

1 Introduction

bla bla

2 Description of the codes

In this section we describe the different codes used in the comparisons.

2.1 EW codes

2.1.1 HORACE

The HORACE code will be described by the HORACE authors.

2.1.2 W/Z GRAD

2.1.3 DKM

2.2 QCD codes

2.2.1 Resbos

2.2.2 POWHEG

2.2.3 MC@NLO

2.2.4 Florence

2.3 EW+QCD recipes

3 Theoretical approximations

3.1 Common approximations for benchmarking

3.2 Inclusion of EW higher orders

3.3 Inclusion of QCD higher orders

4 Numerical set up

- 1.) For the numerical evaluation of the cross sections at the Tevatron ($\sqrt{s} = 1.96$ TeV) and the LHC ($\sqrt{s} = 10$ TeV) we choose the following set of Standard Model input parameters [1]:

$$\begin{aligned}
G_\mu &= 1.16637 \times 10^{-5} \text{ GeV}^{-2}, & \alpha &= 1/137.035999679, & \alpha_s &\equiv \alpha_s(M_Z^2) = 0.118 \\
M_Z &= 91.1876 \text{ GeV}, & \Gamma_Z &= 2.4952 \text{ GeV} \\
M_W &= 80.398 \text{ GeV}, & \Gamma_W &= 2.141 \text{ GeV} \\
M_H &= 115 \text{ GeV}, \\
m_e &= 0.51099891 \text{ MeV}, & m_\mu &= 0.1056583668 \text{ GeV}, & m_\tau &= 1.77684 \text{ GeV} \\
m_u &= 0.06983 \text{ GeV}, & m_c &= 1.2 \text{ GeV}, & m_t &= 171.2 \text{ GeV} \\
m_d &= 0.06984 \text{ GeV}, & m_s &= 0.15 \text{ GeV}, & m_b &= 4.6 \text{ GeV} \\
|V_{ud}| &= 0.975, & |V_{us}| &= 0.222 \\
|V_{cd}| &= 0.222, & |V_{cs}| &= 0.975 \\
|V_{cb}| &= |V_{ts}| = |V_{ub}| &= & |V_{td}| = |V_{tb}| = 0
\end{aligned} \tag{1}$$

We work in the constant width scheme and fix the weak mixing angle by $c_w = M_W/M_Z$, $s_w^2 = 1 - c_w^2$. The Z and W -boson decay widths given above are used in both the LO and NLO evaluations of the cross sections. The fermion masses only enter through loop contributions to the vector boson self energies and as regulators of the collinear singularities which arise in the calculation of the QED contribution. The value of the running electromagnetic coupling at the Z resonance is given by $\alpha(M_Z) = \alpha(0)/(1 - \Delta\alpha)$, $\Delta\alpha = \Delta\alpha_{lep} + \Delta\alpha_{top} + \Delta\alpha_{had}^{(5)}$. The light quark masses are chosen in such a way, that the value for the hadronic five-flavour contribution to the photon vacuum polarization, $\Delta\alpha_{had}^{(5)}(M_Z^2) = 0.027572$ [2], is recovered, which is derived from low-energy e^+e^- data with the help of dispersion relations.

- 2.) To compute the hadronic cross section we use the CTEQ6.6M set of parton distribution functions [3] and take the renormalization scale, μ_r , and the QCD factorization scale, μ_{QCD} , to be $\mu_r = \mu_{QCD} = M_{l\nu}$ in the W boson case and $\mu_r = \mu_{QCD} = M_{l+l-}$ in the Z boson case. The invariant masses, $M_{l\nu}$ and M_{l+l-} are calculated after applying the recombination procedure described in item 5 below.

All numerical evaluations require the subtraction of QED initial state collinear divergences, which is performed using the QED DIS scheme. It is defined analogously to the usual DIS [4] scheme used in QCD calculations, i.e. by requiring the same expression for the leading and next-to-leading order structure function F_2 in deep inelastic scattering, which is given by the sum of the quark

distributions. Since F_2 data are an important ingredient in extracting PDFs, the effect of the $\mathcal{O}(\alpha)$ QED corrections on the PDFs should be reduced in the QED DIS scheme¹. The QED factorization scale is chosen to be equal to the QCD factorization scale, $\mu_{QED} = \mu_{QCD}$.

- 3) We work in the on-shell renormalization scheme and use the following Z and W mass renormalization constants:

$$\delta M_Z^2 = \mathcal{R}e\left(\Sigma^Z(M_Z^2) - \frac{(\hat{\Sigma}^{\gamma Z}(M_Z^2))^2}{M_Z^2 + \hat{\Sigma}^\gamma(M_Z^2)}\right), \quad \delta M_W^2 = \mathcal{R}e\Sigma^W(M_W^2) \quad (2)$$

where $\Sigma^V(\hat{\Sigma}^V)$ denote the transverse parts of unrenormalized(renormalized) vector boson self energies. Using our choice for the EW input parameters one finds $\hat{\Sigma}^{\gamma Z}(M_Z^2) = (-165.16896, -49.3808933)$ and $\hat{\Sigma}^\gamma(M_Z^2) = (-494.132427, 134.841466)$ (please see [5, 6] for details). This choice of the Z mass renormalization constant is motivated by the LEP-I treatment and that LEP-I measurements of the Z mass may be used for detector calibration at hadron colliders.

For the sake of simplicity and to avoid additional sources of discrepancies in the tuned comparison we suggest to use the finestructure constant $\alpha(0)$ throughout in both the calculation of CC and NC cross sections. We will discuss the impact of using different EW input schemes in Section ??.

In the course of the calculation of the W observables the Kobayashi-Maskawa-mixing has been neglected, but the final result for each parton level process has been multiplied with the square of the corresponding physical matrix element V_{ij} . From a numerical point of view, this procedure does not significantly differ from a consideration of the Kobayashi-Maskawa-matrix in the renormalisation procedure as it has been pointed out in [7].

- 4.) We choose to evaluate the running of the strong coupling constant at the two-loop level, with five flavours, using as reference value $\alpha_s(M_Z) = 0.118$, which is consistent with the choice made in the PDF set CTEQ6.6. In Table 1 we provide $\alpha_s(\mu_r^2)$ for several choices of the QCD renormalization scale μ_r .
- 5.) The detector acceptance is simulated by imposing the following transverse momentum (p_T) and pseudo-rapidity (η) cuts:

$$p_T(\ell) > 25 \text{ GeV}, \quad |\eta(\ell)| < 1, \quad \ell = e, \mu, \quad (3)$$

¹The subtraction of the QED initial state collinear divergences is a necessary step to obtain a finite partonic cross section. The absence of a QED evolution in the PDF set CTEQ6.6 has little phenomenological impact on the distributions, much smaller than the change from the massless-charm parametrizations like MRST2004QED to the massive charm sets CTEQ6.6 or MSTW2008. See Section ?? for further discussion.

Table 1: Two-loop running of $\alpha_s(\mu_r^2)$.

μ_r [GeV]	α_s
91.1876	0.117981588
50	0.129786654
100	0.116361764
200	0.105509842
500	0.0939820525

$$p_T > 25 \text{ GeV}, \quad (4)$$

where p_T is the missing transverse momentum originating from the neutrino. These cuts approximately model the acceptance of the CDF II and DØ detectors at the Tevatron, and the ATLAS and CMS detectors at the LHC. In the case of γ/Z production, in addition to the separation cuts of Eq. 3 we apply a cut on the invariant mass of the final-state lepton pair of $M_{ll} > 50 \text{ GeV}$.

Ilija provided a C++ routine *simplesim.cc* (a fortran routine is work in progress) that provides a prescription for photon merging and deals with the MIP energy of the muon. This routine is only needed when calculating observables for the *calo* setup.

Here is Ilija's description of the routine:

The idea is to slice the central ($|\eta| < 1.1$) electromagnetic (CEM) calorimeter into 20 slices in η ($\Delta\eta = 0.11$) and 24 slices in ϕ and then: first check if the photons are not falling into a crack between towers (routine `cracks()`). For electrons we merge the photons to the electron if they are one tower away in η and same ϕ , where we check which of the two neighbouring towers the lepton is closer to. We don't do that for the towers at η of 0 because there is a crack between the two halves of the detector there. We knock out (not included in the recoil) a region of 7 towers around the electron, looking like this (knocked-out towers are 0):

```
1 0 0
0 0 0
1 0 0
```

where $\Delta\phi$ ($\Delta\eta$) is on the x -(y -)axis, and is defined such that the electron is always closest to the tower on the right. The remaining photons go to the recoil.

For Muons, the EM energy deposit is estimated from cosmic events, to which we add the underlying event (UE) and the photons. To decide which photons to add, see the explanation below.

Minimum ionising contribution:

The MIP contribution is estimated from cosmics and has an approximate Gaussian shape in $\text{Log}_{10}E_T$, so I fitted the distribution we use and give the parameters in `Mip::mip_avg` and `mip_sig`, the `mip_zero` is the fraction of events that leave no energy in CEM. I add to it the average UE contribution of 149 MeV (in our simulation this contribution has a η dependence).

Adding photons:

The function `MipE()` estimates these two contributions. Then you need to loop through the photons in the event and add their energy if: EM energy is in the same tower as muon, add its energy to the muon CEM energy. We regard a muon to be in two towers, if it is closer than 1.58 cm from the next tower in z direction (η). Then you use function `MipCutFail` with the total muon CEM energy and its p_T to see if it failed the MIP cut.

