Theoretical Uncertainties in Vector Boson Production at the LHC

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PHENO 2009 – Madison, Wisconsin – May 12, 2009

W and Z Production at the LHC

Vector Boson Production will be an important process at the LHC:

- Standard candle for the precision luminosity measurement (1%).
- Precision EW parameter measurements
- Constraints on PDFs via Z/W rapidity.
- Important for detector calibration.
- New physics searches: Z' predicted by various SM extensions – few TeV range accessible.

Precision Event Generator

- An event generator is desired at the 1% precision level.
- The present best event generators incorporate NLO QCD with a parton shower: MC@NLO or POWHEG.
- NNLO QCD is available, but not interfaced to a shower: Vrap (Anastasiou, Dixon, Melnikov, Petriello) and FEWZ (Melnikov, Petriello).
- Electroweak corrections cannot be neglected.
  HORACE (Carloni-Calame)

Theoretical Uncertainty Studies

- We decided to study the state of the art programs to determine how well Z production could really be calculated at this time.

  [Adams, Halyo, Yost: JHEP 05 (2008) 062]
- The results can be useful in selecting experimental cuts to minimize systematic errors, as well as in identifying the most fruitful course for improving the precision.
- The analysis was extended to W production.

  [Adams, Halyo, Yost, Zhu: JHEP 09 (2008) 133]

Theoretical Uncertainty Studies

- These studies focused on three areas:
  - Electroweak Corrections
  - NNLO QCD
  - Parton Distribution Functions

- The basic generators used were HERWIG 6.5 and MC@NLO.
- Electroweak corrections were evaluated using PHOTOS and HORACE 3.1.
- NNLO QCD was calculated using FEWZ.

Electroweak Effects

- Since $\alpha \approx \alpha_s^2$ at LHC energies, NLO QED naively should enter at a comparable level to NNLO QCD.

- But EW corrections are enhanced by big logs (generically $\log^n(s/m^2)$) which increase at high energy: NLO QED and QCD can be comparable.

- This especially affects new physics searches (Z’, …) in the TeV range, where the W and Z begin to look increasingly “massless”.

Electroweak Effects

- We calculated the EW effects in HORACE3.1
  - Event Generator with LO QCD + Shower and $\mathcal{O}(\alpha)$ EW + FSR photon shower.
- We also compared PHOTOS (Wąs)
  - Add-on program that generates photon radiation from charged final-state particles.
- What is the best way to incorporate mixed QCD/EW effects?
  - PHOTOS can be run with NLO QCD.
  - HORACE cannot, but has more complete EW.

Cut Selections

- The comparisons were made for sets of experimental cuts typical of those that might be used in a Luminosity measurement, or precision W/Z parameter measurements.
- We are interested not just in the total cross section, but also in the detector acceptances for these cuts. The error estimates for acceptances and total cross sections can differ greatly.

$$\text{Acceptance} = \sigma(\text{cut})/\sigma(\text{total})$$

σ(total) already includes basic “generator-level” cuts, such as a lower bound on M_{ll} in Z production to remove the photon-dominated region.

Cut Selections: EW Calculation

We used the following cuts:

$$q\bar{q} \rightarrow Z/\gamma \rightarrow l\bar{l}$$

$$\eta = \log\cot\left(\frac{\theta}{2}\right)$$

CUT	M_{ll}	p_{Tl}	$\|\eta_l\|$
Loose	> 40 GeV	> 5 GeV	< 50
Tight	40 < M_{ll} < 140 GeV	> 20 GeV	< 2

