Rassegna Teorica di QCD

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Roma, April 07, 2010

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1. Why (N)NLO QCD calculations?

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1. Why (N)NLO QCD calculations?
2. Recent developments and 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:

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

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

$$\Longrightarrow$$

  1. multileg (N)NLO calculations and MCs needed

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

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

- This talk mostly based on 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

NLO Tools

Analytic formulae

- MCFM [Campbell *et al.*]

Feynman Diagrams

- DKU, HAWK $\cdots$ [Denner, Dittmaier *et al.*]
- FormCalc/LoopTools/FeynCalc [Hahn *et al.*]
- GOLEM [Binoth *et al.*]

OPP/Unitarity

- HELAC-NLO/CutTools [Papadopoulos, Pittau *et al.*]
- BlackHat/SHERPA [Berger *et al.*]
- Rocket/MCFM [Ellis *et al.*]
- C++ [Lazopoulos]

Tuned comparisons

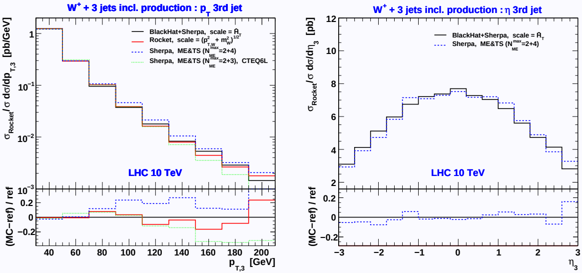
Process	$\sigma^{\text{LO}}_{\text{FD}}$ [fb]	$\sigma^{\text{LO}}_{\text{OPP}}$ [fb]	$\sigma^{\text{NLO}}_{\text{FD}}$ [fb]	$\sigma^{\text{NLO}}_{\text{OPP}}$ [fb]
$q\bar{q} \to t\bar{t}b\bar{b}$	85.522(26)	85.489(46)	87.698(56)	87.545(91)
$pp \to t\bar{t}b\bar{b}$	1488.8(1.2)	1489.2(0.9)	2638(6)	2642(3)

$pp \to t\bar{t}b\bar{b} + X$ *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