We knock out a region of 3 towers around the muon, looking like this (Towers with 0 are knocked out):

```
1 0 1
1 0 1
1 0 1
```

The rest of the photons go to recoil.

So, in practise you loop through photons, use the routines

`ElectronPhoton(electron4mom,photon4mom)` and

`MuonPhoton(muon4mom,photon4mom)` to see if the photons fall in a crack, need to be merged, knocked out or added to the recoil. The Muon CEM energy (without the photons) is estimated using `MipE()`. If the muon with this MIP energy with photon contribution fails the MIP cut is checked using `MipCutFail(...)`.

The simulation of the leakage of the showers into the hadronic calorimeter and the energy losses in the coil have not been simulated, as they require more detailed parameterisations. I have also not added the nonlinear response parameterisation of the calorimeter, since it depends on the modelling of the leakage.

- 6.) Since we consider predictions inclusive with respect to QCD radiation, we do not impose any jet definition.

5 Tuning

5.1 Total cross sections

code	LO no cuts	LO cuts	NLO-QCD no cuts	NLO-QCD cuts	NLO-EW no cuts	NLO-EW cuts
HORACE	981.1(2)	344.28(3)				
WGRAD						
DKM						
POWHEG-w	978.43(4)		1186.55(5)	377.8(1)		
Florence		344.1(1)		382.1(2)		
MC@NLO						
RESBOS						

Table 2: W cross sections at the Tevatron.

code	LO no cuts	LO cuts	NLO-QCD no cuts	NLO-QCD cuts	NLO-EW no cuts	NLO-EW cuts
HORACE	196.3(6)	37.995(4)				
ZGRAD						
DKM						
POWHEG-z		37.28(4)	581.5(1)	45.28(6)		
Florence		37.97(1)		45.53(2)		
MC@NLO						
RESBOS						

Table 3: Z cross sections at the Tevatron.

5.2 Distributions

I do not know if we can define a precise and sensible way of tuning the codes by comparing the gauge boson transverse momentum distributions and fixing the extra parameters (resummation scale, non perturbative parameters).

code	LO no cuts	LO cuts	NLO-QCD no cuts	NLO-QCD cuts	NLO-EW no cuts	NLO-EW cuts
HORACE						
WGRAD						
DKM						
POWHEG-w						
Florence						
MC@NLO						
RESBOS						

Table 4: W cross sections at the LHC 10 TeV.

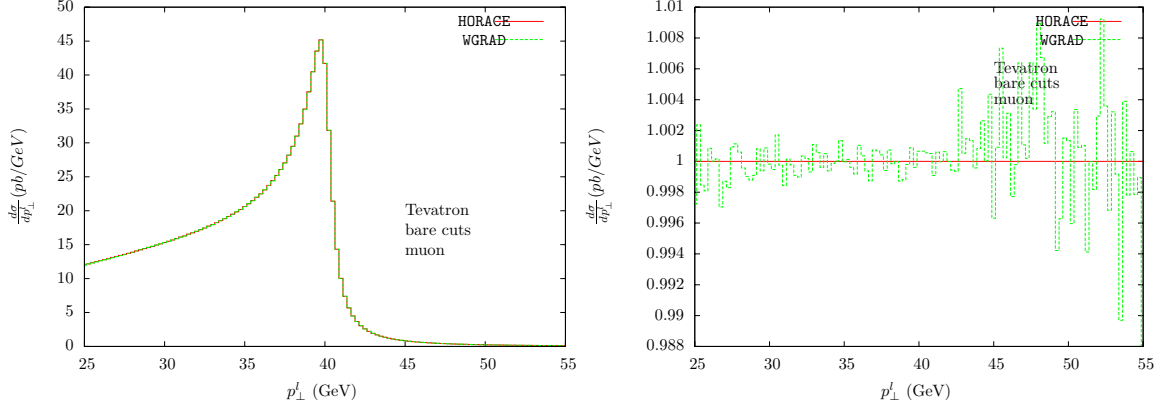
code	LO no cuts	LO cuts	NLO-QCD no cuts	NLO-QCD cuts	NLO-EW no cuts	NLO-EW cuts
HORACE						
ZGRAD						
DKM						
POWHEG-z						
Florence						
MC@NLO						
RESBOS						

Table 5: Z cross sections at the LHC 10 TeV.

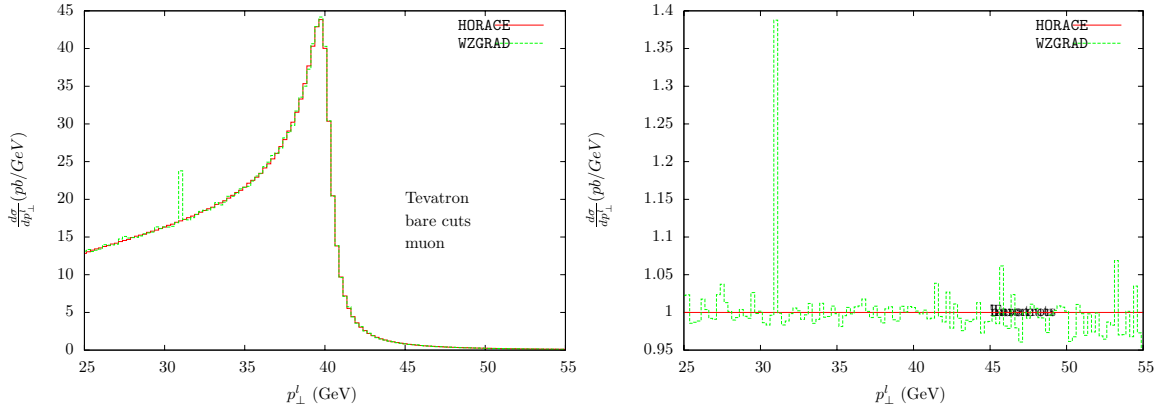
6 W Predictions

6.1 Lepton transverse momentum

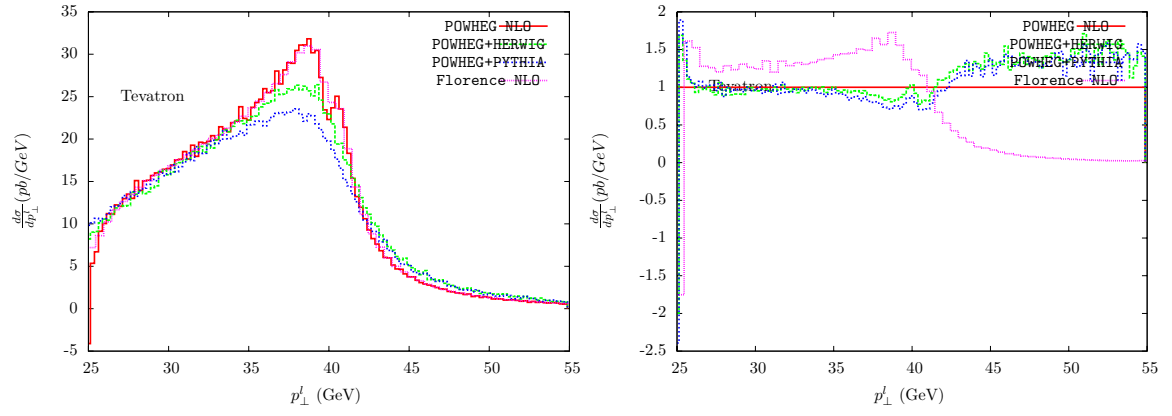
6.1.1 LO



6.1.2 EW



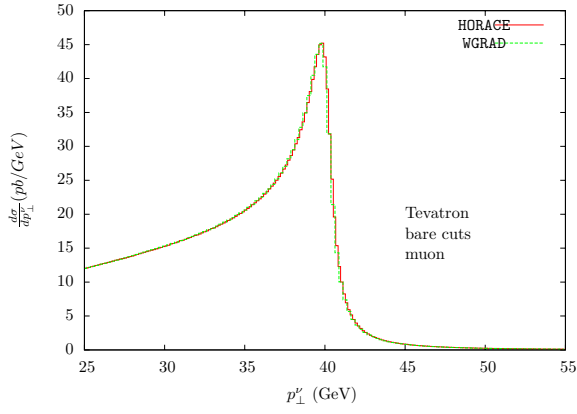
6.1.3 QCD



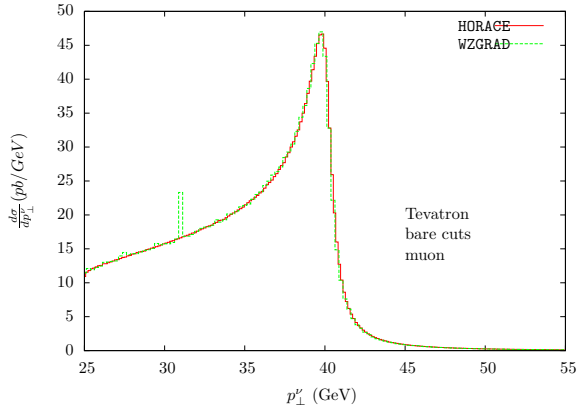
6.1.4 EW+QCD

6.2 Missing transverse momentum

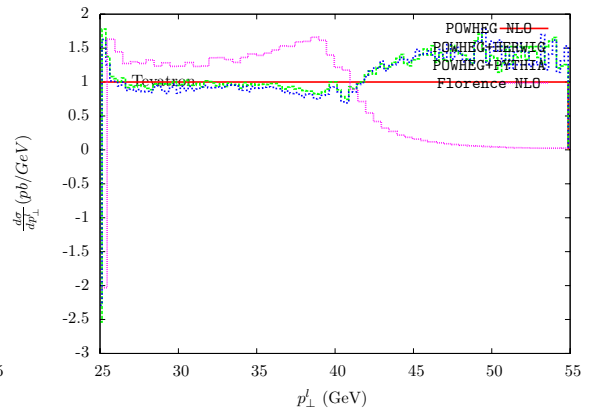
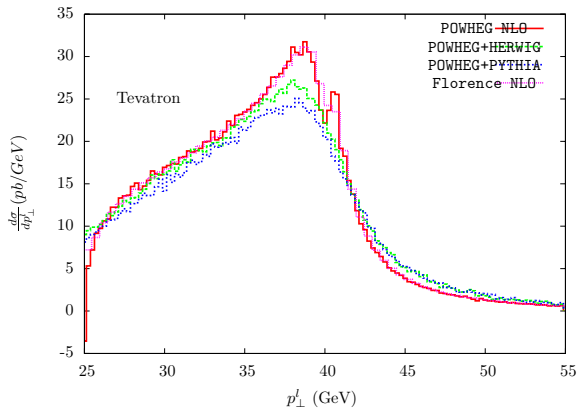
6.2.1 LO



