Recent developments and results in theoretical perturbative QCD

R. Pittau (U. of Granada)
WSA, June 29^{th}, 2010

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3. Tools

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2. Techniques (mainly NLO)
3. Tools
4. Recent Results

Why (N)NLO QCD calculations?

- (N)NLO QCD calculations at Hadron Colliders are needed for:

  1. computing Backgrounds for New Physics Searches
  2. Measurements of fundamental quantities:

$$\begin{matrix} \alpha_s & m_t & \\ M_W & M_H & \cdots \end{matrix}$$

- Heavy New Physics states undergo long chain decays
- SM Processes accompanied by multi-jet activity

$$\Longrightarrow$$

1. multileg (N)NLO calculations and MCs needed

From Dixon's talk at HO-2010

How best to control SM backgrounds?

Increasing availability ↑

1. Get the **best theoretical prediction** you can, whether
   - Basic Monte Carlo [PYTHIA, HERWIG, Sherpa, …]
   - LO QCD parton level
   - LO QCD matched to parton showers [MadGraph/MadEvent, ALPGEN/PYTHIA, Sherpa, …]
   - NLO QCD at parton level
   - NLO matched to parton showers [MC@NLO, POWHEG,…]
   - NNLO inclusive at parton level
   - NNLO with flexible cuts at parton level

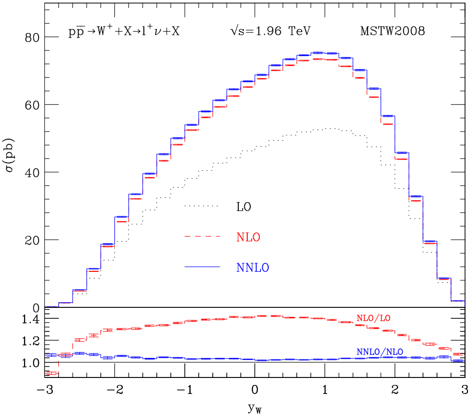
Increasing accuracy ↓

2. Take **ratios** whenever possible
   - QCD effects cancel when event kinematics are similar
   - Closely related to "data driven" strategies

L. Dixon Precision QCD for the LHC CERN HO10 23 June 2010 10

W NNLO rapidity distribution at TEVATRON

Catani, Ferrera, Grazzini

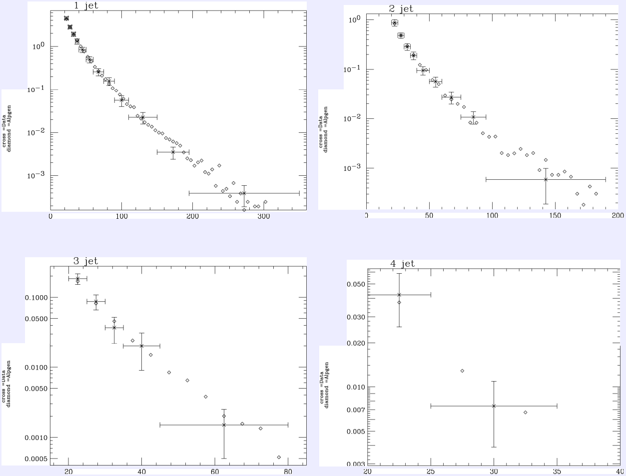


- Now the normalization is trustable

Tuning LO Monte Carlos with NLO calculations

Moretti, Piccinini, R. P., Treccani using MLM matching

ALPGEN vs Tevatron $W + j$ data



The Les Houches NLO Wishlist (LHC but also Tevatron)

Priority list of processes experimentalist wish to know at NLO

Z. Bern *et. al.*, arXiv:0803.0494

NLO Wishlist 2007

- $pp \to W + j$
- $pp \to H + 2j$
- $pp \to VVV$
- $pp \to t\bar{t} + 2j$
- $pp \to VVb\bar{b}$
- $pp \to VV + 2j$
- $pp \to V + 3j$
- $pp \to t\bar{t}b\bar{b}$
- $pp \to b\bar{b}b\bar{b}$

2009 update

- $pp \to t\bar{t}t\bar{t}$
- $pp \to Z + 3j$
- $pp \to 4j$
- $pp \to Wb\bar{b}j$
- $pp \to W + 4j$

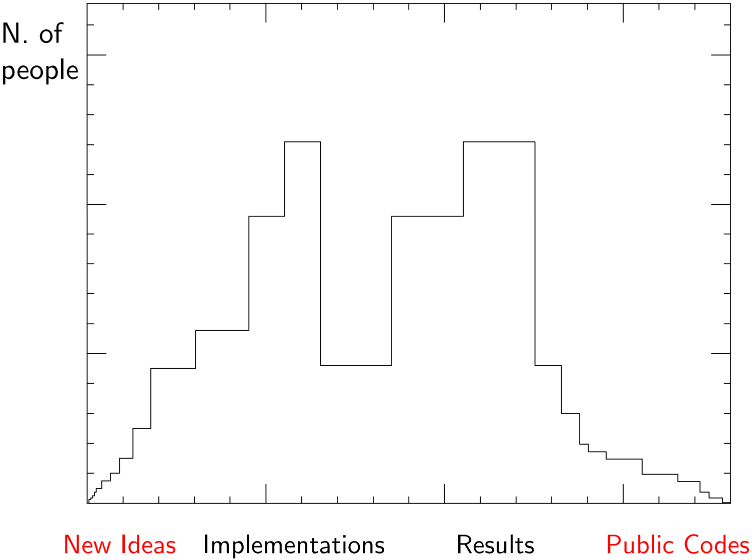
- See the *Les Houches 2009 Proceedings*

