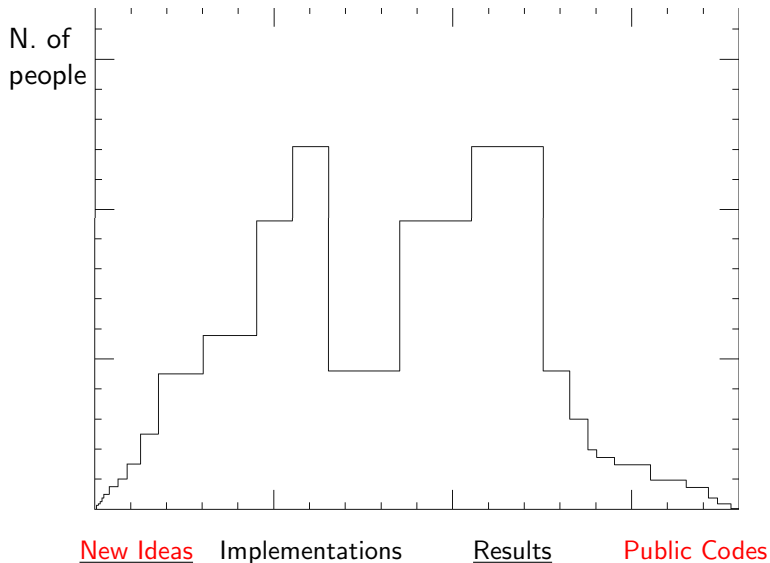


Recent news and results in the computation of NLO processes with non standard techniques

R. Pittau (U. of Granada)
CERN, June 25, 2010

Effort Distribution at NLO



Testing and improving the numerical accuracy of the NLO predictions (1006.3773 [hep-ph])

- 1 To trust multi-leg NLO calculations one has to trust the numerical accuracy (especially for the Virtual Part)
- 2 To use multi-precision always is CPU-wise inviable
- 3 I present a new and reliable method to test the numerical accuracy of NLO calculations based on modern OPP/Generalized Unitarity techniques
- 4 A convenient solution to *rescue* most of the detected numerically inaccurate points is also proposed

Key point: These non standard techniques have the potential to self detect stability problems

The decomposition of any 1-loop amplitude

$$\begin{aligned}
 A = & \sum_{i_0 < i_1 < i_2 < i_3}^{m-1} d(i_0 i_1 i_2 i_3) \int d^n \bar{q} \frac{1}{\bar{D}_{i_0} \bar{D}_{i_1} \bar{D}_{i_2} \bar{D}_{i_3}} \\
 & + \sum_{i_0 < i_1 < i_2}^{m-1} c(i_0 i_1 i_2) \int d^n \bar{q} \frac{1}{\bar{D}_{i_0} \bar{D}_{i_1} \bar{D}_{i_2}} \\
 & + \sum_{i_0 < i_1}^{m-1} b(i_0 i_1) \int d^n \bar{q} \frac{1}{\bar{D}_{i_0} \bar{D}_{i_1}} \\
 & + \sum_{i_0}^{m-1} a(i_0) \int d^n \bar{q} \frac{1}{\bar{D}_{i_0}} + R_1 + (R_2)
 \end{aligned}$$

The OPP expansion

$$\begin{aligned}
 N(q) = & \mathcal{D}^{(m)}(q) + \sum_{i_0 < i_1 < i_2}^{m-1} c(i_0 i_1 i_2; \textcolor{red}{q}) \prod_{i \neq i_0, i_1, i_2}^{m-1} D_i \\
 & + \sum_{i_0 < i_1}^{m-1} b(i_0 i_1; \textcolor{red}{q}) \prod_{i \neq i_0, i_1}^{m-1} D_i + \sum_{i_0}^{m-1} a(i_0; \textcolor{red}{q}) \prod_{i \neq i_0}^{m-1} D_i
 \end{aligned}$$

$$\mathcal{D}^{(m)}(q) = \sum_{i_0 < i_1 < i_2 < i_3}^{m-1} d(i_0 i_1 i_2 i_3; \textcolor{red}{q}) \prod_{i \neq i_0, i_1, i_2, i_3}^{m-1} D_i$$