6.2.2 EW



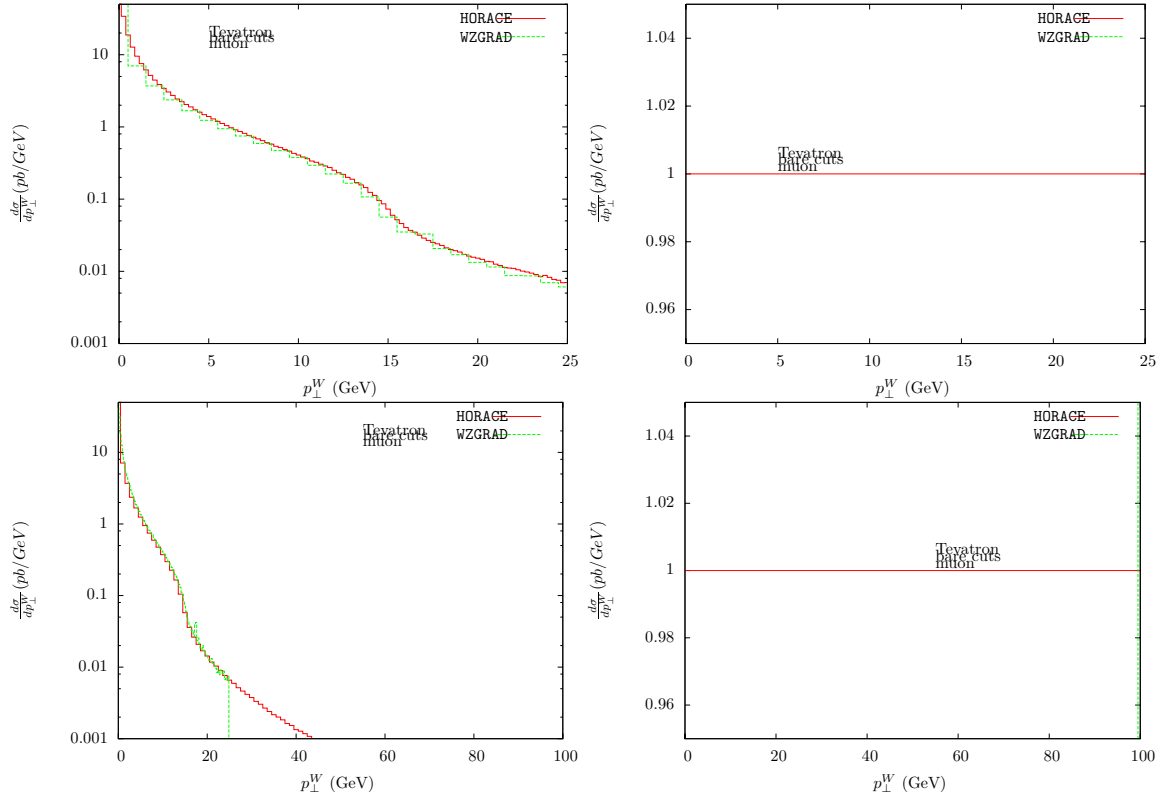
6.2.3 QCD



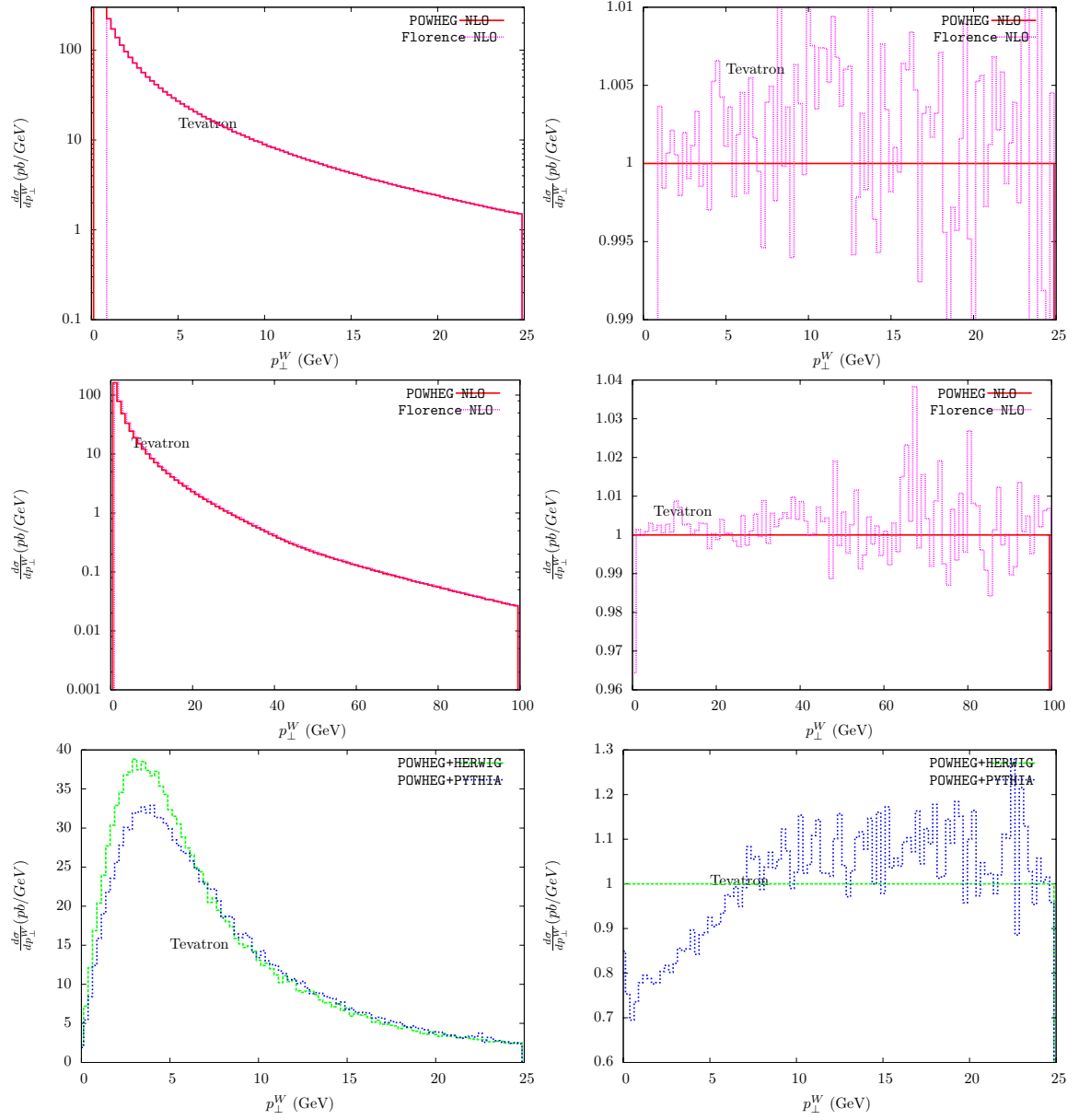
6.2.4 EW+QCD

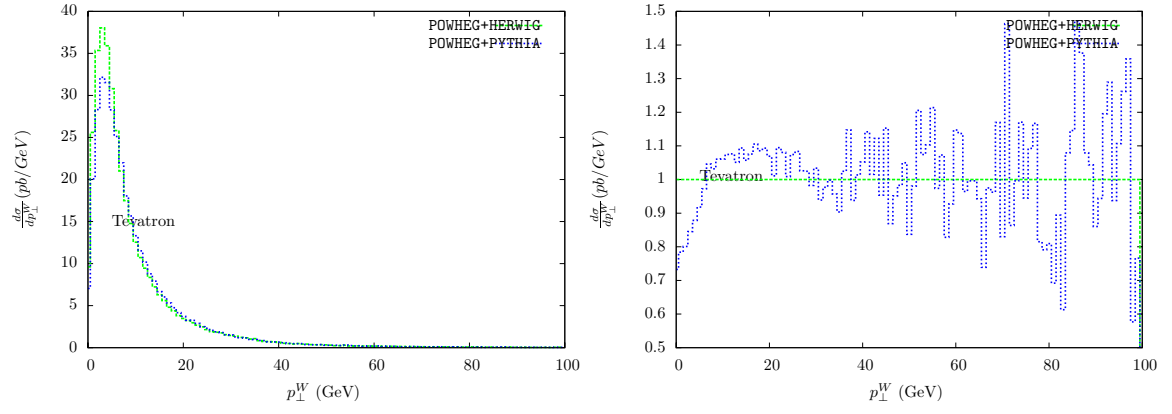
6.3 W transverse momentum

6.3.1 EW



6.3.2 QCD

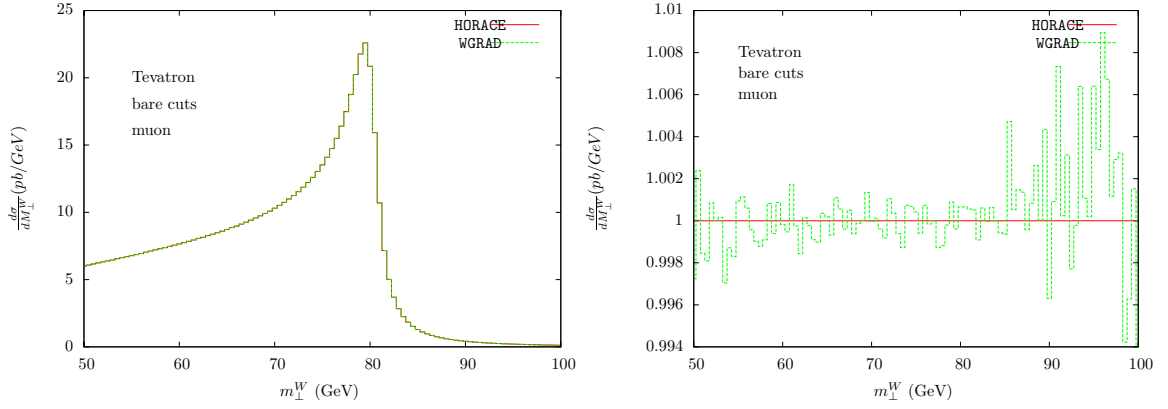




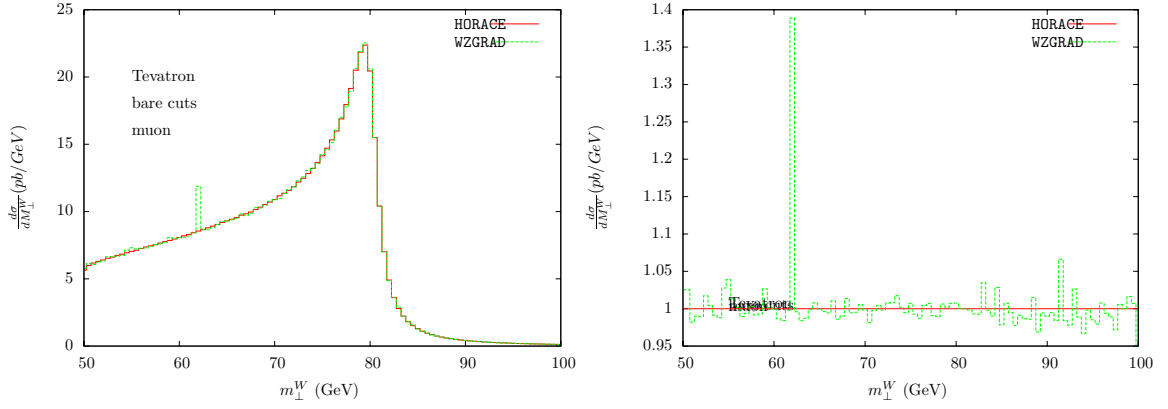
6.3.3 EW+QCD

6.4 W transverse mass

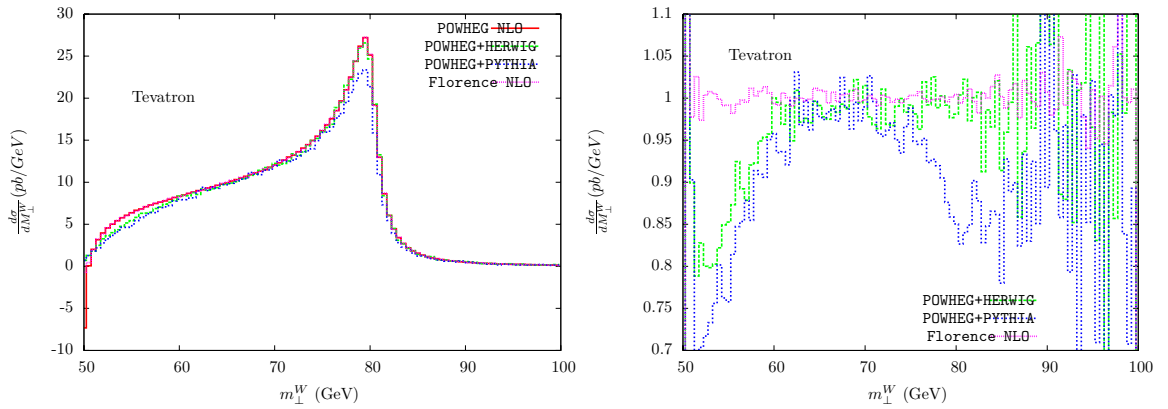