  J. R. Andersen *et. al.*, arXiv:1003.1241 [hep-ph]

The SM and NLO multileg working group

J.R. Andersen, J. Archibald, S. Badger, R.D. Ball, G. Bevilacqua, I. Bierenbaum, T. Binoth, F. Boudjema, R. Boughezal, A. Bredenstein, R. Britto, M. Campanelli, J. Campbell, L. Carminati, G. Chachamis, V. Ciulli, G. Cullen, M. Czakon, L. Del Debbio, A. Denner, G. Dissertori, S. Dittmaier, S. Forte, R. Frederix, S. Frixione, E. Gardi, M.V. Garzelli, S. Gascon-Shotkin, T. Gehrmann, A.Gehrmann-De Ridder, W. Giele, T. Gleisberg, E.W.N. Glover, N. Greiner, A. Guffanti, J.-Ph. Guillet, A. van Hameren, G. Heinrich, S. Hoeche, M. Huber, J. Huston, M. Jaquier, S. Kallweit, S. Karg, N. Kauer, F. Krauss, J.I. Latorre, A. Lazopoulos, P. Lenzi, G. Luisoni, R. Mackeprang, L. Magnea, D. Maitre, D. Majumder, I. Malamos, F. Maltoni, K. Mazumdar, P. Nadolsky, P. Nason, C. Oleari, F. Olness, C.G. Papadopoulos, G. Passarino, E. Pilon, R. Pittau, S. Pozzorini, T. Reiter, J. Reuter, M. Rodgers, G. Rodrigo, J. Rojo, G. Sanguinetti, F.-P. Schilling, M. Schumacher, S. Schumann, R. Schwienhorst, P. Skands, H. Stenzel, F. Stoeckli, R. Thorne, M. Ubiali, P. Uwer, A. Vicini, M. Warsinsky, G. Watt, J. Weng, I. Wigmore, S. Weinzierl, J. Winter, M. Worek, G. Zanderighi

Effort Distribution at NLO



A typical $2 \to m$ process at NLO

$$\sigma^{NLO} = \int_m d\sigma^B + \int_m \left(d\sigma^V + \int_1 d\sigma^A \right) + \int_{m+1} \left(d\sigma^R - d\sigma^A \right)$$

1. $d\sigma^B$ is the Born cross section
2. $d\sigma^V$ is the Virtual correction (loop diagrams)
3. $d\sigma^R$ is the Real correction
4. $d\sigma^A$ and $\int_1 d\sigma^A$ are *unintegrated* and *integrated* counterterms (allowing to compute the Real part in 4 dimensions)

The Virtual corrections

$$\mathcal{M}^{1-loop} = \sum_i d_i \text{ Box}_i + \sum_i c_i \text{ Triangle}_i + \sum_i b_i \text{ Bubble}_i + \sum_i a_i \text{ Tadpole}_i + R + \mathcal{O}(\epsilon)$$

Scalar Loop Functions *

Tadpole$_i = \int d^n\bar{q}\frac{1}{\bar{D}_0}$ Bubble$_i = \int d^n\bar{q}\frac{1}{\bar{D}_0\bar{D}_1}$

Triangle$_i = \int d^n\bar{q}\frac{1}{\bar{D}_0\bar{D}_1\bar{D}_2}$ Box$_i = \int d^n\bar{q}\frac{1}{\bar{D}_0\bar{D}_1\bar{D}_2\bar{D}_3}$

* Known analytically

$$\bar{D}_i = (\bar{q} + p_i)^2 - m_i^2 \qquad \text{and} \qquad n = 4 + \epsilon$$

The OPP Method (Ossola, Papadopoulos, Pittau, 2007)

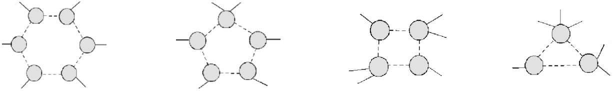
Working at the *integrand* level

$$\mathcal{M}^{1-loop} = \int d^n\bar{q} \; \left[\mathcal{A}(q) + \tilde{A}(q,\tilde{q},\epsilon)\right]$$

$$\left(\begin{array}{c} \bar{q} = q + \tilde{q} \\ n = 4 + \epsilon \end{array} \right)$$

- For example, in the case of $pp \to t\bar{t}b\bar{b}$

$$\mathcal{A}(q) = \sum \underbrace{\frac{N_i^{(6)}(q)}{\bar{D}_{i_0}\bar{D}_{i_1}\cdots\bar{D}_{i_5}}} + \underbrace{\frac{N_i^{(5)}(q)}{\bar{D}_{i_0}\bar{D}_{i_1}\cdots\bar{D}_{i_4}}} + \underbrace{\frac{N_i^{(4)}(q)}{\bar{D}_{i_0}\bar{D}_{i_1}\cdots\bar{D}_{i_3}}} + \underbrace{\frac{N_i^{(3)}(q)}{\bar{D}_{i_0}\bar{D}_{i_1}\bar{D}_{i_2}}} + \cdots$$