$$q\bar{q}' \rightarrow W^{\pm} \rightarrow l^{\pm}\nu$$

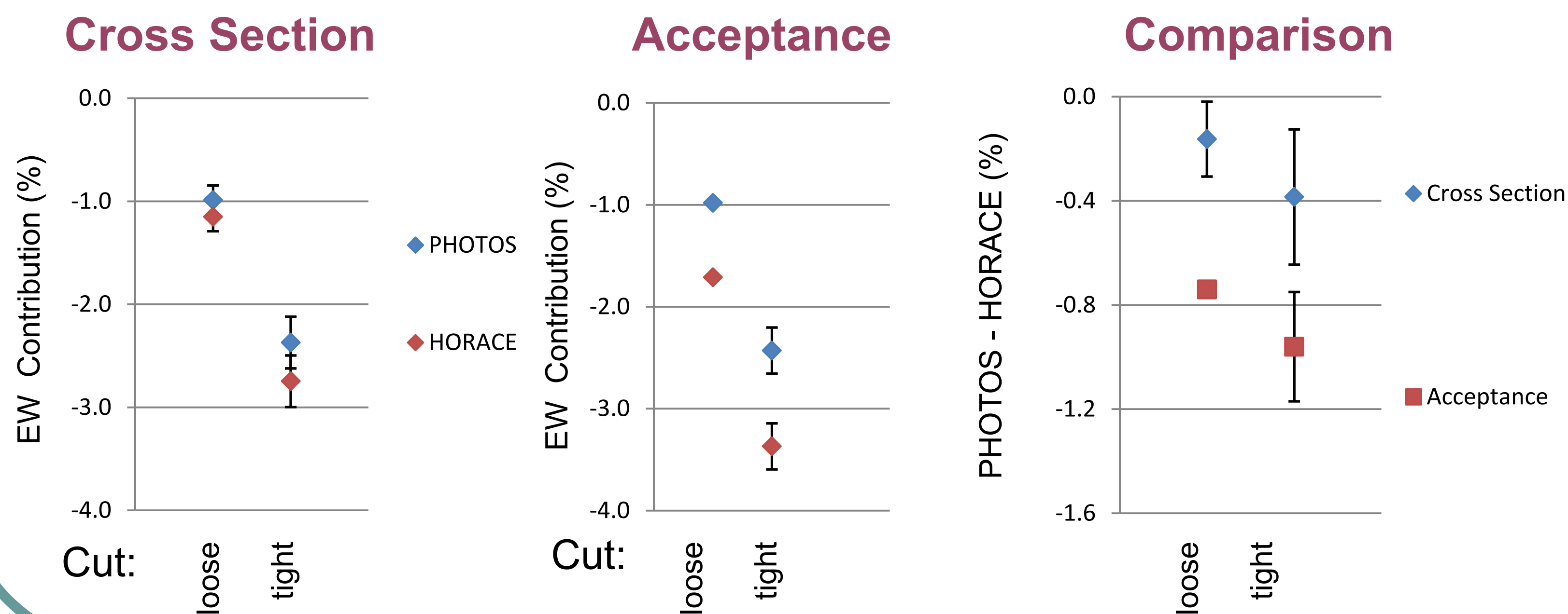
CUT	p_{Tl}	$p_{T\nu}$	$\|\eta_l\|$
Basic	> 25 GeV	> 20 GeV	< 1
Larger η	> 25 GeV	> 20 GeV	1 < $\|\eta_l\|$ < 2.2
Higher $p_{T\nu}$	> 25 GeV	> 30 GeV	< 1

Electroweak Effects: Z Production

Compare HORACE and PHOTOS in Z Production:

- EW correction in σ: 1 – 3%. Difference: 0.2 – 0.4%
- Recommendation: Use MC@NLO + PHOTOS.