6.4.1 LO



6.4.2 EW



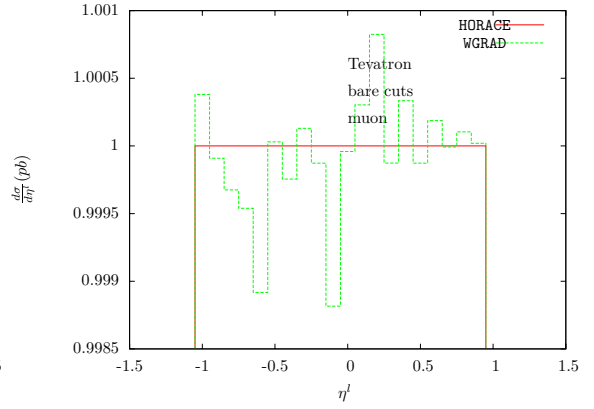
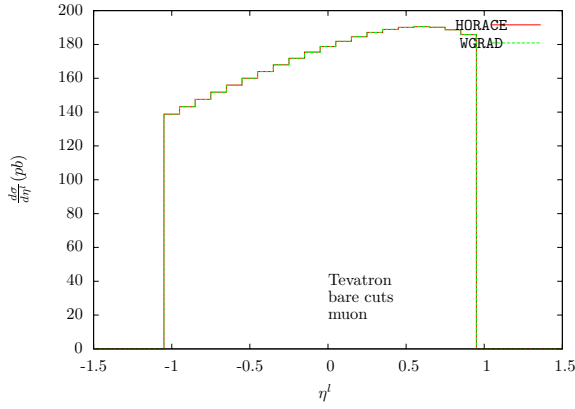
6.4.3 QCD



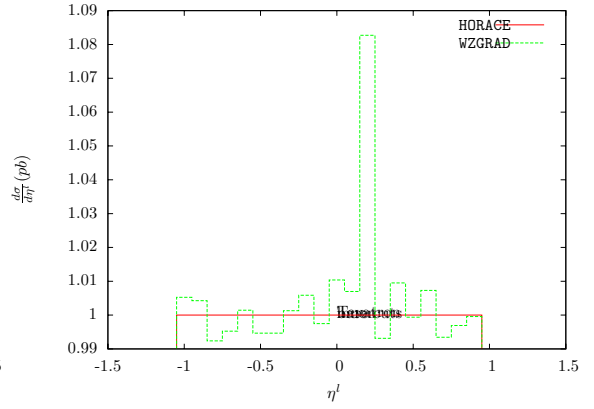
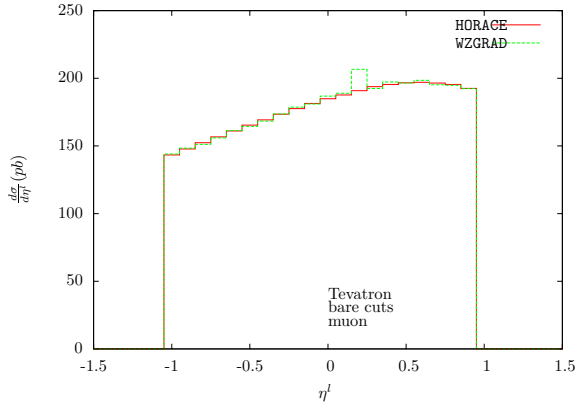
6.4.4 EW+QCD

6.5 Lepton pseudo-rapidity

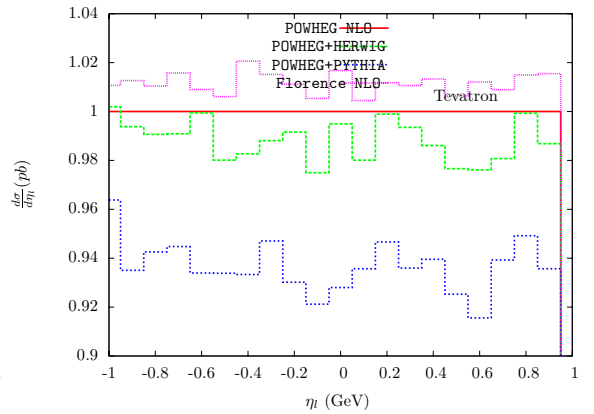
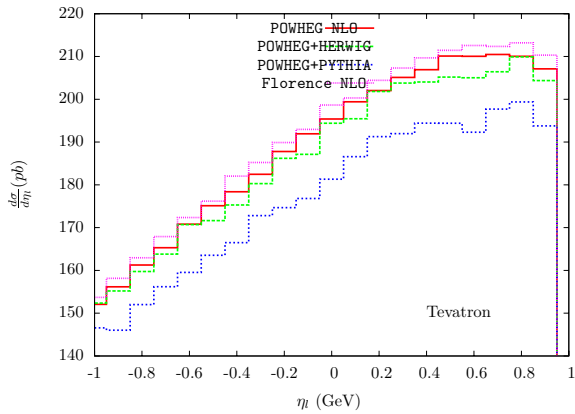
6.5.1 LO