The function to be sampled *numerically* to extract the coefficients

$$
\begin{aligned}
N_i^{(6)}(q) &= \sum_{i_0<i_1<i_2<i_3}^{5} \left[d(i_0 i_1 i_2 i_3) + \tilde{d}(q; i_0 i_1 i_2 i_3) \right] D_{i_4} D_{i_5} \\
&+ \sum_{i_0<i_1<i_2}^{5} \left[c(i_0 i_1 i_2) + \tilde{c}(q; i_0 i_1 i_2) \right] D_{i_3} D_{i_4} D_{i_5} \\
&+ \sum_{i_0<i_1}^{5} \left[b(i_0 i_1) + \tilde{b}(q; i_0 i_1) \right] D_{i_2} D_{i_3} D_{i_4} D_{i_5} \\
&+ \sum_{i_0}^{5} \left[a(i_0) + \tilde{a}(q; i_0) \right] D_{i_1} D_{i_2} D_{i_3} D_{i_4} D_{i_5} \\
&+ \tilde{P}(q) D_{i_0} D_{i_1} D_{i_2} D_{i_3} D_{i_4} D_{i_5}
\end{aligned}
$$

Solving the OPP Equation 1

- The functional form of the *spurious* terms should be known
  Ossola, Papadopoulos, R. P., Nucl.Phys.B763:147-169,2007
  del Aguila, R. P., JHEP 0407:017,2004

Example ($p_0 = 0$)

$$\tilde{d}(q;0123) = \tilde{d}(0123)\,\epsilon(qp_1p_2p_3)$$

$$\int d^n\bar{q}\,\frac{\tilde{d}(q;0123)}{\bar{D}_0\bar{D}_1\bar{D}_2\bar{D}_3} = \tilde{d}(0123)\int d^n\bar{q}\,\frac{\epsilon(qp_1p_2p_3)}{\bar{D}_0\bar{D}_1\bar{D}_2\bar{D}_3} = 0$$

- The coefficients $\{d_i, c_i, b_i, a_i\}$ and $\{\tilde{d}_i, \tilde{c}_i, \tilde{b}_i, \tilde{a}_i\}$ are extracted by solving linear systems of equations

Solving the OPP Equation 2

The use of special values of q helps

$$D_0(q^\pm) = D_1(q^\pm) = D_2(q^\pm) = D_3(q^\pm) = 0$$

$$N^{(m-1)}(q^\pm) \quad = \left[d(0123) + \tilde{d}(q^\pm; 0123)\right] \prod_{i \neq 0,1,2,3}^{m-1} D_i(q^\pm)$$

$$d(0123) = \frac{1}{2}\left[\frac{N^{(m-1)}(q^+)}{\prod_{i\neq 0,1,2,3}^{m-1} D_i(q^+)} + \frac{N^{(m-1)}(q^-)}{\prod_{i\neq 0,1,2,3}^{m-1} D_i(q^-)}\right]$$

A classical example

$$\int d^n\bar{q} \frac{1}{\bar{D}_0\bar{D}_1\bar{D}_2\bar{D}_3\bar{D}_4\bar{D}_5\bar{D}_6}$$

- $N(q) = 1$
- $D_0(q^{\pm}) = D_1(q^{\pm}) = D_2(q^{\pm}) = D_3(q^{\pm}) = 0$

$$d(0123) = \frac{1}{2}\left[\frac{1}{D_4(q^+)D_5(q^+)D_6(q^+)} + \frac{1}{D_4(q^+)D_5(q^+)D_6(q^+)}\right]$$

...

What about R $(= R_1 + R_2)$?

The origin of R_1

$$\frac{1}{\bar{D}_i} = \frac{1}{D_i}\left(1 - \frac{\tilde{q}^2}{\bar{D}_i}\right)$$ $\Rightarrow$ predicted within OPP

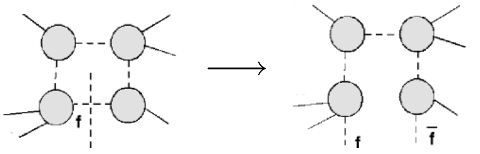
The origin of R_2

$$R_2 = \int d^n\bar{q}\,\frac{\tilde{N}(q,\tilde{q},\epsilon)}{\bar{D}_0\cdots\bar{D}_{m-1}}$$ $\Rightarrow$ effective tree-level Feynman Rules*

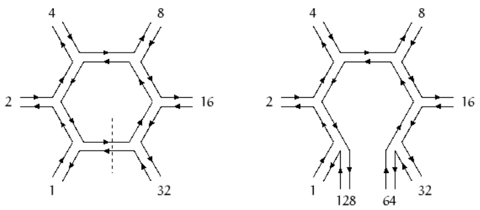
* QCD: Draggiotis, Garzelli, Papadopoulos, R. P., JHEP 0904:072,2009
  EW: Garzelli, Malamos, R. P., JHEP 1001:040,2010

Recursion Relations at 1-loop (cutting)

- OPP + hard-cut allow to use *the same tree-level Recursion Relations* for $m+2$ tree-like structures



- The color can be treated *as at the tree level*

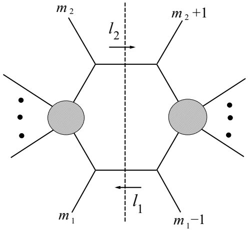


In the meanwhile· · ·

· · · on the other side of the ocean· · ·

Cutting ··· (Gluing ···)

• Double cuts ⇔ gluing 2 tree-level amplitudes
(Bern, Dixon, Dunbar, Kosower 1994)

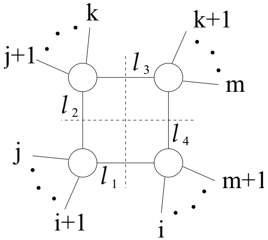


• Different double cuts are applied to disentangle 1-loop scalar functions *by looking at the analytic structure of the result*

• R is reconstructed by looking at collinear and infrared limits

$\cdots$ and more cutting ($\cdots$ more gluing)