Sampling at different $\textcolor{red}{q}$ allows to get the set \mathcal{S} of 1-loop coefficients

$$\mathcal{S} = \begin{cases} d(i_0 i_1 i_2 i_3), & c(i_0 i_1 i_2), \\ b(i_0 i_1), & a(i_0), \end{cases} \quad R_1$$

The “N=N” test

Since a reconstruction of a function is involved here

$$N(q') = N_{rec}(q')$$

at an *independent* value of q' allows (in principle) to test the goodness of the set of coefficients

Ossola, Papadopoulos, R. P. (2007)

Also the fact that combinations of coefficients should sum up to zero can be used

Mastrolia, Ossola, Reiter, Tramontano (2010)

- 1 The *arbitrariness* of q' introduces a unwanted, parameter upon which the check depends in an unpredictable way
- 2 Not *all* the reconstructed coefficients enter into the actual computation

If we could get **independently** the set of coefficients

$$\mathcal{S}' = \begin{cases} d'(i_0 i_1 i_2 i_3), & c'(i_0 i_1 i_2), \\ b'(i_0 i_1), & a'(i_0), \end{cases} \quad R'_1$$

an **independent** determination would become possible

$$\begin{aligned} A' = & \sum_{i_0 < i_1 < i_2 < i_3}^{m-1} d'(i_0 i_1 i_2 i_3) \int d^n \bar{q} \frac{1}{\bar{D}_{i_0} \bar{D}_{i_1} \bar{D}_{i_2} \bar{D}_{i_3}} \\ & + \sum_{i_0 < i_1 < i_2}^{m-1} c'(i_0 i_1 i_2) \int d^n \bar{q} \frac{1}{\bar{D}_{i_0} \bar{D}_{i_1} \bar{D}_{i_2}} \\ & + \sum_{i_0 < i_1}^{m-1} b'(i_0 i_1) \int d^n \bar{q} \frac{1}{\bar{D}_{i_0} \bar{D}_{i_1}} \\ & + \sum_{i_0}^{m-1} a'(i_0) \int d^n \bar{q} \frac{1}{\bar{D}_{i_0}} + R'_1 + (R_2) \end{aligned}$$

⇒ a **reliable** estimator of the accuracy

$$E^A \equiv \frac{|A - A'|}{|A|}$$

- 1 The way to obtain \mathcal{S}' is similar to the technique used to determine R_1
- 2 Under a shift $m_i^2 \rightarrow m_i^2 - \tilde{q}^2$ in the denominators of the OPP equation (testing the *same* $N(q)$ at shifted values)

$$\begin{aligned}\bar{c}(i_0 i_1 i_2) &= c(i_0 i_1 i_2) + \tilde{q}^2 c^{(2)}(i_0 i_1 i_2) \\ \bar{b}(i_0 i_1) &= b(i_0 i_1) + \tilde{q}^2 b^{(2)}(i_0 i_1) \\ \bar{a}(i_0) &= a(i_0)\end{aligned}$$

Incidentally

$$\begin{aligned}R_1 &= -\frac{i}{96\pi^2} d^{(2m-4)} - \frac{i}{32\pi^2} \sum_{i_0 < i_1 < i_2}^{m-1} c^{(2)}(i_0 i_1 i_2) \\ &\quad - \frac{i}{32\pi^2} \sum_{i_0 < i_1}^{m-1} b^{(2)}(i_0 i_1) \left(m_{i_0}^2 + m_{i_1}^2 - \frac{(p_{i_0} - p_{i_1})^2}{3} \right)\end{aligned}$$

- ① Under a **new** mass shift $m_i^2 \rightarrow m_i^2 - \tilde{q}_1^2$

$$\bar{c}_1(i_0 i_1 i_2) = c(i_0 i_1 i_2) + \tilde{q}_1^2 c^{(2)}(i_0 i_1 i_2)$$

$$\bar{b}_1(i_0 i_1) = b(i_0 i_1) + \tilde{q}_1^2 b^{(2)}(i_0 i_1)$$

$$\bar{a}_1(i_0) = a(i_0)$$



$$a'(i_0) = \bar{a}_1(i_0)$$

$$b'(i_0 i_1) = \frac{\bar{b}(i_0 i_1) + \bar{b}_1(i_0 i_1)}{2} - \frac{\tilde{q}^2 + \tilde{q}_1^2}{2} b^{(2)}(i_0 i_1)$$

$$c'(i_0 i_1 i_2) = \frac{\bar{c}(i_0 i_1 i_2) + \bar{c}_1(i_0 i_1 i_2)}{2} - \frac{\tilde{q}^2 + \tilde{q}_1^2}{2} c^{(2)}(i_0 i_1 i_2)$$

