

$p\bar{p} \longrightarrow VV'$ and $p\bar{p} \longrightarrow V\gamma$ with $V, V' = W, Z$

Anomalous triple gauge boson couplings at the LHC:



hep-ph/0002138

$\longrightarrow$ F. Olness

DIPHOX/EPHOX

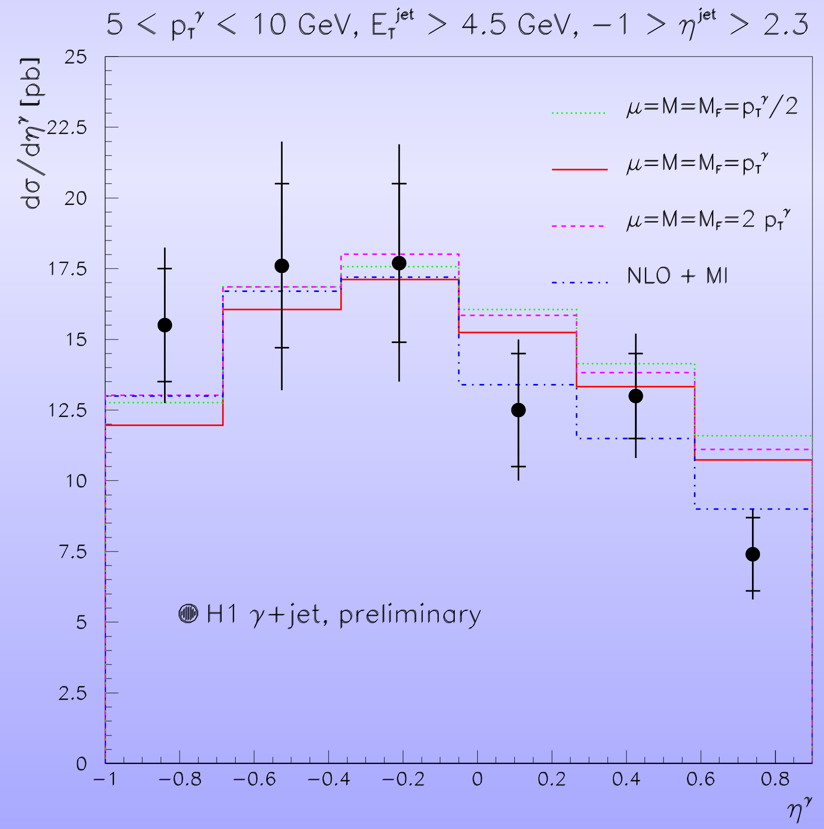
Author(s): P. Aurenche, T.Binoth, M. Fontannaz, J. Ph. Guillet,
G. Heinrich, E. Pilon, M. Werlen
`http://wwwlapp.in2p3.fr/lapth/PHOX_FAMILY/main.html`
Fortran code to compute processes involving photons, hadrons and jets in DIS and hadron colliders.

$p\bar{p} \longrightarrow \gamma + \leq 1$ jet

$p\bar{p} \longrightarrow \gamma\gamma$

$\gamma p \longrightarrow \gamma +$ jet

Preliminary H1 data,
hep-ph/0312070.