1. Quadruple cuts $\Leftrightarrow$ gluing 4 tree-level amplitudes (Britto, Cachazo, Feng, hep-th/0412103)



2. q integration frozen $\Rightarrow$ *coefficient d_i of the box extracted*
3. 3 bubbles are connected together, the box contributions subtracted and the *coefficients c_i of the triangles extracted*
4. $\cdots$

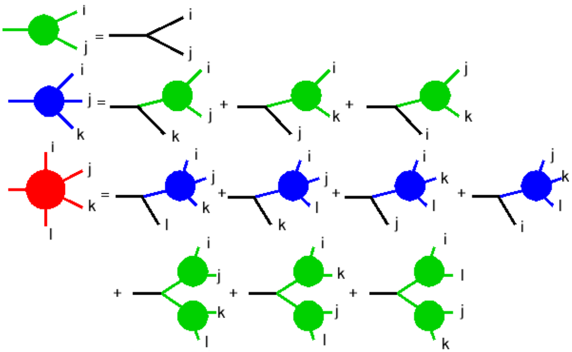
$\Longrightarrow$

Generalized Unitarity (Relevant References)

- Bern, Dixon, Dunbar, Kosower (1994)
- Ossola, Papadopoulos, R. P., hep-ph/0609007
- Forde, 0704.1835
- Ellis, Giele, Kunszt, 0708.2398
- Berger et al., 0803.4180

The Real Corrections

Recursion Relations at tree level



(figure by A. van Hameren)

- Feynman Diagrams avoided
  (Berends, Giele, Caravaglios, M. Moretti)

The Counterterms

The Catani-Seymour dipoles

- Catani, Seymour, Nucl. Phys. B485, 291 (1997)
- Catani, Dittmaier, Seymour, Trocsanyi, Nucl. Phys. B627, 189 (2002)
- Czakon, Papadopoulos, Worek, JHEP 0908 (2009) 085

- Massless
- Massive
- Polarized

The FKS subtraction

- Frixione, Kunszt, Signer, hep-ph/9512328

The Antenna subtraction

- Kosower, Phys. Rev. D 71 (2005) 045016
- Campbell, Cullen Glover, Eur. Phys. J. C 9 (1999) 245

NLO Parton Level Tools

Analytic formulae

- MCFM [Campbell *et al.*]

Feynman Diagrams

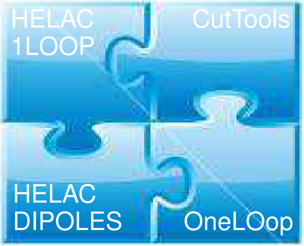
- DKU, HAWK ··· [Bredenstein, Denner, Dittmaier, Pozzorini *et al.*]
- FormCalc/LoopTools/FeynCalc [Hahn *et al.*]
- GOLEM [Binoth *et al.*]
- GRACE [Belanger, Boudjema *et al.*]

OPP/Unitarity

- HELAC-NLO/CutTools [Papadopoulos, R. P. *et al.*]
- BlackHat/SHERPA [Berger *et al.*]
- Rocket/MCFM [Ellis *et al.*]
- Samurai [Mastrolia, Ossola, Reiter, Tramontano]

The Helac-NLO System

1. CutTools
   $\{d_i, c_i, b_i, a_i\}$ and R_1
2. HELAC-1LOOP
   $N(q)$ and R_2
3. OneLOop
   scalar 1-loop integrals
4. HELAC-DIPOLES
   Real correction and CS dipoles



(figure by G. Bevilacqua)

- Ossola, Papadopoulos, R. P., JHEP 0803 (2008) 042
- van Hameren, Papadopoulos, R. P., JHEP 0909 (2009) 106
- Czakon, Papadopoulos, Worek, JHEP 0908 (2009) 085

The HELAC-NLO group *

*

G. Bevilacqua	M. Czakon	M. Garzelli
A. van Hameren	A. Kardos	A. Lazopoulos
J. Malamos	C.G. Papadopoulos	R. P.
M. Worek		

Contributors

Caffarella Draggiotis Kanaki Ossola

Tuned comparisons

Process	$\sigma^{\rm LO}_{\rm FD}$ [fb]	$\sigma^{\rm LO}_{\rm OPP}$ [fb]	$\sigma^{\rm NLO}_{\rm FD}$ [fb]	$\sigma^{\rm NLO}_{\rm OPP}$ [fb]
$q\bar{q} \to t\bar{t}b\bar{b}$	85.522(26)	85.489(46)	87.698(56)	87.545(91)
$pp \to t\bar{t}b\bar{b}$	1488.8(1.2)	1489.2(0.9)	2638(6)	2642(3)

$pp \to t\bar{t}b\bar{b} + X$ *at the LHC,* $\mu_F = \mu_R = m_t$.