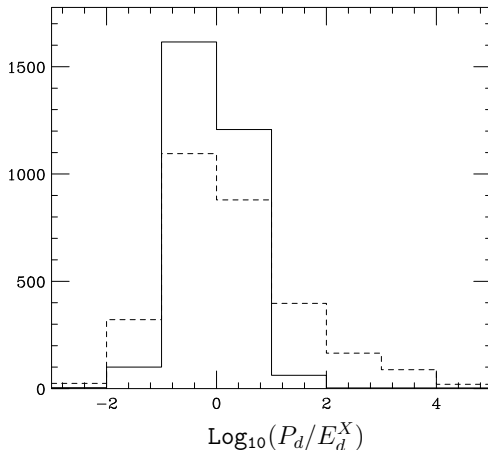
- ② Analogously one obtains independent determinations of **box coefficients** and R_1 , namely the whole set \mathcal{S}'

Important

*One can fit $N_{rec}(q)$ instead of $N(q)$
 \Rightarrow very moderate CPU cost*

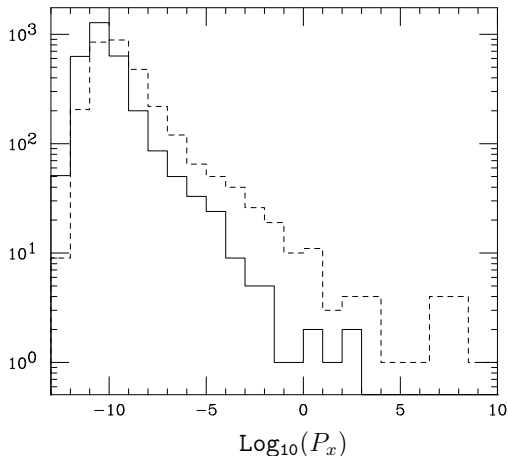
Testing the Estimators $E^A \equiv \frac{|A-A'|}{|A|}$ and $E^N \equiv \frac{|N-N_{rec}|}{|N|}$

- ❶ 3000 P.S. Points for 1 FD of $\gamma\gamma \rightarrow 4\gamma$ with **CutTools**
- ❷ Ratio of True Precision/Estimator:

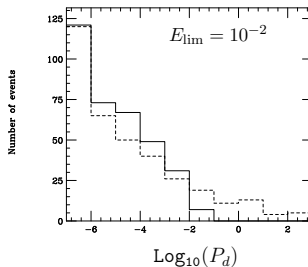
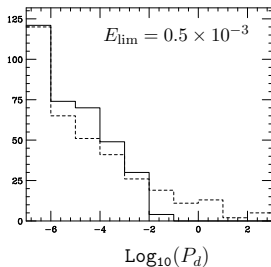
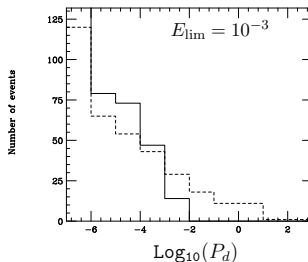
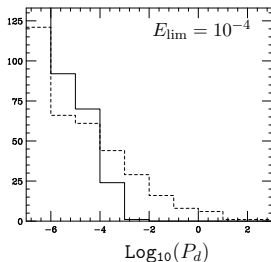


Rescuing the inaccurate points

- 1 Fitting the set \mathcal{S} in multi-precision *while keeping $N(q)$ in double precision* (important for interfacing)



Using E^A to rescue *only* the inaccurate points



The number of recomputed and discarded points

E_{lim}	N_{mp}	N_{dis}
10^{-4}	90	14
10^{-3}	62	8
$.5 \times 10^{-3}$	44	6
10^{-2}	40	6

Over a total of 3000 points

Concluding remarks

- 1 The rescue procedure is able to recover **most** of the inaccurate points
- 2 The estimator E^A efficiently detects and discards the unrecoverable points