6.5.2 EW

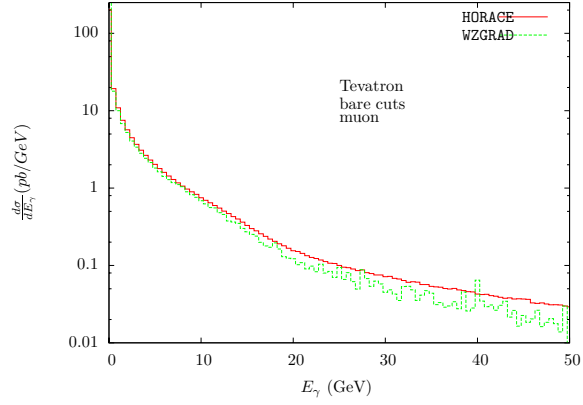


6.5.3 QCD

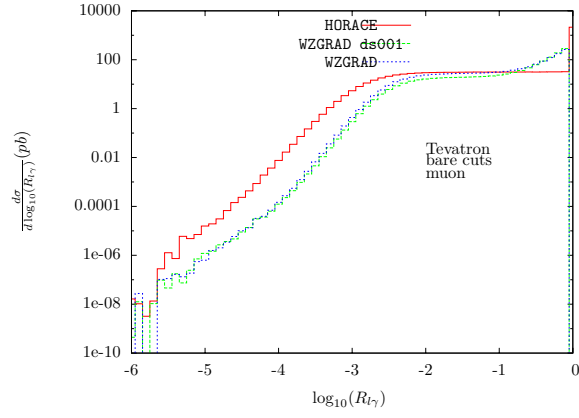


6.5.4 EW+QCD

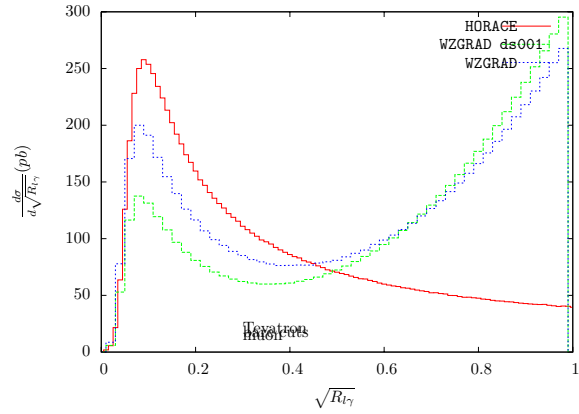
6.6 Energy spectrum hardest photon



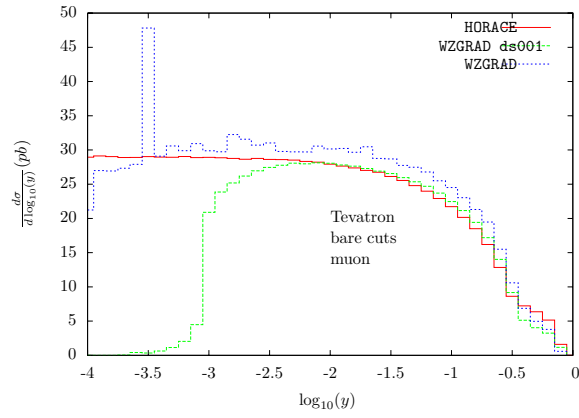
6.7 $\log R_{l\gamma}$ hardest photon



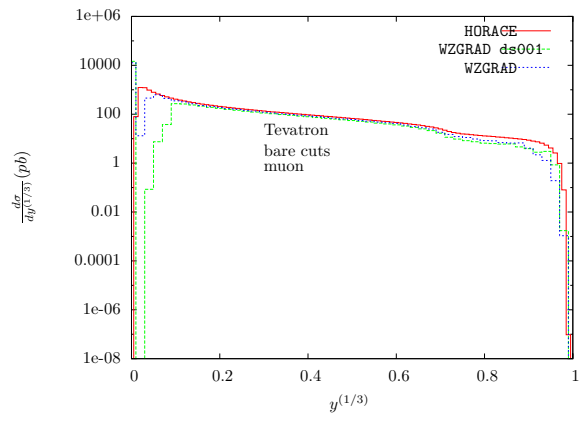
6.8 $\sqrt{R_{l\gamma}}$ hardest photon



6.9 $\log y$ hardest photon



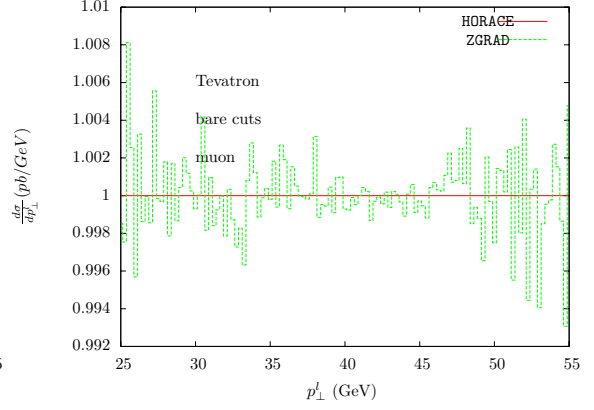
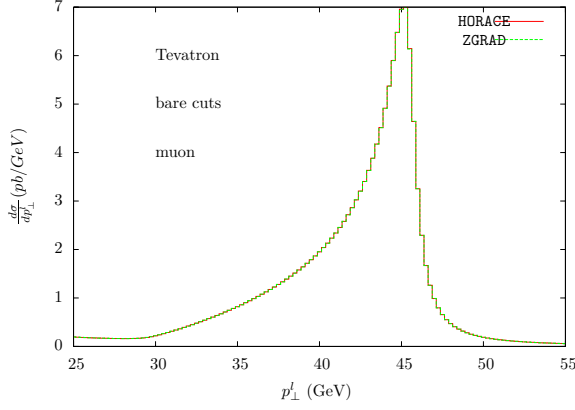
6.10 $y^{1/3}$ hardest photon



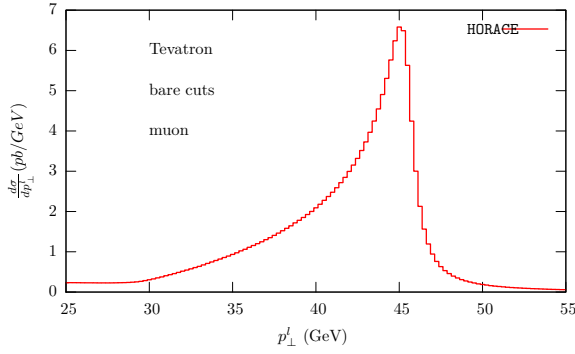
7 Z Predictions

7.1 Lepton transverse momentum

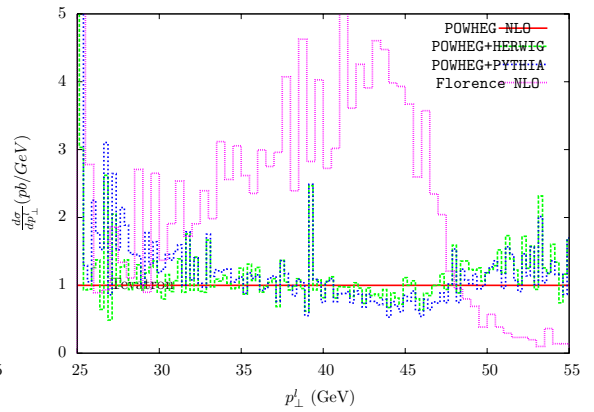
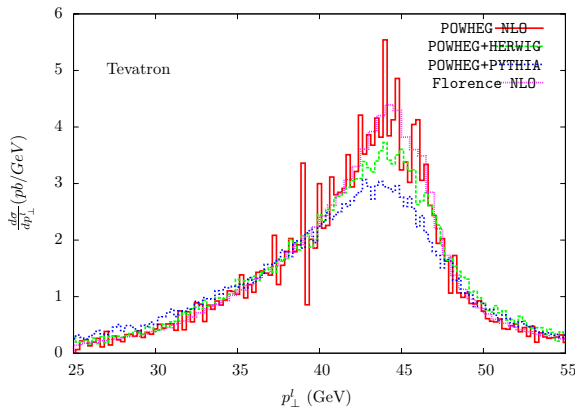
7.1.1 LO