- Agreement between two completely different techniques
- Agreement on $pp \to ZZ + j + X$ between GOLEM and Dittmaier, Kallweit and Uwer

A Les Houches Accord to merge Real (R) and Virtual (V) parts

Monte Carlo (R)		One Loop Program (V)

Contract

$\Longleftrightarrow$

A proposal for $\Longleftrightarrow$ can be found in

Binoth *et al.* arXiv:1001.1307

Tools for the Real Radiation

Automation of the subtraction methods

- Gleisberg, Krauss, 0709.2881
- Seymour, Tevlin, 0803.2231
- Hasegawa, Moch, Uwer, 0807.3701
- Frederix, Gehrmann, Greiner, 0808.2128
- Czakon, Papadopoulos, Worek, 0905.0883
- Frederix, Frixione, Maltoni, Stelzer, 0908.4272
- Frederix, Gehrmann, Greiner, 1004.2905

Adding PS consistently at NLO

- MC@NLO Frixione, Webber (2002)
- POWHEGNason(2004); Frixione, Nason, Oleari (2007)
- GenEvABauer, Tackmann, Thaler (2008)

Not yet for arbitrary complex final states

A NLO analysis of ttH production vs $ttbb$ and $ttjj$ backgrounds

Based on arXiv:1003.1241 [hep-ph],
Phys.Rev.Lett.104:162002,2010 and JHEP 0909:109,2009

Cross sections at NLO

$pp \longrightarrow t\bar{t}b\bar{b} + X$

σ^B_{LO} [fb]	σ^B_{NLO} [fb]	K-factor
1489.2 ± 0.9	2642 ± 3	1.77

$\mu_R = \mu_F = \mu_0 = m_t$ (CTEQ6)

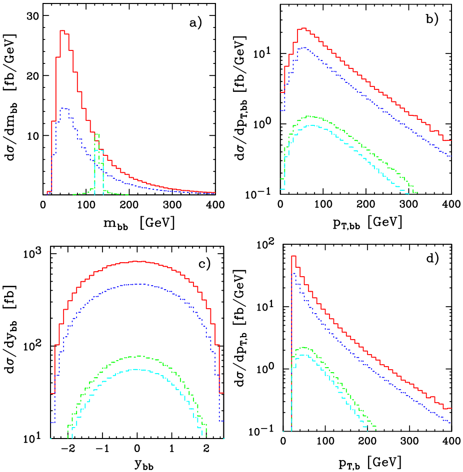
$pp \longrightarrow t\bar{t}H + X \longrightarrow t\bar{t}b\bar{b} + X$

σ^S_{LO} [fb]	σ^S_{NLO} [fb]	K-factor
150.375 ± 0.077	207.268 ± 0.150	1.38

$\mu_R = \mu_F = \mu_0 = m_t + m_H/2$ (CTEQ6)

- $p_T(b) > 20 \text{ GeV}\,, \quad \Delta R(b,\bar{b}) > 0.8\,, \quad |\eta_b| < 2.5$

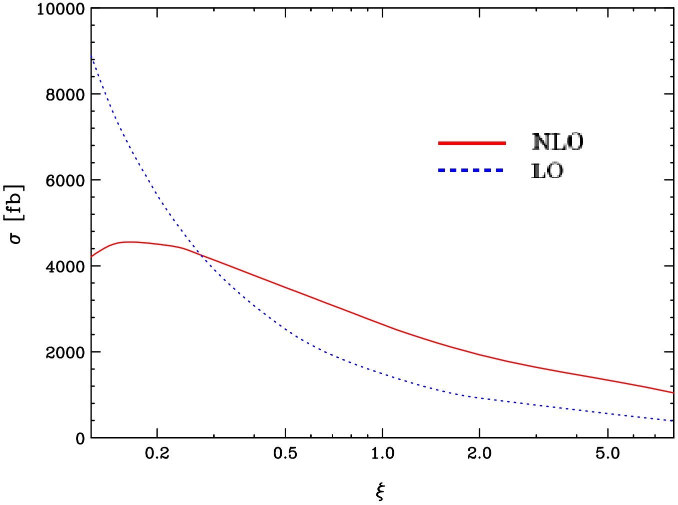
Distributions at NLO



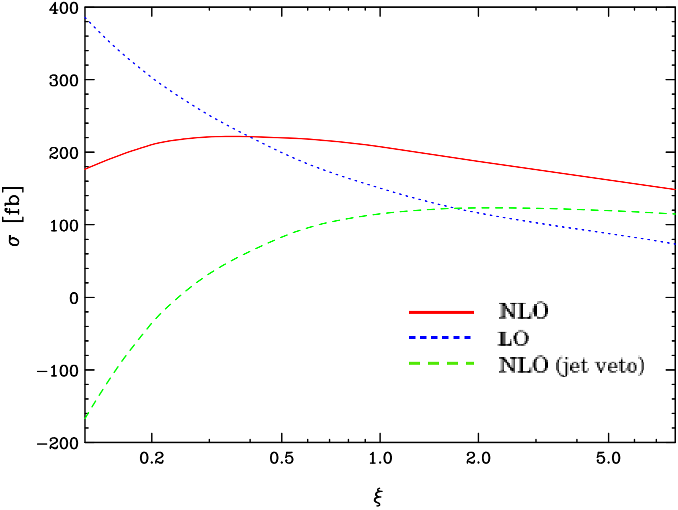
______ NLO Signal ______ NLO $ttbb$ Background

______ LO Signal ______ LO $ttbb$ Background

Scale dependence of the $ttbb$ Background



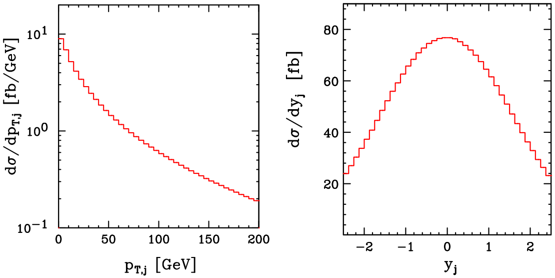
Scale dependence of the Signal



The effect of a jet veto on the Signal/Background ratio

The extra radiation is mainly at low p_T and in the central region

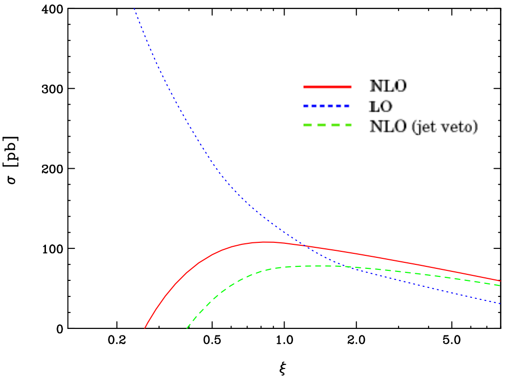
Signal



- With $p_T(j) < 50$ GeV:

$$(S/B)_{LO} = 0.10 \qquad (S/B)_{NLO-veto} = 0.064$$
$$(S/B)_{NLO} = 0.079$$

Scale dependence of the $ttjj$ Background

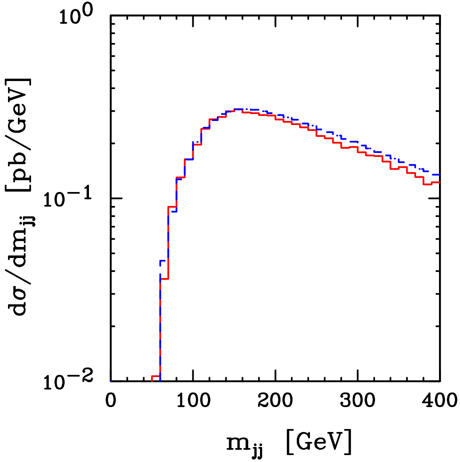


$$\sigma(ttjj)_{LO} = 120.17\ (8)\ \text{pb}$$

$$\sigma(ttjj)_{NLO} = 106.97(17)\ \text{pb}$$

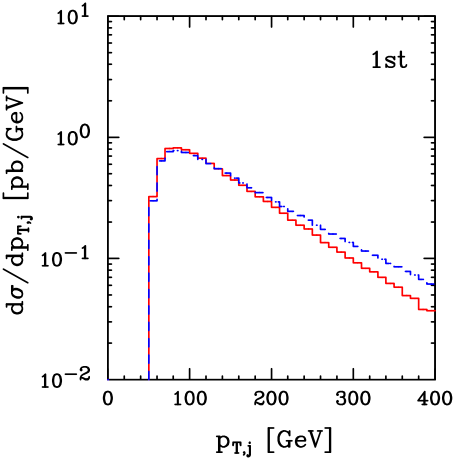
$\mu_R = \mu_F = \mu_0 = m_t$ (CTEQ6)

m_{jj} distribution of the $ttjj$ Background



______ NLO ______ LO

Hardest jet p_T distribution of the $ttjj$ Background



_____ NLO _____ LO

NLO QCD corrections to $pp \to e^+e^-$ at the LHC

Parameters

$$\sqrt{s} = 7 \text{ TeV} \qquad p_T(\ell^\pm) > 1 \text{ GeV} \qquad |\eta(\ell^\pm)| < 5$$

$$m_{\ell^+\ell^-} > 60 \text{ GeV} \qquad \mu_F = \mu_R = M_Z$$

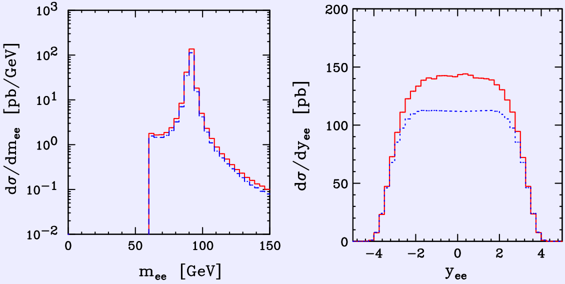
Results cross-checked with MCFM

The Cross section

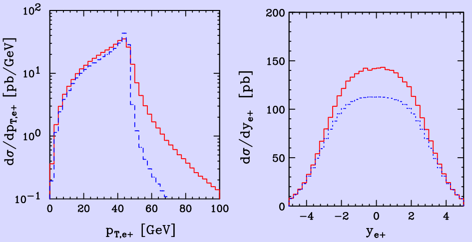
$$\sigma_{LO} = \quad 720.9(1) \quad \begin{matrix} -66.2\ (9.2\%) \\ +56.3\ (7.8\%) \end{matrix} \quad \text{pb}$$

$$\sigma_{NLO} = \quad 878.2(2) \quad \begin{matrix} -10.4\ (1.2\%) \\ +13.4\ (1.5\%) \end{matrix} \quad \text{pb}$$

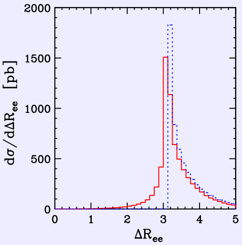
The $m_{\ell^+\ell^-}$ and $y_{\ell^+\ell^-}$ distributions



The $p_t(\ell^+)$ and $y(\ell^+)$ distributions



The $\Delta R_{\ell^+\ell^-}$ distribution



NLO QCD corrections to $pp \to W^+ \to e^+\nu_e$ at the LHC

Parameters

$$\sqrt{s} = 7\ \text{TeV} \quad p_T(\ell^\pm) > 1\ \text{GeV}$$
$$|\eta(\ell^\pm)| < 5 \quad \mu_F = \mu_R = M_W$$