Fractional EW Contribution in Z Production

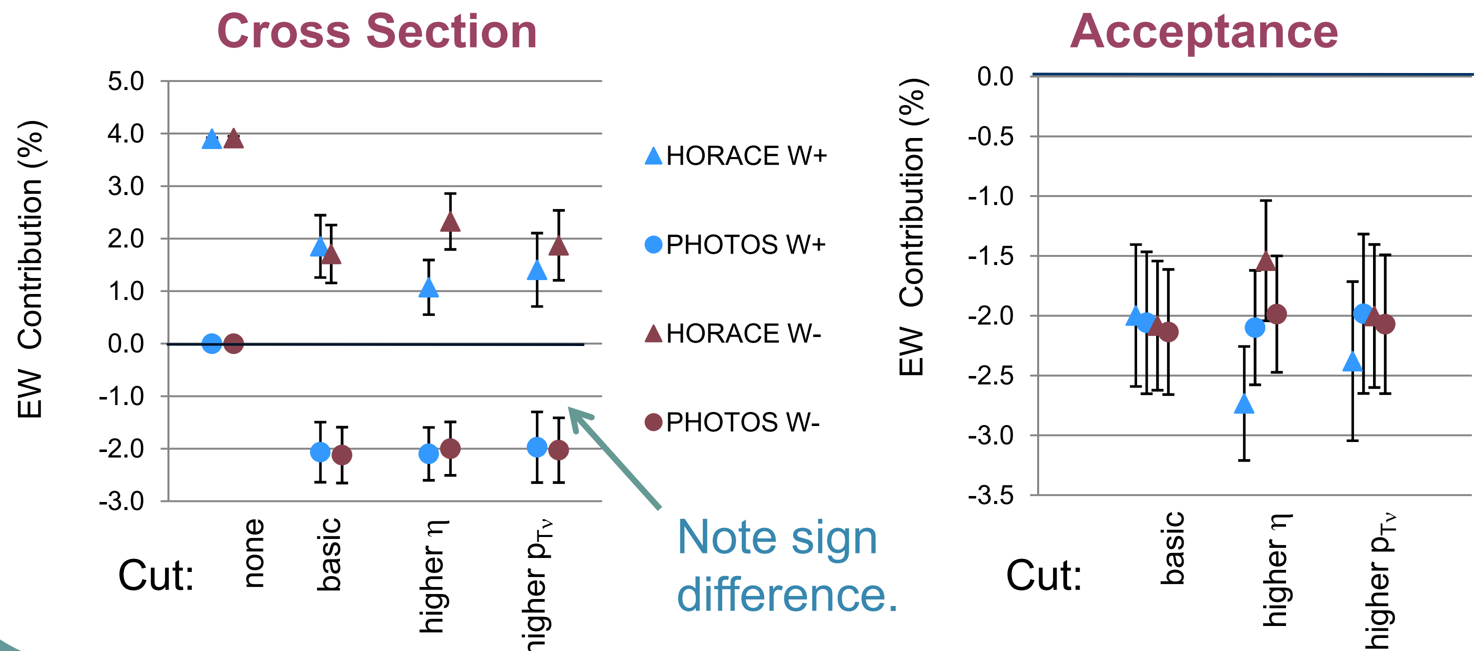


Electroweak Effects: W Production

Compare HORACE and PHOTOS for W Production:

- Using PHOTOS for W production is not as well motivated: the W can radiate also. Use HORACE if EW is important.

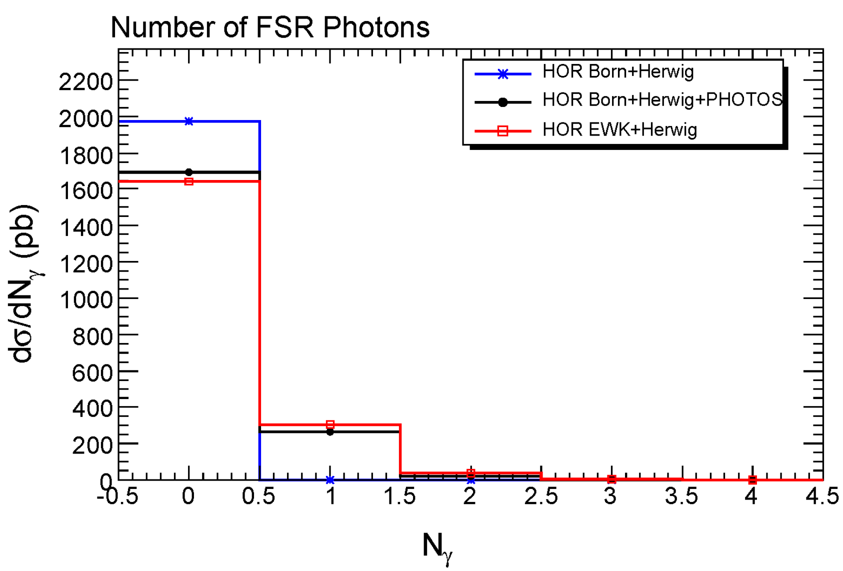
Fractional EW Contribution in W Production



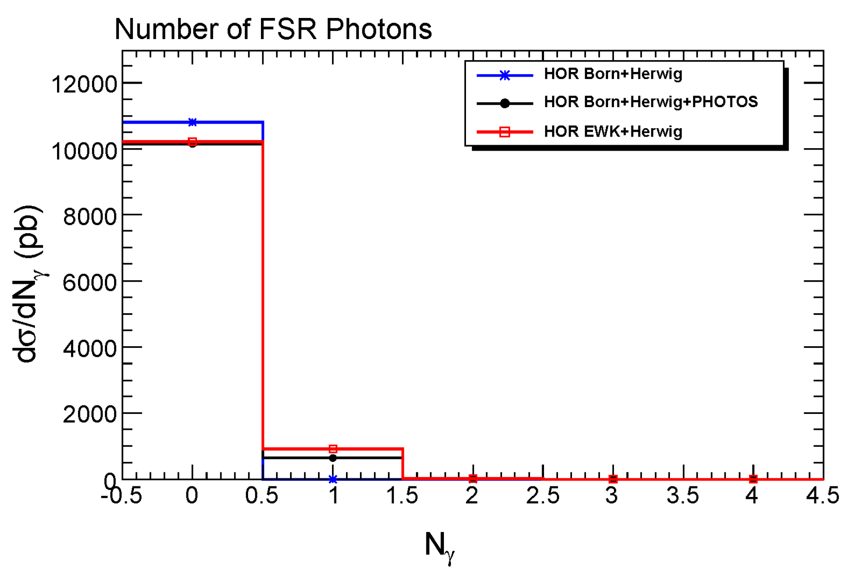
Number of Photons Generated

Comparison of the numbers of photons gnerated by PHOTOS (black) or HORACE (red).