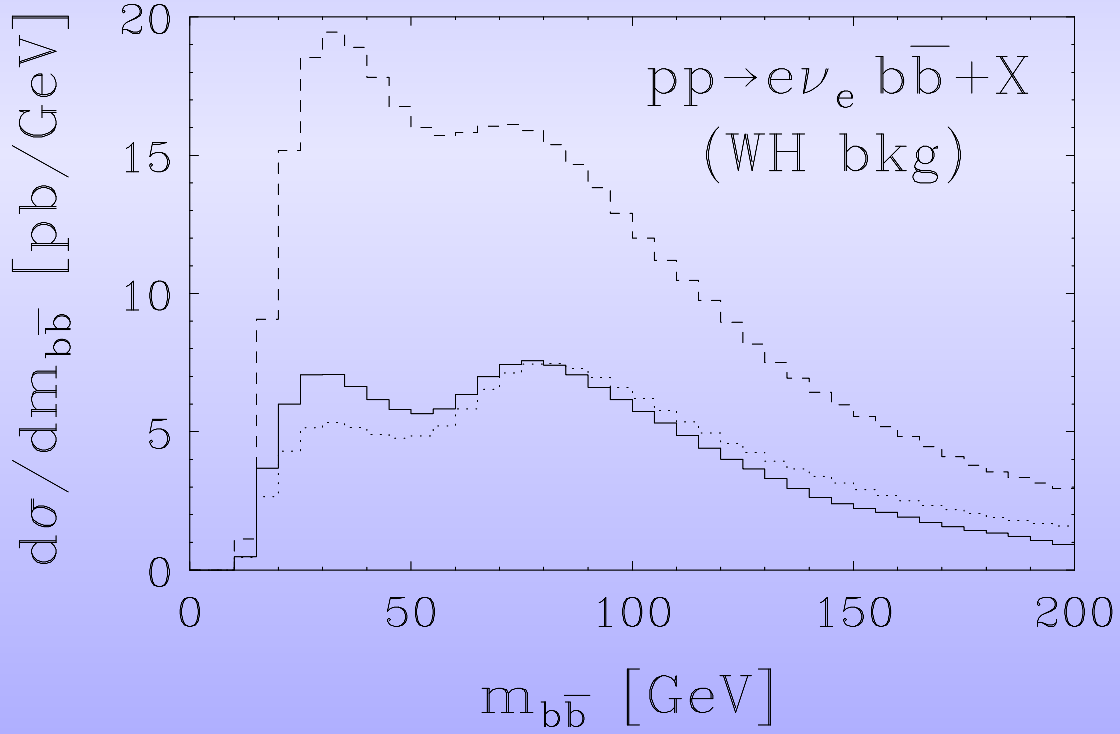
MCFM

Author(s): JC, R. K. Ellis
`http://mcfm.fnal.gov`
Fortran package for calculating a number of processes involving vector bosons, Higgs, jets and heavy quarks at hadron colliders.

$p\bar{p} \longrightarrow V+ \leq 2$ jets

$p\bar{p} \longrightarrow V + b\bar{b}$

with $V = W, Z$.

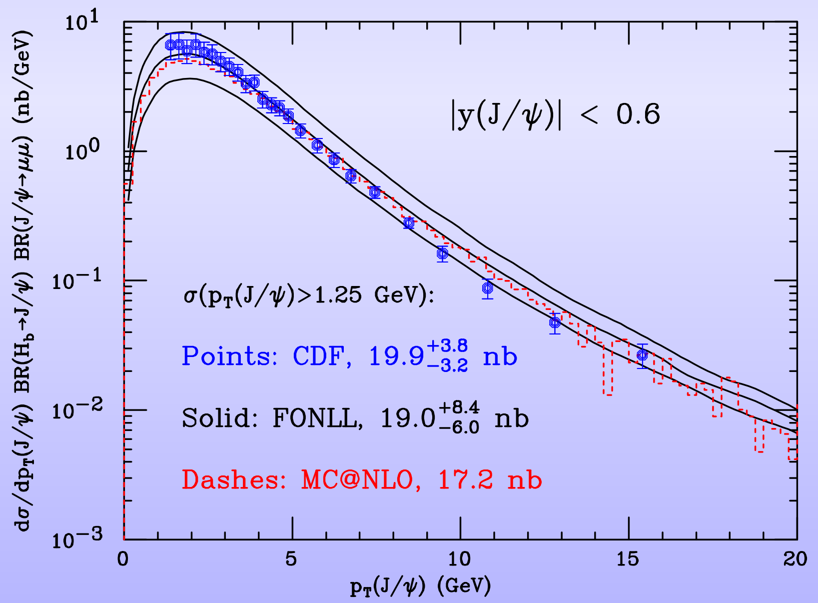


hep-ph/0308195

Heavy quark production

Author(s): M. L. Mangano, P. Nason and G. Ridolfi
http://www.ge.infn.it/˜ridolfi/hvqlibx.tgz
Fortran code for the calculation of heavy quark cross-sections and distributions in a fully differential manner