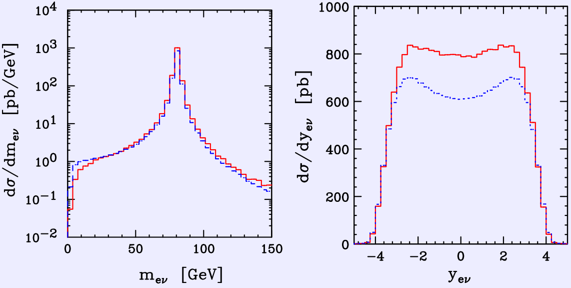
Results cross-checked with MCFM

The Cross section

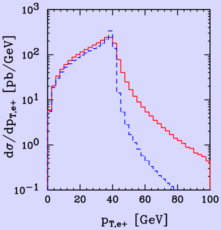
$$\sigma_{LO} = 4737.7(1.0) \begin{array}{c} -492.2\ (10\%) \\ +426.9\ (9\%) \end{array} \text{pb}$$

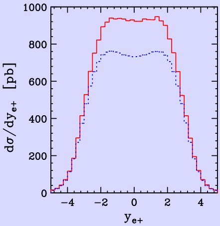
$$\sigma_{NLO} = 5670.6(1.6) \begin{array}{c} -85.8\ (1.5\%) \\ +107.5\ (1.9\%) \end{array} \text{pb}$$

The $m_{e\nu}$ and $y_{e\nu}$ distributions

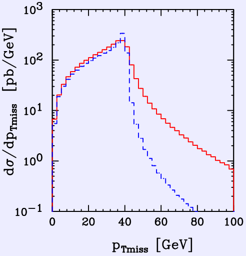


The $p_t(e^+)$ and $y(e^+)$ distributions



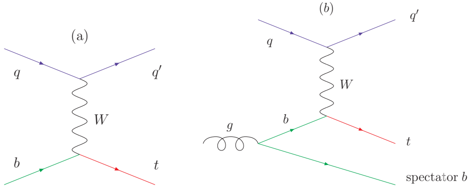


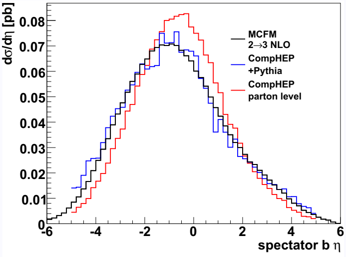
The $p_{t,miss}$ distribution



Single-top production at Tevatron

Schwienhorst, Frederix, Maltoni





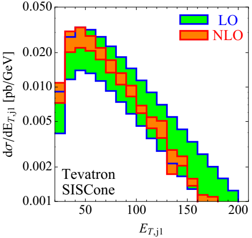
W +3 jets at NLO

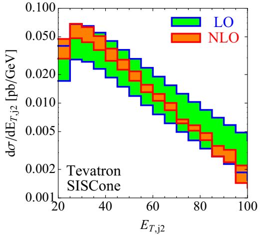
- Melnikov, Zanderighi, arXiv:0910.3671
- Ellis, Melnikov, Zanderighi, arXiv:0906.1445
- Ellis, Melnikov, Zanderighi, arXiv:0901.4101

- Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre (BlackHat)
  - arXiv:0907.1984
  - arXiv:0902.2760

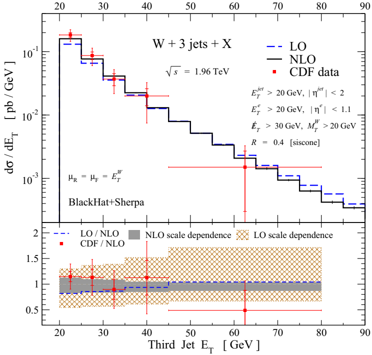
Z + 3 jets at NLO

- BlackHat
  - arXiv:0912.4927
  - arXiv:1004.1659
  - arXiv:1005.3728

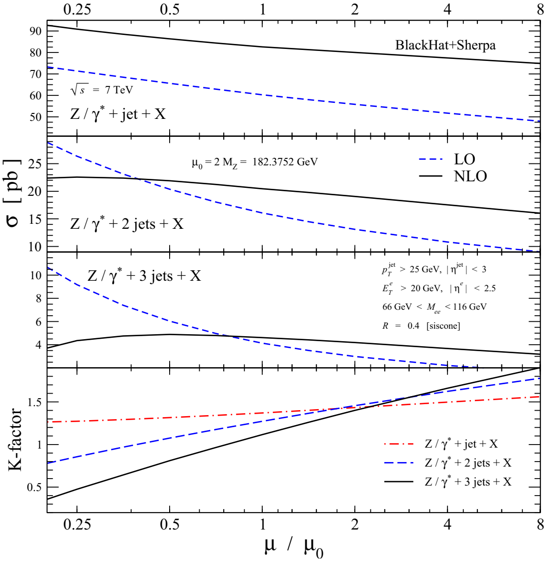




Ellis et al.



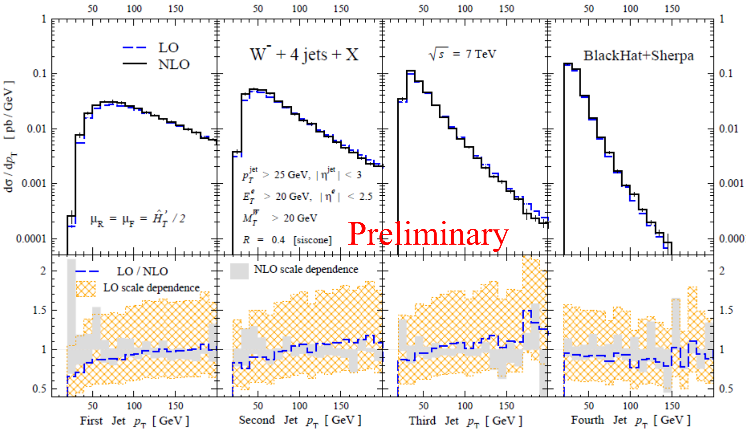
BlackHat



BlackHat+Sherpa
$\sqrt{s}$ = 7 TeV
Z / γ* + jet + X
μ0 = 2 MZ = 182.3752 GeV
LO
NLO
Z / γ* + 2 jets + X
Z / γ* + 3 jets + X
p_T^{jet} > 25 GeV, |η^jet| < 3
E_T^e > 20 GeV, |η^e| < 2.5
66 GeV < M_{ee} < 116 GeV
R = 0.4 [siscone]
σ [pb]
K-factor
Z / γ* + jet + X
Z / γ* + 2 jets + X
Z / γ* + 3 jets + X
μ / μ0