7.1.2 EW



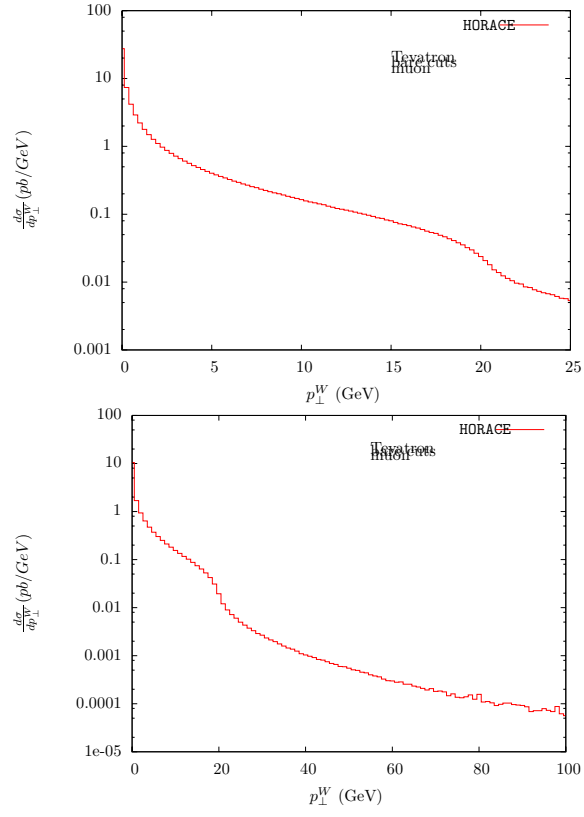
7.1.3 QCD



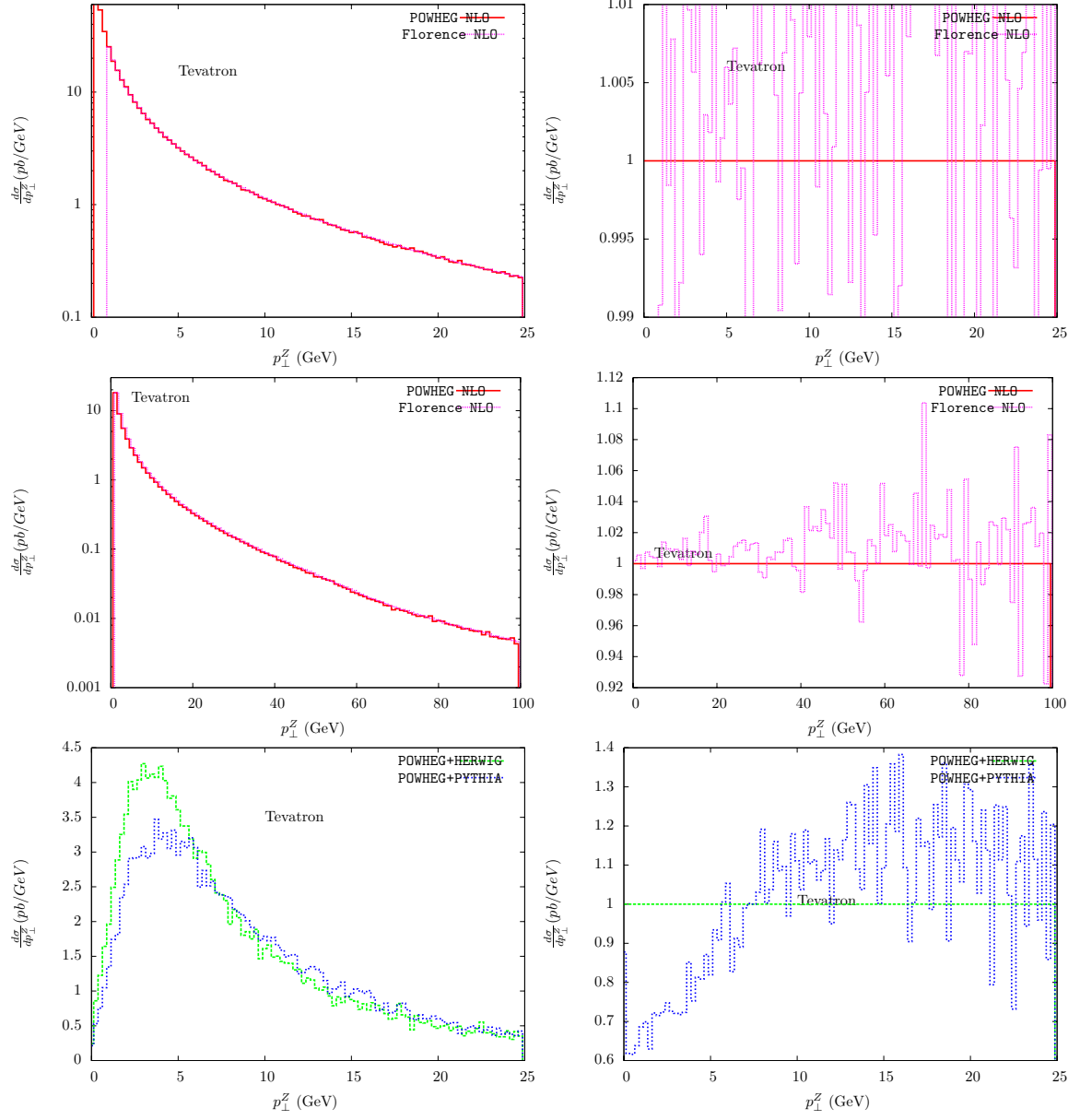
7.1.4 EW+QCD

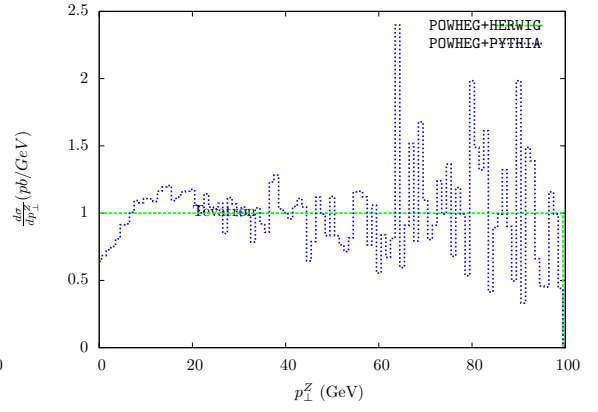
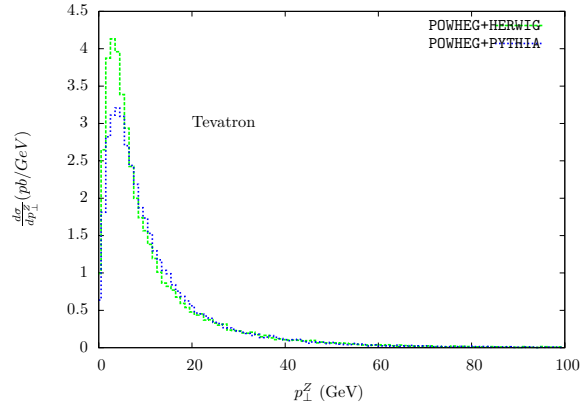
7.2 Z transverse momentum

7.2.1 EW



7.2.2 QCD

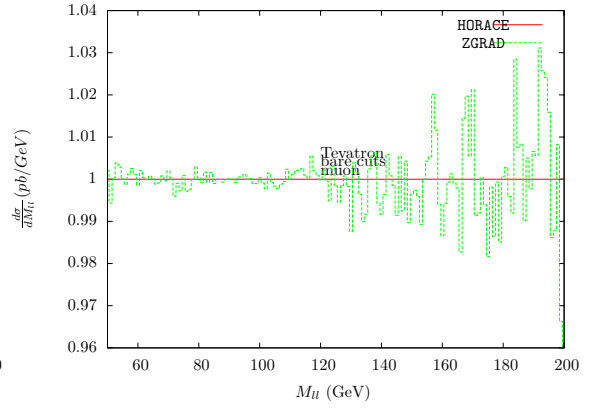
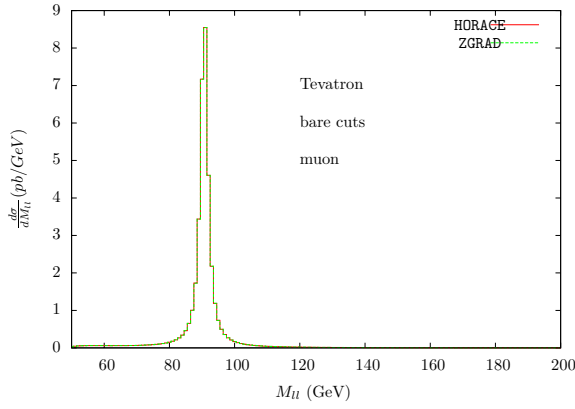




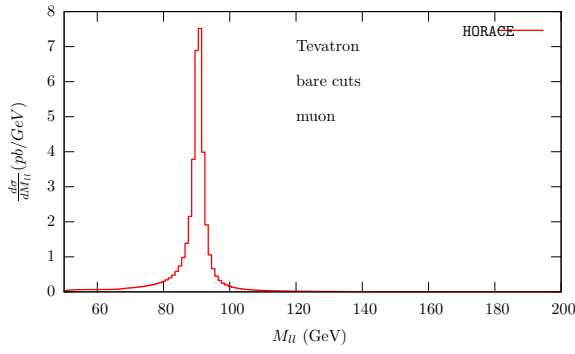
7.2.3 EW+QCD

7.3 Z invariant mass

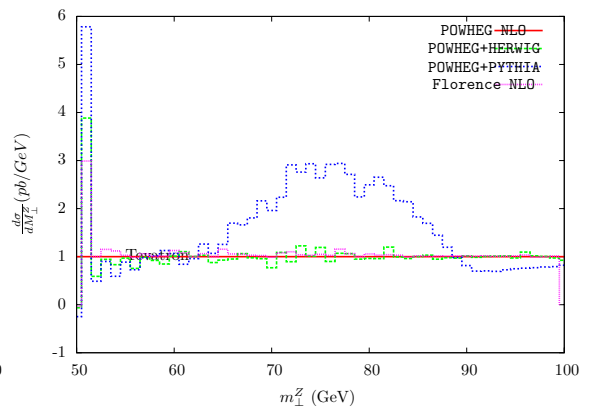
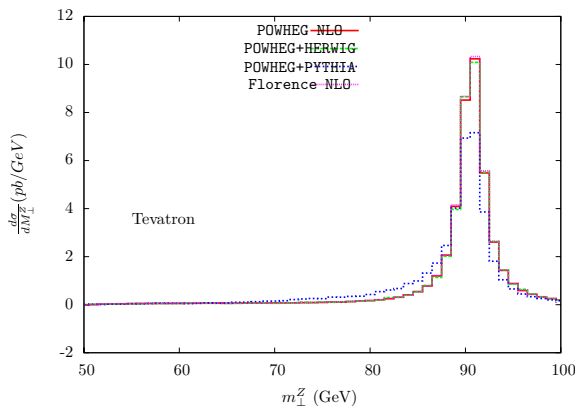
7.3.1 LO