[Born level (no photon generation) = blue]



Z Production



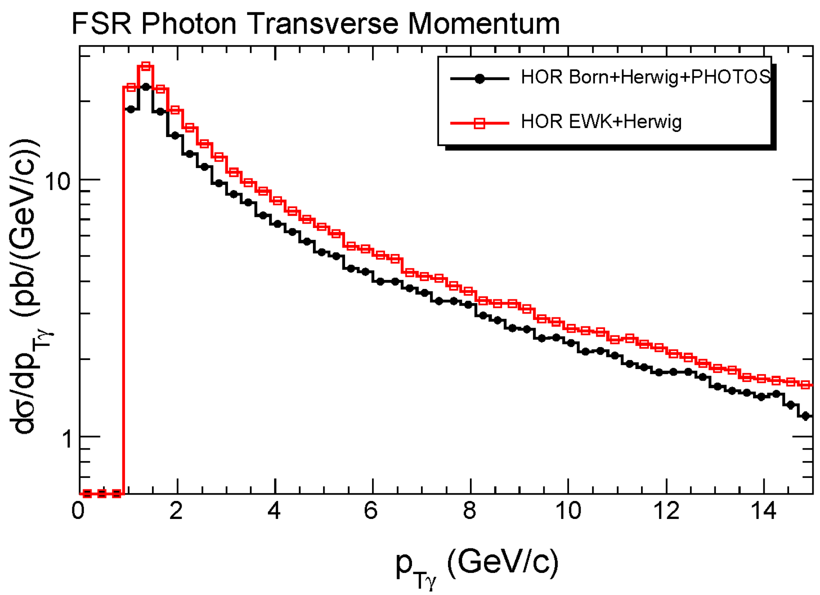
W^+ Production

Total Photon P_T

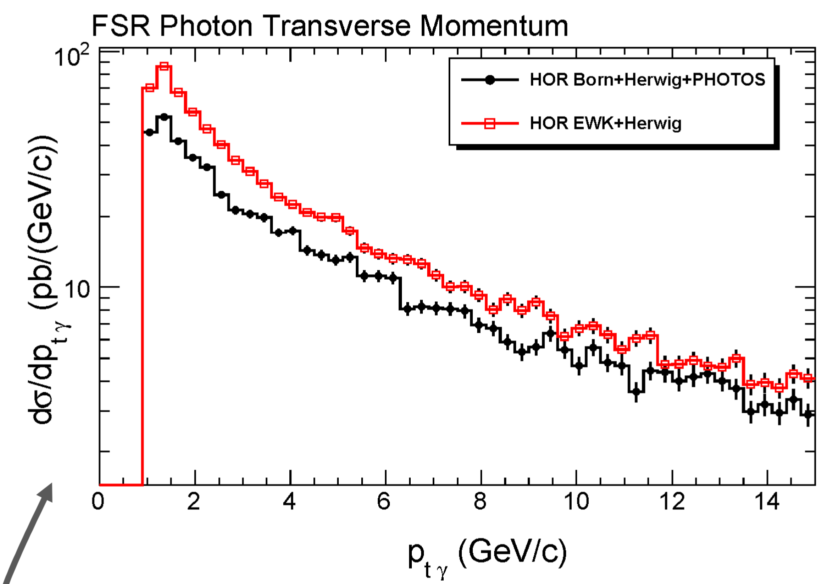
Comparison of photon P_T in PHOTOS and HORACE:

- HORACE gives slightly more photon P_T.

Z Production



W+ Production



Larger scale

Cut Selections: NNLO Calculation

We used the following cuts: (generator cut: M_{ll}> 40GeV)