BlackHat

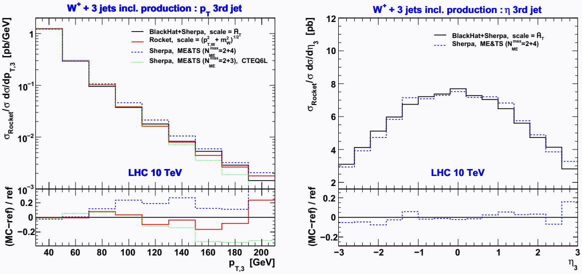
W +4 jets at NLO



BlackHat

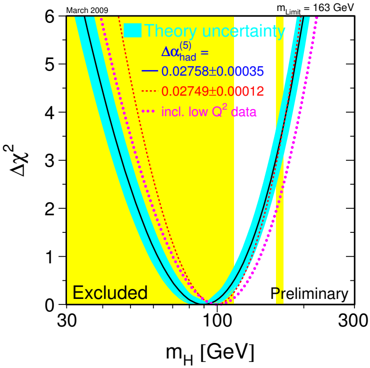
$W + 3j$ unleashed comparisons

BlackHat/SHERPA, Rocket/MCFM, SHERPA+PS



- The use of a scale=HT reproduces the shape of the NLO calculation at LO for many relevant kinematic distributions
- The largest shape differences, of the order of 20% and 40%, are seen in the third-jet pT and HT distributions, respectively

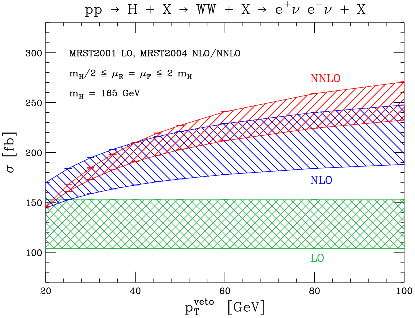
Higgs searches at Tevatron



- Anastasiou, Melnikov, hep-ph/0207004
- Anastasiou, Melnikov, Petriello, hep-ph/0409088
- Anastasiou, Boughezal, Petriello, arXiv:0811.3458

NNLO QCD effects on $H \to WW \to \ell\nu\ell\nu$

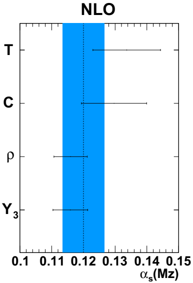
G. Dissertori and F. Stöckli

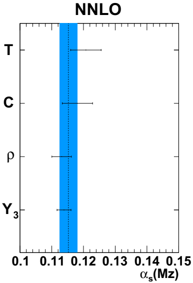


- Jet vetoing reduces the K factor

NNLO Determination of $\alpha_s(M_z)$ at LEP from event shapes

Dissertori, Gehrmann-De Ridder, Gehrmann, Glover, Heinrich, Jaquier, Luisoni, Stenzel





$$\alpha_S(M_Z)^{NLO} = 0.1200 \pm 0.0021(exp) \pm 0.0062(th)$$
$$\alpha_S(M_Z)^{NNLO} = 0.1153 \pm 0.0017(exp) \pm 0.0023(th)$$

Understanding soft and collinear divergences at all orders

Gardi and Magnea, Becker and Neubert

$$\mathcal{M}\left(p_i/\mu, \alpha_s(\mu^2), \epsilon\right) = Z\left(p_i/\mu_f, \alpha_s(\mu_f^2), \epsilon\right) \; \mathcal{H}\left(p_i/\mu, \mu/\mu_f, \alpha_s(\mu^2), \epsilon\right)$$

$$Z\left(p_i/\mu, \alpha_s(\mu^2), \epsilon\right) = \exp\left\{ \int_0^{\mu^2} \frac{d\lambda^2}{\lambda^2} \left[\frac{1}{8} \widehat{\gamma}_K \left(\alpha_s(\lambda^2, \epsilon)\right) \sum_{i \neq j} \ln\left(\frac{2 p_i \cdot p_j \, \mathrm{e}^{-\mathrm{i}\pi\phi_{ij}}}{\lambda^2} \right) \mathrm{T}_i \cdot \mathrm{T}_j - \frac{1}{2} \sum_{i=1}^{n} \gamma_{J_i} \left(\alpha_s(\lambda^2, \epsilon)\right) \right] \right\}.$$

- Very simple dipole structure

Conclusions and Outlooks

1. I reviewed recent developments in the field of

   QCD (N)NLO

   calculations relevant for Hadron Collider phenomenology

2. The status of multileg NLO calculations is now at the same stage of multileg tree level calculations 10 years ago

3. An analysis of *all of the LHC data* (at least) at the NLO accuracy is possible

4. NLO public codes in preparation