Results

The HELAC-NLO group *

*

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A. Kardos

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Contributors

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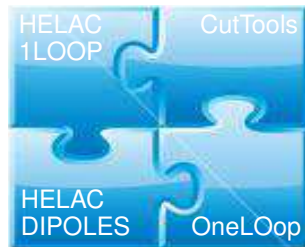
Draggiotis

Kanaki

Ossola

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

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

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

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

$$\mu_R = \mu_F = \mu_0 = m_t \text{ (CTEQ6)}$$

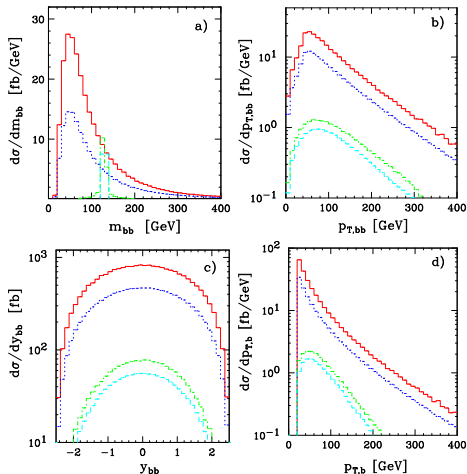
$$pp \rightarrow t\bar{t}H + X \rightarrow t\bar{t}b\bar{b} + X$$