7.3.2 EW



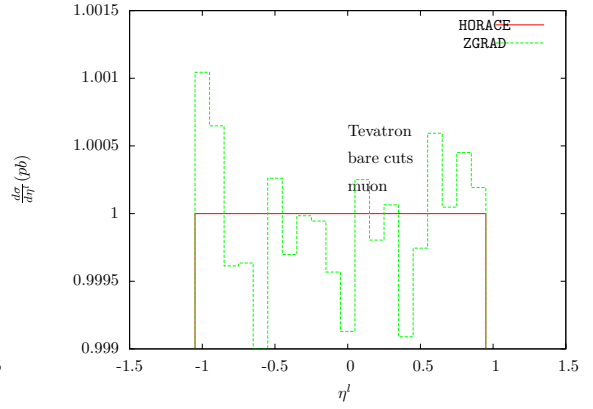
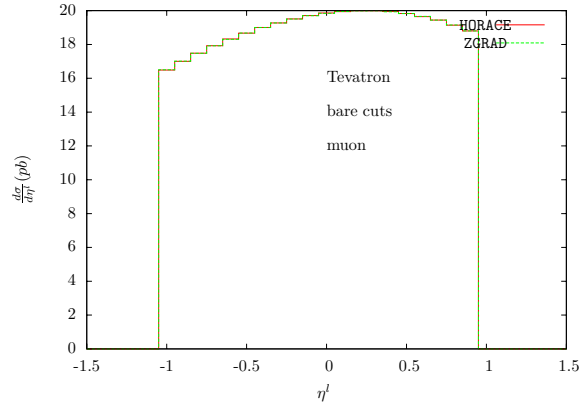
7.3.3 QCD



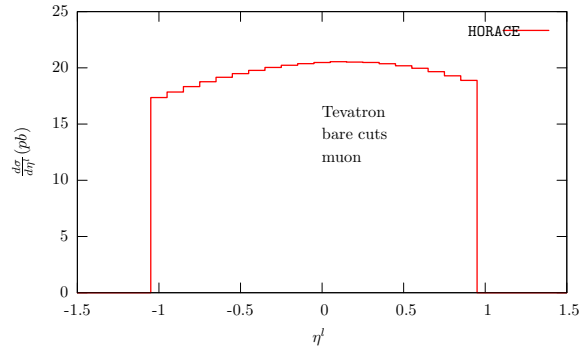
7.3.4 EW+QCD

7.4 Lepton pseudo-rapidity

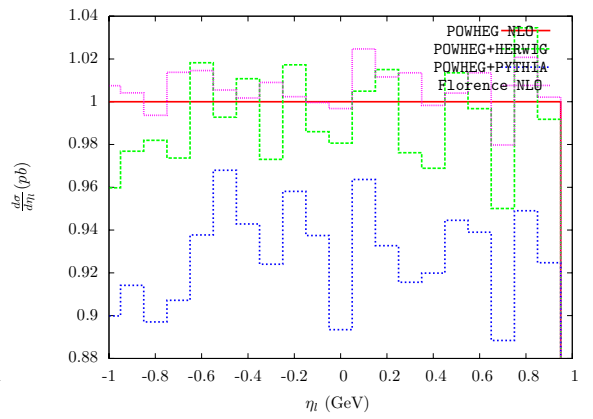
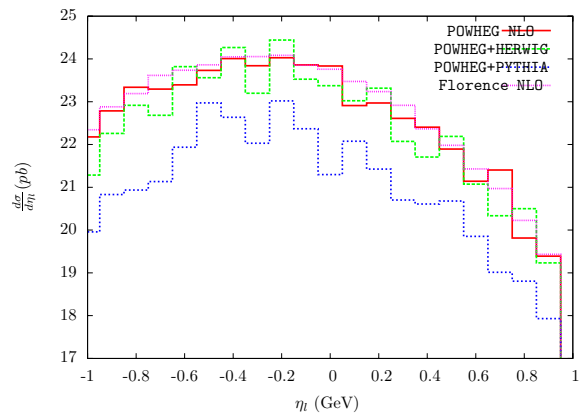
7.4.1 LO



7.4.2 EW



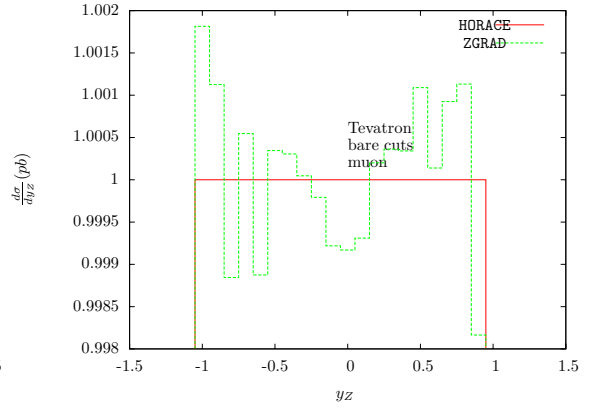
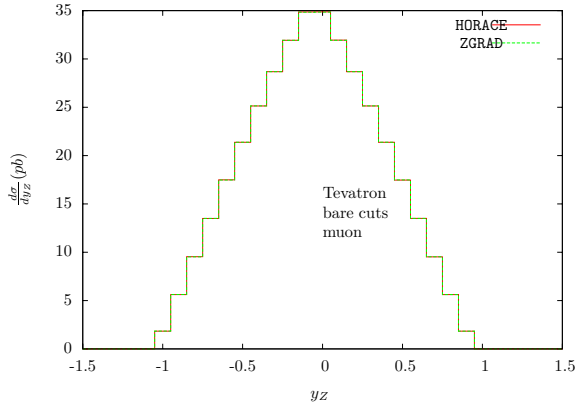
7.4.3 QCD



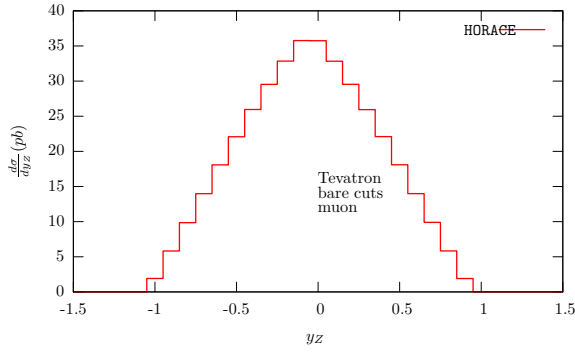
7.4.4 EW+QCD

7.5 Z rapidity

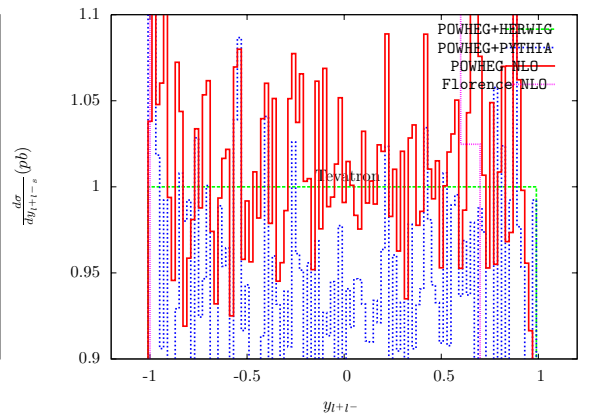
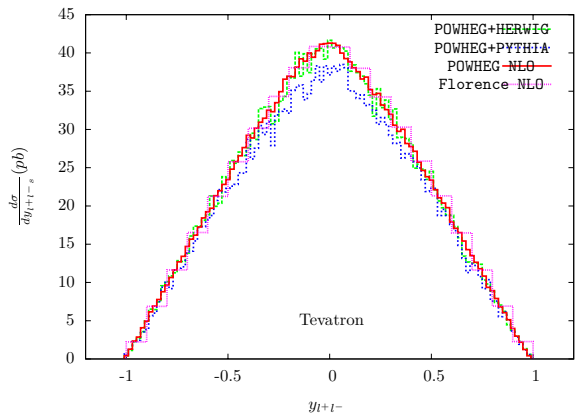
7.5.1 LO