- Based on the more inclusive calculations of Dawson et al, Beenakker et al.
- Does not include multiple gluon radiation, $\log(p_T/m_b)$ (FONLL)
  Cacciari et al., hep-ph/9803400
- These are the same matrix elements that are incorporated into MC@NLO
  Frixione et al., hep-ph/0305252



hep-ph/0312132

$\longrightarrow$ R. K. Ellis

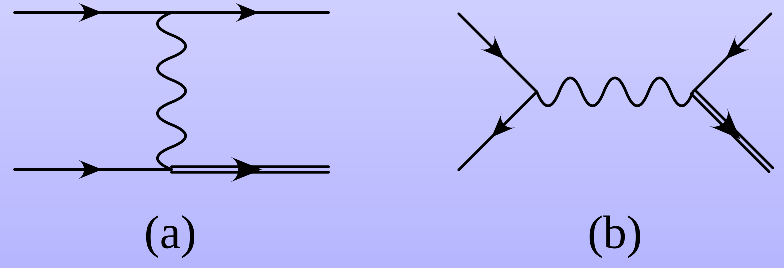
Single top production

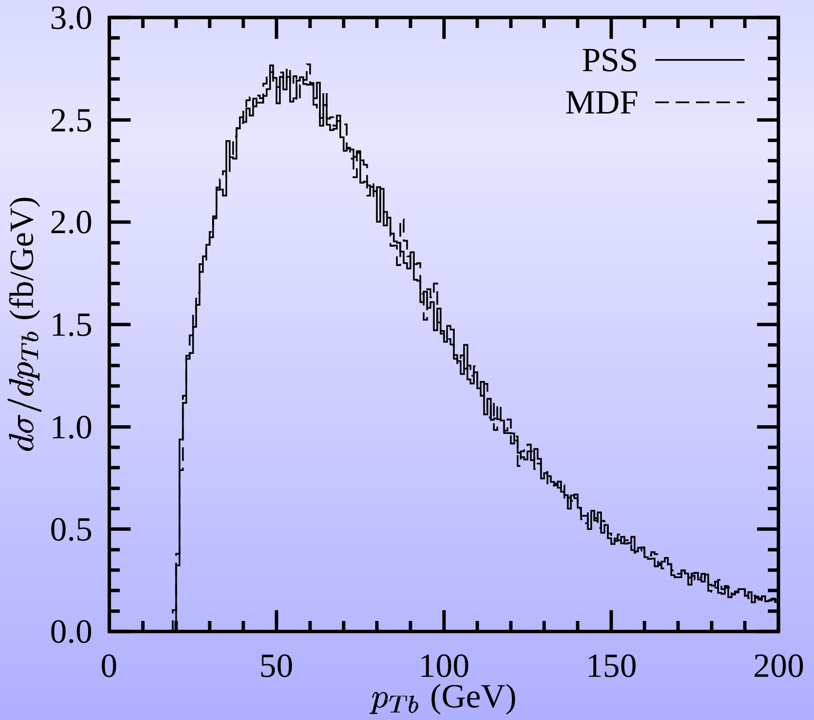
Author(s): B. W. Harris, E. Laenen, L. Phaf, Z. Sullivan, S. Weinzierl
(No public code released)

Fully differential calculation of single top production in hadron-hadron collisions, via both channels:

(a) $u + b \longrightarrow t + d$

(b) $u + \bar{d} \longrightarrow t + \bar{b}$





hep-ph/0207055

$\longrightarrow$ T. Tait

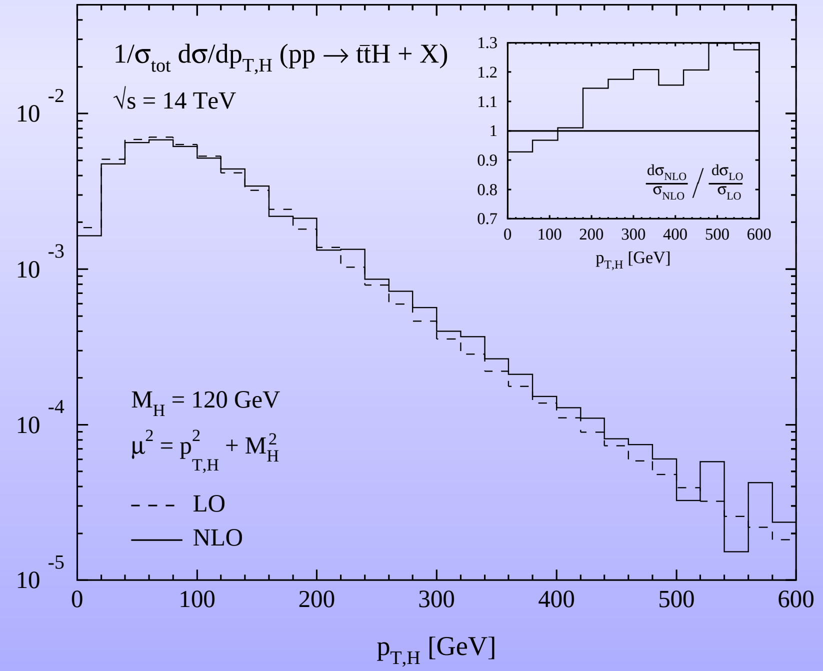
Higgs + $Q\bar{Q}$

Author(s): S. Dawson, C. B. Jackson, L. H. Orr, L. Reina, D. Wackeroth; W. Beenakker, S. Dittmaier, M. Kramer, B.Plumper, M. Spira, P. Zerwas

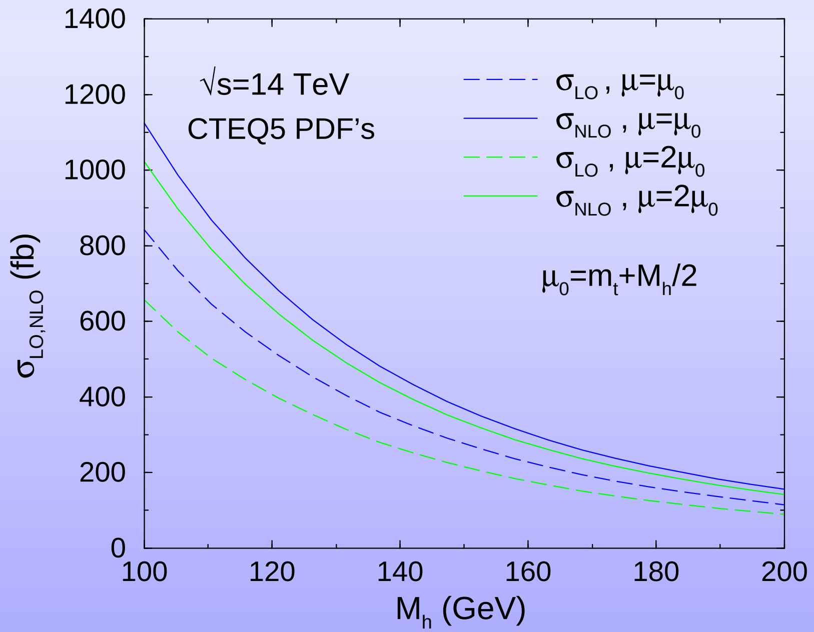
(No public code released)

Associated production of a Higgs and a pair of heavy quarks,

$$p\bar{p} \longrightarrow Q\bar{Q}H, \quad \text{with } Q = t, b.$$



hep-ph/0211352



hep-ph/0311216

⟶ B. Kilgore

HEPCODE database

- A new initiative to maintain a list of available Monte Carlo codes, including lowest order, NLO and resummed predictions
- Eventual aim is to produce a searchable database

`http://www.ippp.dur.ac.uk/~wjs/HEPCODE/`

HEPCODE PROGRAMME LISTING

The idea of making a comprehensive database of programmes for cross section calculations and event simulations arose out of a discussion at the Collider Physics Conference at the KITP, Santa Barbara in January 2004. The database will eventually be integrated into the HEPDATA databases in Durham, and will incorporate a "search" facility that will enable users to identify a set of available programmes simply by entering the details of a particular scattering process. In the meantime, we need to build up a comprehensive list of all available codes. The emphasis so far is on hadron-collider processes, but it is hoped to eventually include also a comprehensive list for other colliders.