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

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

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

Distributions at NLO



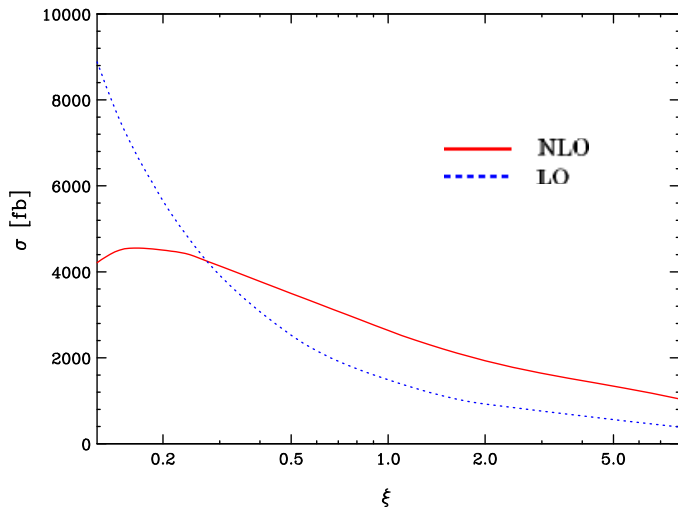
----- NLO Signal

----- NLO $ttbb$ Background

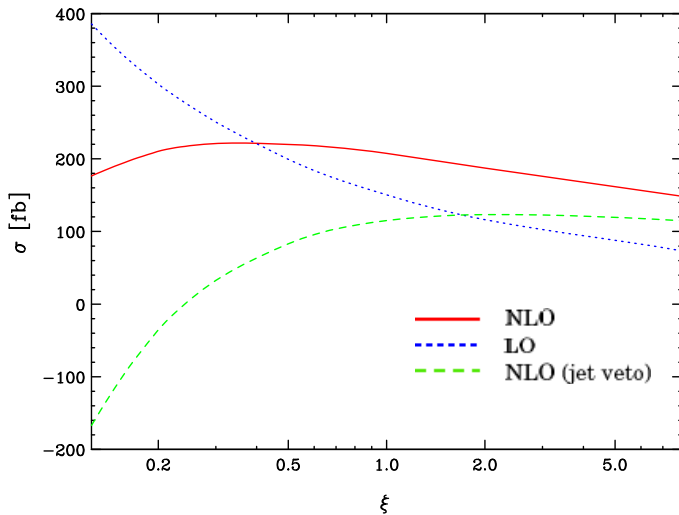
----- LO Signal

----- LO $ttbb$ Background

Scale dependence of the $t\bar{t}b\bar{b}$ Background



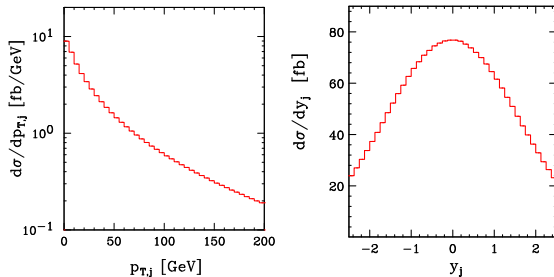
Scale dependence of the Signal



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

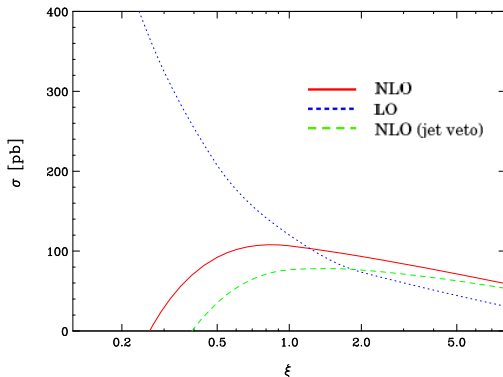
Signal



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

$$\begin{aligned}
 (S/B)_{LO} &= 0.10 & (S/B)_{NLO-veto} &= 0.064 \\
 (S/B)_{NLO} &= 0.079
 \end{aligned}$$

Scale dependence of the $ttjj$ Background

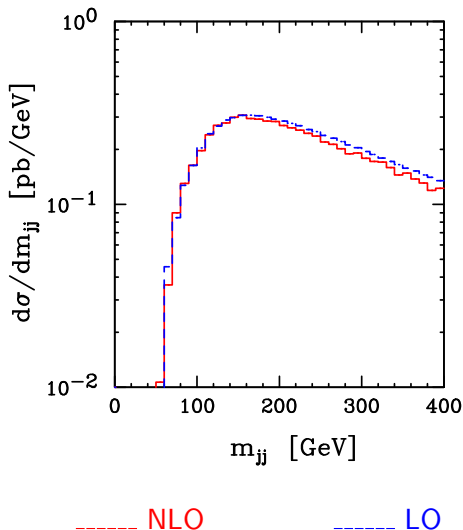


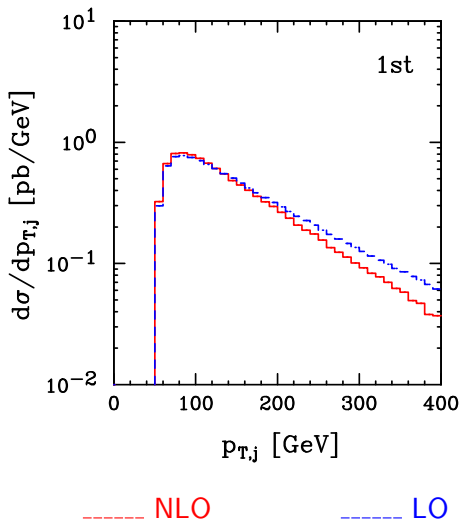
$$\sigma(ttjj)_{LO} = 120.17 (8) \text{ pb}$$

$$\mu_R = \mu_F = \mu_0 = m_t \text{ (CTEQ6)}$$

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

m_{jj} distribution of the $t\bar{t}jj$ Background



Hardest jet p_T distribution of the $ttjj$ Background

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

Parameters

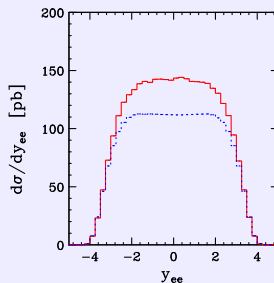
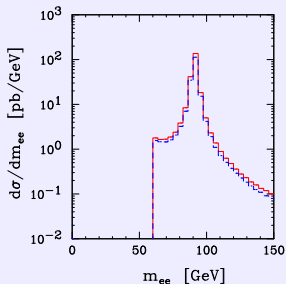
$$\begin{aligned} \sqrt{s} &= 7 \text{ TeV} & p_T(\ell^\pm) &> 1 \text{ GeV} & |\eta(\ell^\pm)| &< 5 \\ m_{\ell^+\ell^-} &> 60 \text{ GeV} & \mu_F = \mu_R &= M_Z \end{aligned}$$