7.5.2 EW



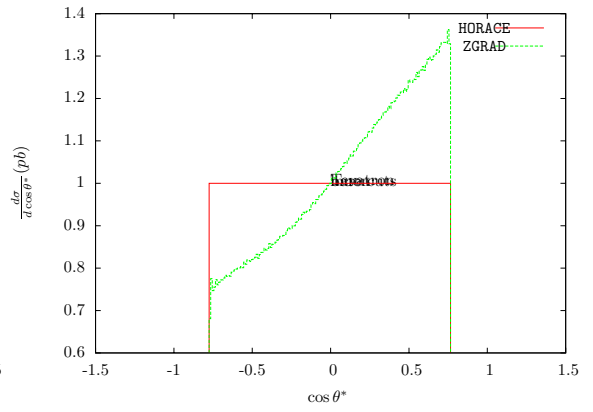
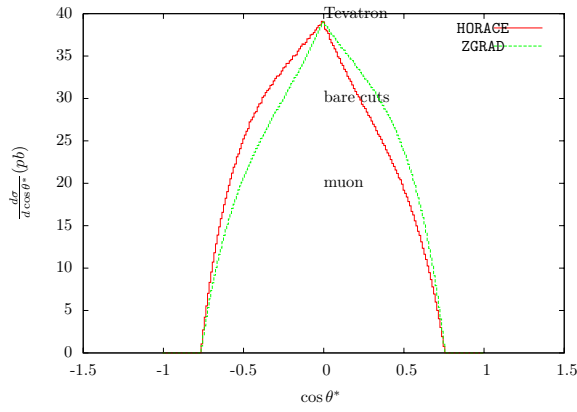
7.5.3 QCD



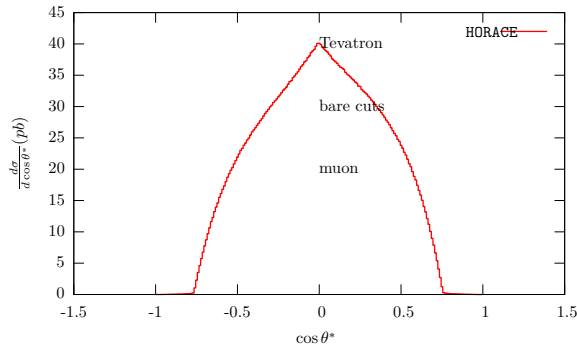
7.5.4 EW+QCD

7.6 $Z \cos \theta^*$

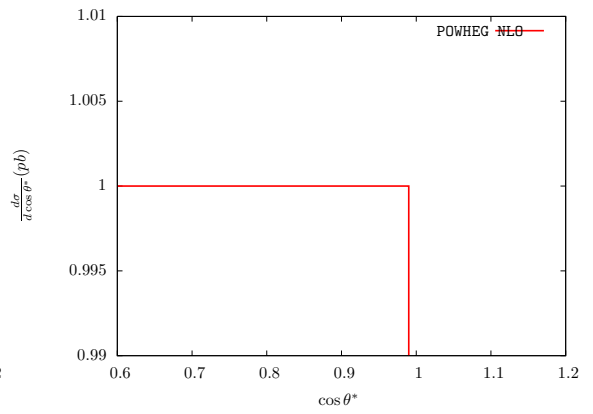
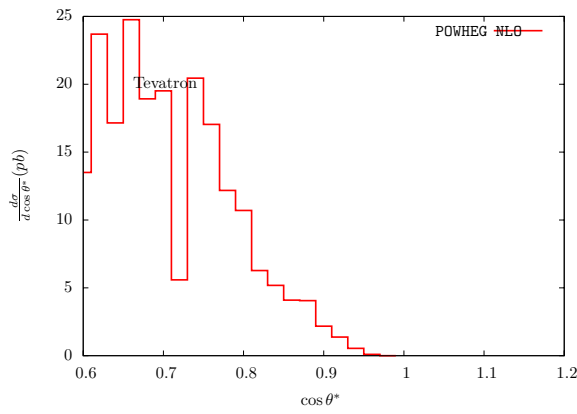
7.6.1 LO



7.6.2 EW



7.6.3 QCD

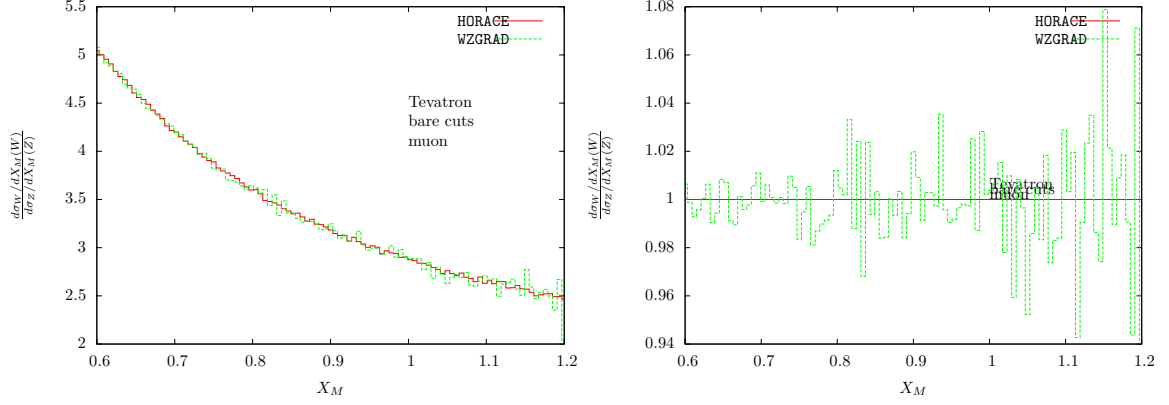


7.6.4 EW+QCD

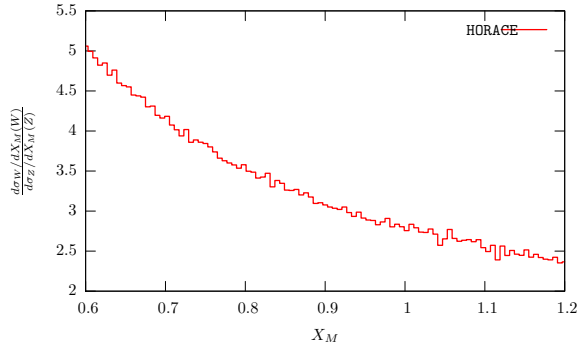
8 Prediction of W/Z ratios

8.1 Lepton transverse momentum

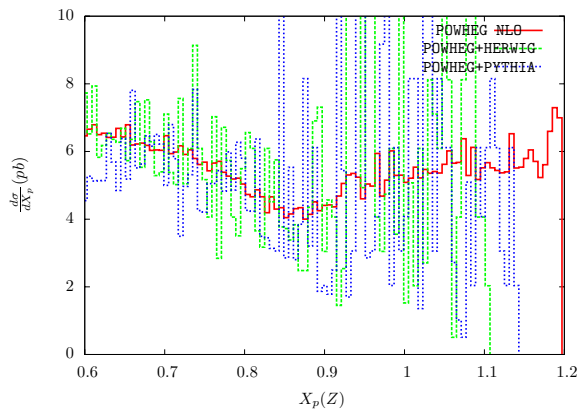
8.1.1 LO



8.1.2 EW



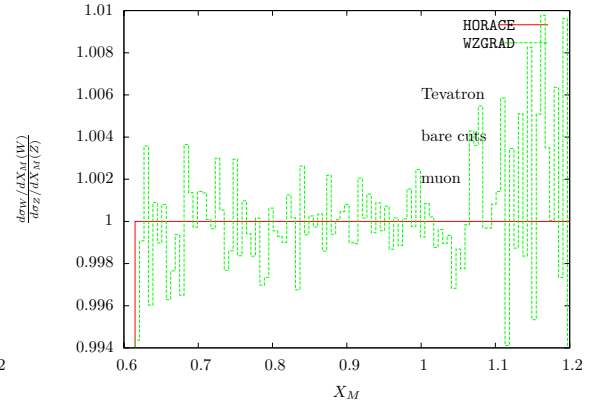
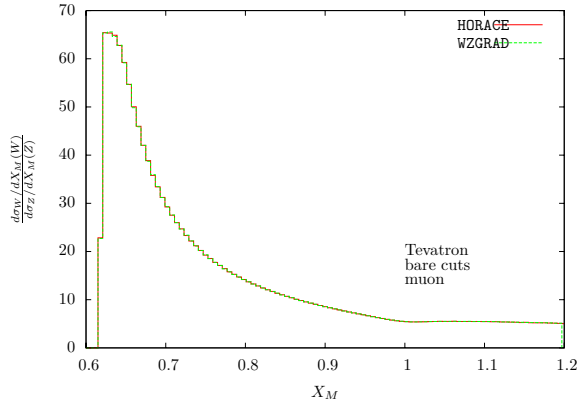
8.1.3 QCD



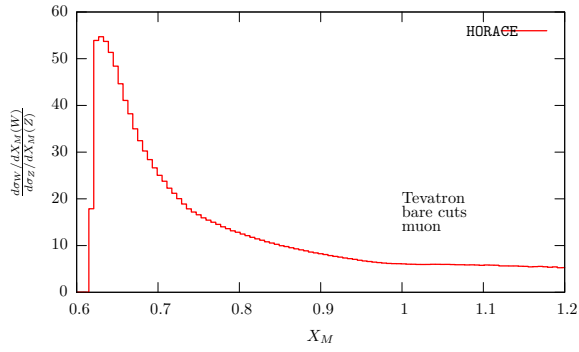
8.1.4 EW+QCD

8.2 Transverse masses

8.2.1 LO



8.2.2 EW



8.2.3 QCD

8.2.4 EW+QCD

9 Conclusions

smaller errors

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