Comments on the list below (for example, if your programme is listed but the information is incomplete/incorrect) and particularly suggestions for new entries are very welcome and should be sent to James Stirling (IPPP, Durham) at w.j.stirling@durham.ac.uk, using the automated submission tool.

(Thanks to: John Campbell, Guenther Dissertori, Thomas Gehrmann, Bill Kilgore, Adrian Signer)

Key

- ee, ep, pp are used as shorthand for electron-positron, lepton-hadron, and proton - (anti)proton collisions respectively
- V = W or Z, and sometimes also a Drell-Yan virtual photon, g = real photon, l = lepton, H = Higgs boson
- j = light (u,d,s,c?) quark or gluon jet; Q = generic heavy (c?,b,t) quark
- TL = tree level; PS = parton shower; NLO = NLO QCD, NNLO = NNLO QCD; NLOEW = NLO electroweak, RS=resummed
- F = Fortran, C = C++

Name/ description	processes	order	code?		authors	comments
VECBOS	pp V + <=4j	TL	yes	F	W. Giele	
ALPGEN	pp V + QQbar + <=4j V + <=6j V + c + <=5j nV + mH + <=3j QQbar + <=6j QQbar + Q'Q'bar + <=4j QQbar + H + <=4j <=6j ng + mj, n+m<=8, m<=6	TL	yes	F	M. Mangano M. Moretti F. Piccinini R. Pittau A. Polosa	a collection of codes for the generation of multi-parton processes in hadronic collisions based on the Alpha matrix element generator
MADEVENT		TL	yes	F	T. Stelzer F. Maltoni	combines MADGRAPH matrix element calculations with phase space integration
HELAC		TL	yes	F	C. Papadopoulos	
AMEGIC++		TL	yes	C	F. Krauss	
GRACE		TL	yes	F		
GR@PPA	pp bbbar + bbbar V + <=3j VV' ttbar W + <=2g	TL	yes	F	S. Tsuno S. Shimma J. Fujimoto T. Ishikawa Y. Kurihara S. Odaka	an extension of the GRACE system to hadron collider processes; includes full decays of vector bosons and top quarks; can be embedded in PYTHIA and HERWIG
COMPHEP		TL	yes	F	A. Pukhov E. Boos M. Dubinin V. Edneral V. Ilyin D. Kovalenko A. Kryukov V. Savrin S. Shichanin A. Semenov	
AcerMC	pp ...	TL	yes	F	B. Kersevan E. Richter-Was	generates a variety of Standard Model background

Where now for NLO?

- As we've seen, NLO calculations are very useful for improving our understanding in many cases
- Unfortunately, they also have a number of drawbacks
  - ⋆ Existing calculations are spread out over many different codes
  - ⋆ Predictions are limited to fairly low particle-multiplicity ($2 \to 3$) processes
  - ⋆ The programs are parton-level only, so there's no hadronization and no simulation of detector effects
  - ⋆ Morever, the 'events' have both positive and negative weights
- All of these drawbacks aren't a problem for a parton shower Monte Carlo such as PYTHIA or HERWIG
- There's recently been much work to try to merge these two approaches. The most successful program to date is MC@NLO

  S. Frixione and B. R. Webber, hep-ph/0402116
- Expect more progress in this direction in the future

Thoughts to leave with ...

- NLO tools are an invaluable aid to experimental studies now and will continue to be so in the future
- It's important to have at least a basic grasp of the underlying theory, if only to appreciate the feasibility of a desired calculation
  - ⋆ Even though PYTHIA and HERWIG have been the simulation tools of choice in the past, it's likely that the next generation of programs will be based on a NLO core
- There are many programs available for making NLO predictions at the Tevatron and the LHC, in a variety of forms:
  - ⋆ author-controlled
    single top, $H + Q\bar{Q}$
  - ⋆ single class of processes
    $V\gamma$, $Q\bar{Q}$
  - ⋆ generic programs
    NLOJET++, PHOX-family, MCFM