$$q\bar{q} \to Z / \gamma \to l\bar{l}$$

11.5° – 25.2°

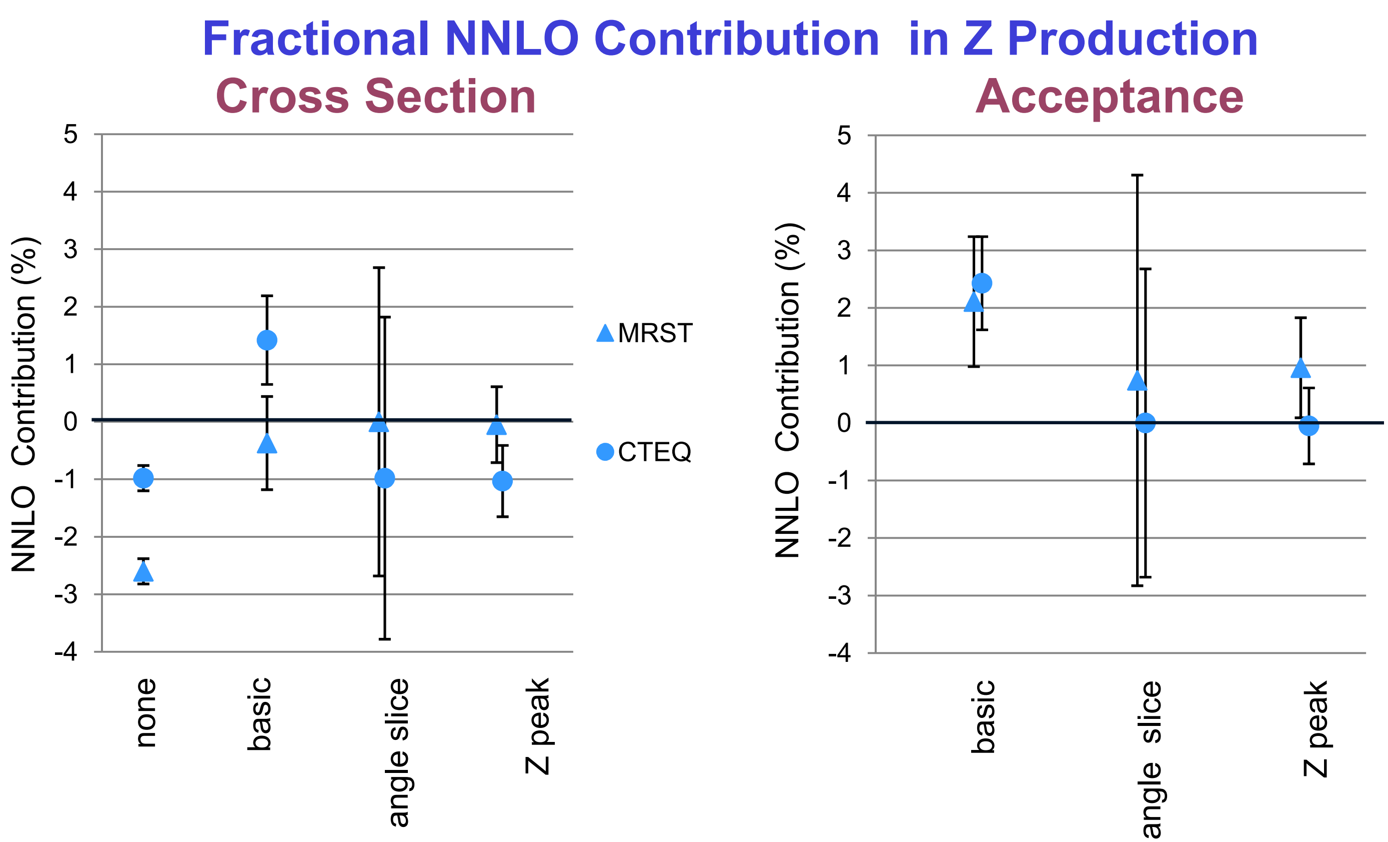
CUT	M_{ll}	p_{Tl}	$\|\eta_l\|$
Basic	> 40 GeV	> 20 GeV	< 2
Angle Slice	> 40 GeV	> 20 GeV	$1.5 < \|\eta_l\| < 2.3$
Z Peak	$79 < M_{ll} < 104$ GeV	> 20 GeV	< 2

$$q\bar{q}' \to W^{\pm} \to l^{\pm}\nu$$

CUT	p_{Tl}	$p_{T\nu}$	$\|\eta_l\|$
Basic	> 25 GeV	> 20 GeV	< 1
Larger η	> 25 GeV	> 20 GeV	$1 < \|\eta_l\| < 2.2$
Higher $p_{T\nu}$	> 25 GeV	> 30 GeV	< 1