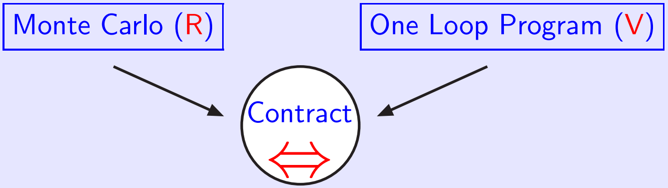
$W+3j$ unleashed comparisons

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

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

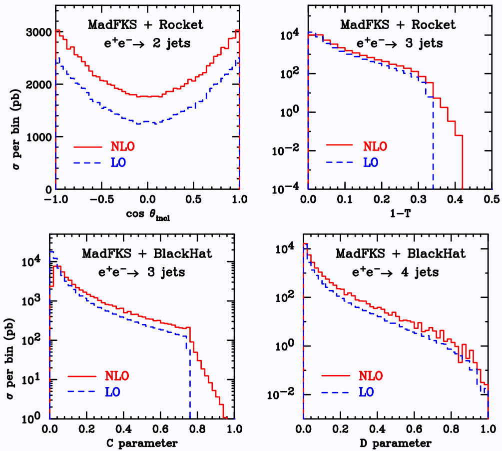


A proposal for ⇔ can be found in

Binoth *et al.* arXiv:1001.1307

Example of MC/OLP interface

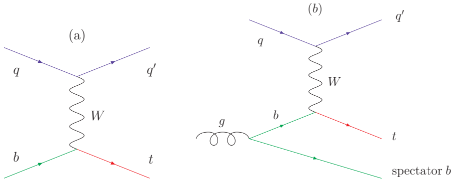
BlackHat/Rocket to MadFKS

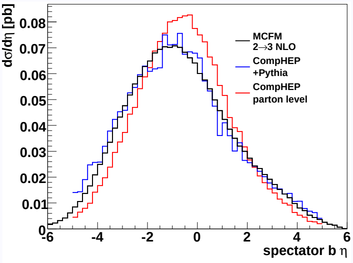


Frederix, Maitre, Zanderighi

Single-top production at Tevatron

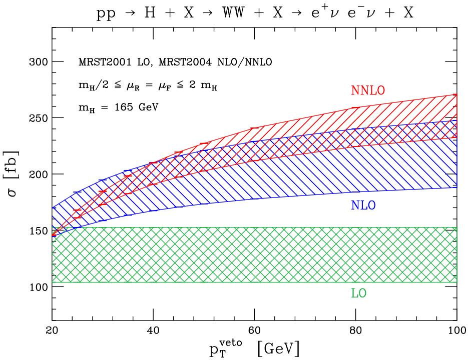
Schwienhorst, Frederix, Maltoni





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

G. Dissertori and F. Stöckli



- Jet vetoing reduces the K factor

Understanding soft and collinear divergences at all orders

Gardi and Magnea

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

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

- Very simple dipole structure

Matching NLO with Parton shower

An actual implementation

- MC@NLO + POWHEG
  Frixione, Webber, Nason, Oleari

New standard for the output necessary

- A Standard format for Les Houches Events Files, Version 2
  Lönnbald *et al.* arXiv:1003.1643 [hep-ph]

Cross sections at NLO (by the HELAC-NLO group)

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

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)

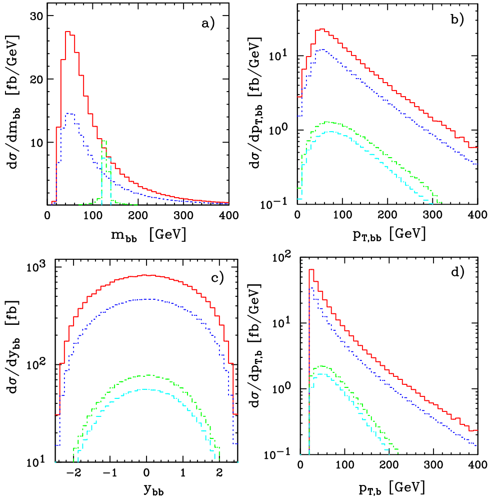
$pp \longrightarrow t\bar{t}H + X \longrightarrow t\bar{t}b\bar{b} + X$

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

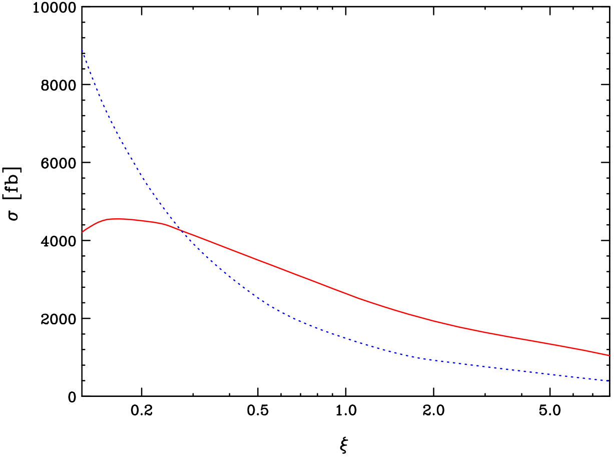
$\mu_R = \mu_F = \mu_0 = m_t + m_H/2$ (CTEQ6)

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

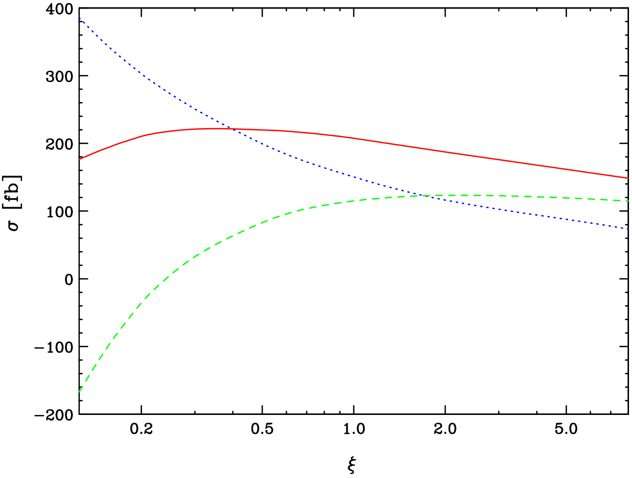
Distributions at NLO



Scale dependence of the Background



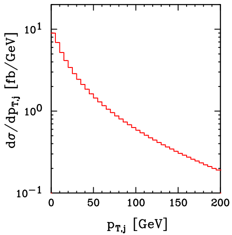
Scale dependence of the Signal



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:

  $R_{LO} = 0.10 \rightarrow R_{NLO} = 0.079 \rightarrow R_{NLO-veto} = 0.064$

- Tuning necessary

  (e.g. Bredenstein, Denner, Dittmaier, Pozzorini, [arXiv:1001.4727])

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