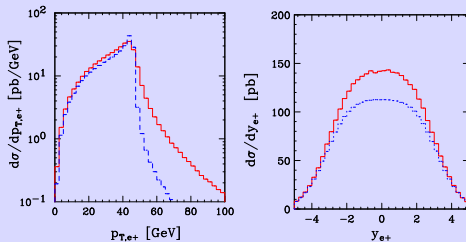
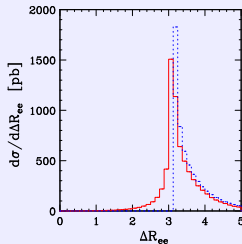
Results cross-checked with **MCFM**

The Cross section

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

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

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

The $p_t(\ell^+)$ and $y(\ell^+)$ distributionsThe $\Delta R_{\ell^+\ell^-}$ distribution

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

Parameters

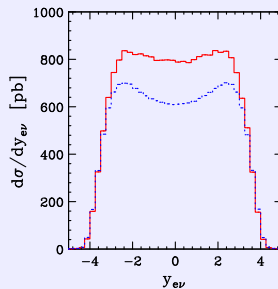
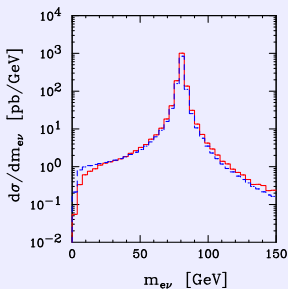
$$\begin{aligned} \sqrt{s} &= 7 \text{ TeV} & p_T(\ell^\pm) &> 1 \text{ GeV} \\ |\eta(\ell^\pm)| &< 5 & \mu_F = \mu_R &= M_W \end{aligned}$$

Results cross-checked with **MCFM**

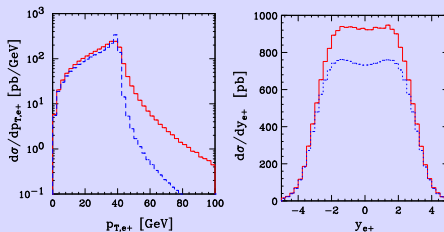
The Cross section

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

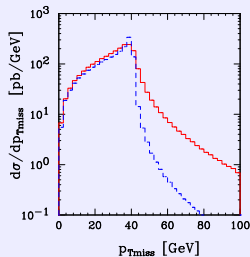
$$\sigma_{NLO} = 5670.6(1.6) \begin{array}{l} -85.8 \text{ (1.5\%)} \\ +107.5 \text{ (1.9\%)} \end{array} \text{ pb}$$

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

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



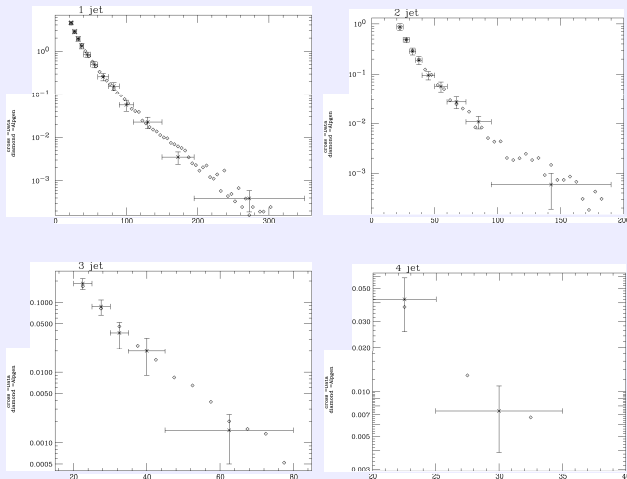
The $p_{t,miss}$ distribution



Tuning LO Monte Carlos with NLO calculations

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

ALPGEN vs Tevatron $W + j$ data



Conclusions

- ① **New** developments and **ideas** are important in the field of NLO calculations
 - I discussed a way to test/improve the numerical stability of OPP/Generalized Unitarity based computations
- ② I presented results obtained in the framework of the **HELAC-NLO** system
 - An NLO analysis of $t\bar{t}b\bar{b}$ Higgs signal vs $t\bar{t}b\bar{b}$ and $t\bar{t}j\bar{j}$ background
 - $pp \rightarrow Z\gamma^* \rightarrow e^+e^-$ at 7 TeV
 - $pp \rightarrow W^+ \rightarrow e^+\nu_e$ at 7 TeV
- ③ The final goal is delivering **public NLO codes** (matched with Parton shower) useful for analyzing the data