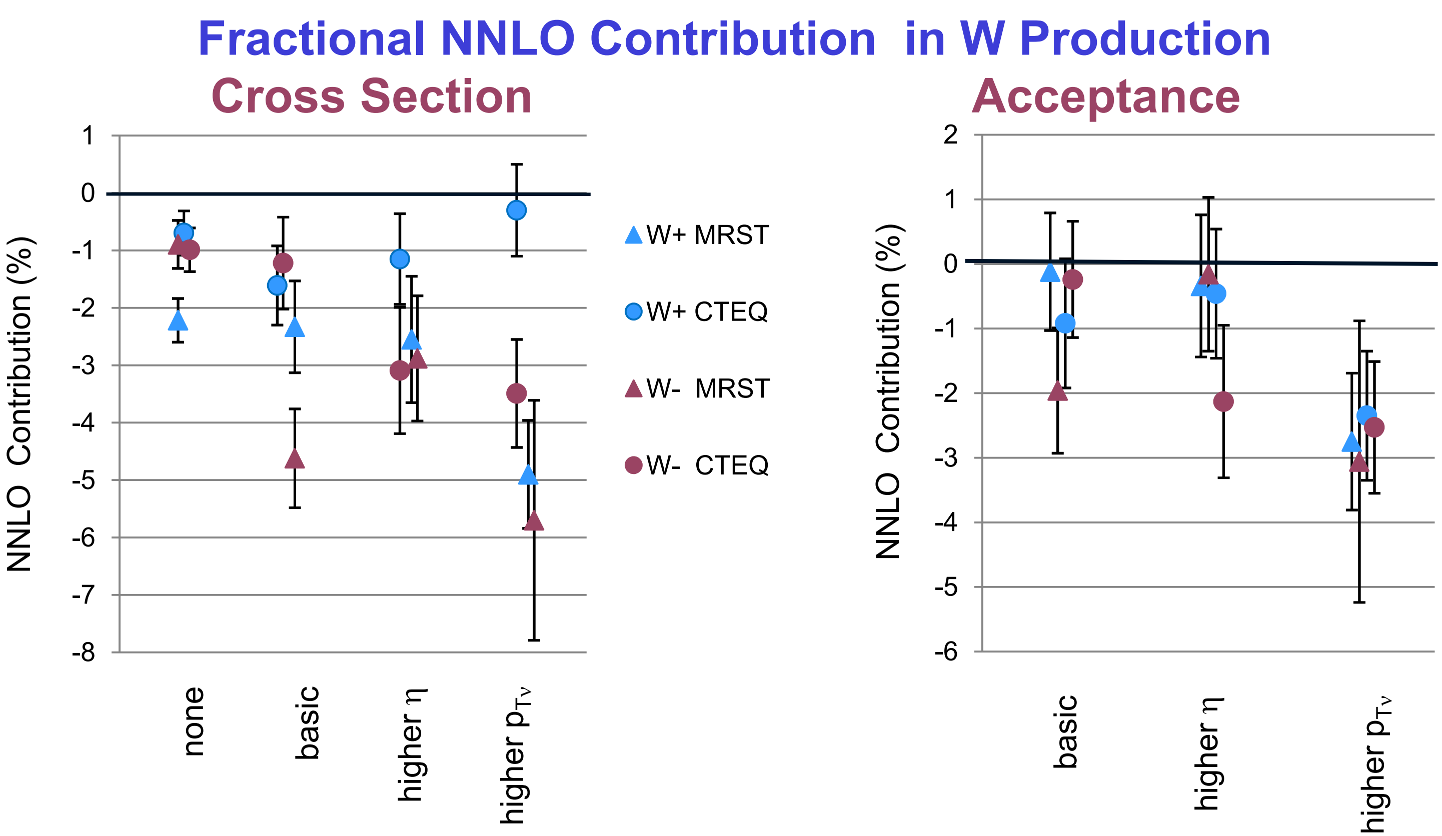
Z: NNLO QCD Contribution

The size of the NNLO correction calculated with two PDFs:



W: NNLO QCD Contribution

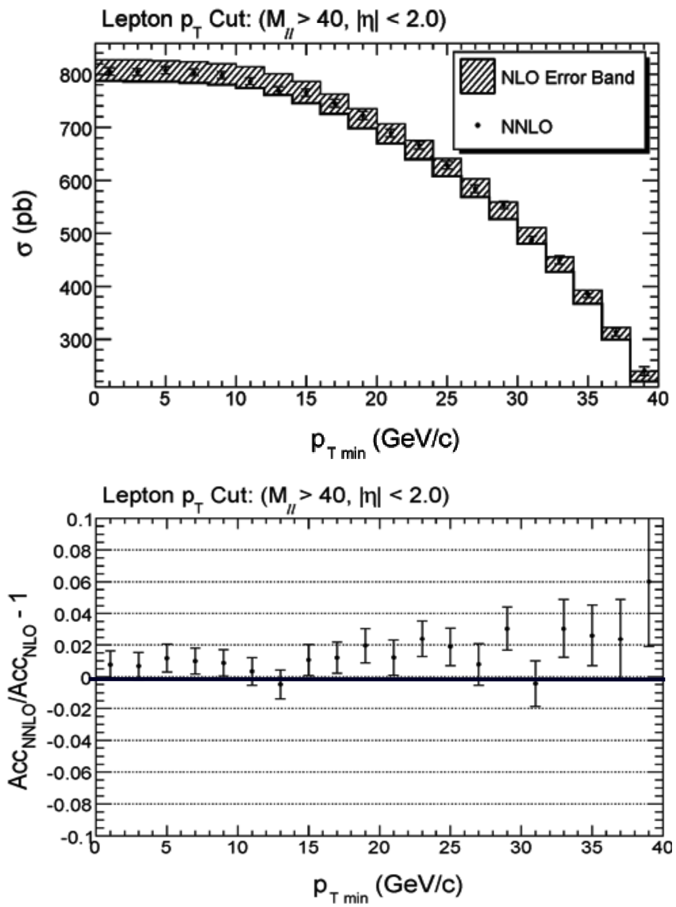
The same calculation for W production:



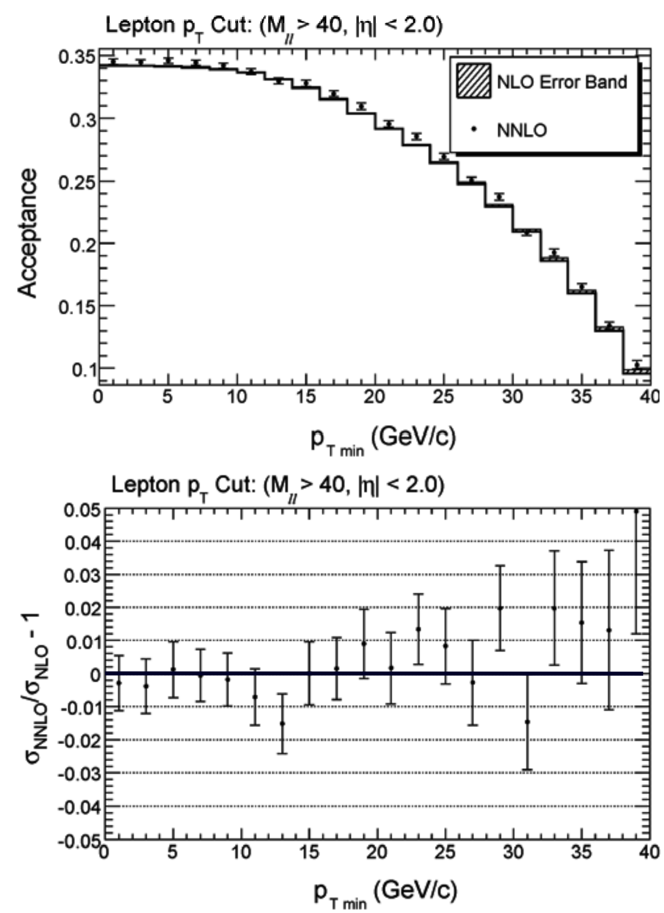
NNLO Dependence on P_T Cut: Z

NNLO contribution dependence on lepton P_T cuts for Z production

cross section



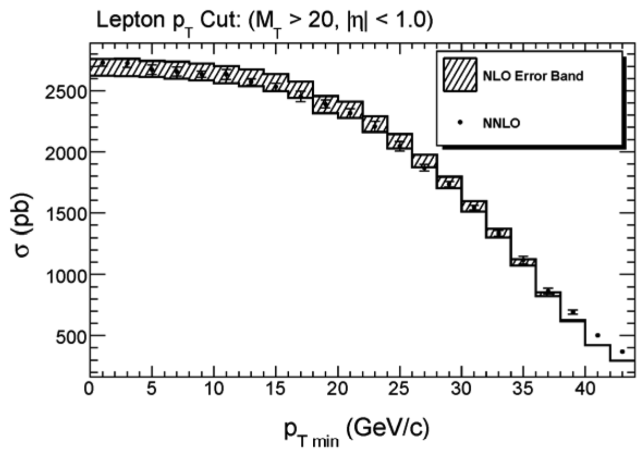
acceptance

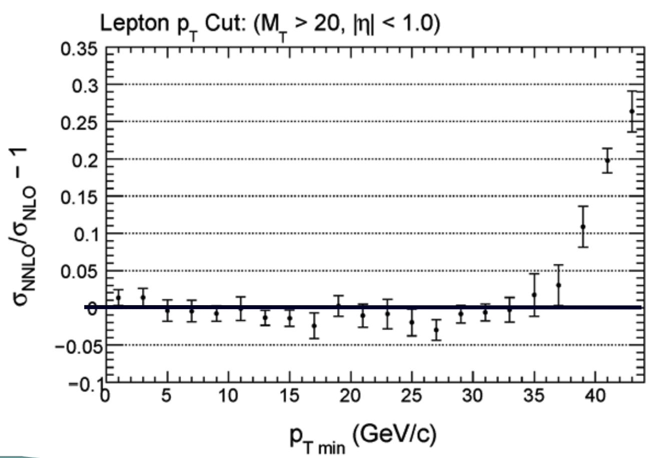


NNLO Dependence on P_T Cut: W^+

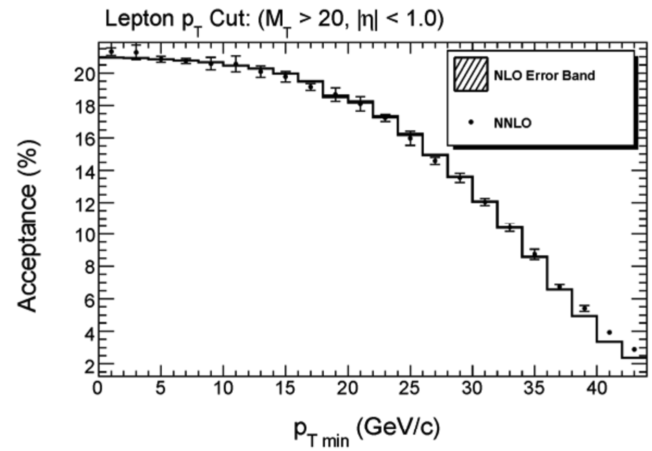
NNLO contribution dependence on lepton P_T cuts for W^+ production

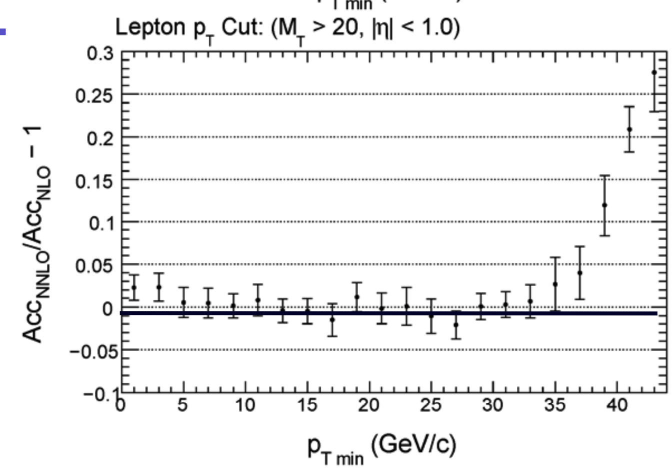
cross section





acceptance

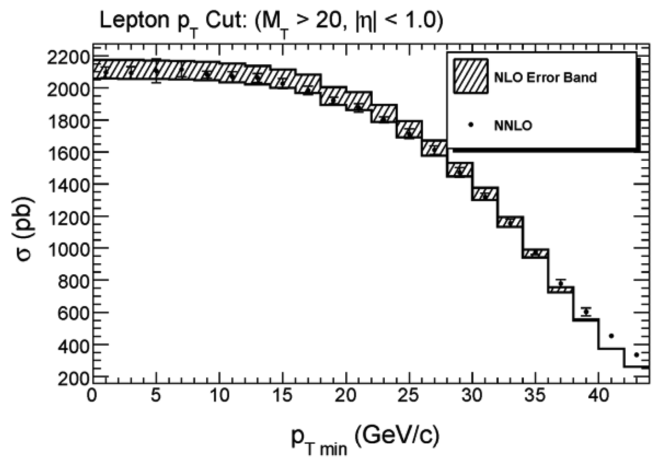


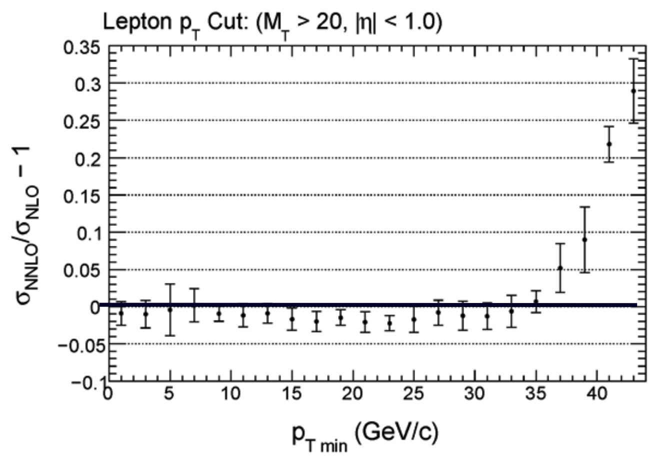


NNLO Dependence on P_T Cut: W^-

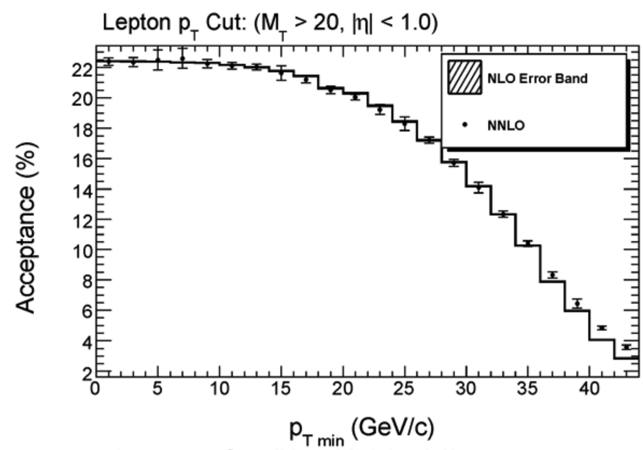
NNLO contribution dependence on lepton P_T cuts for W^- production

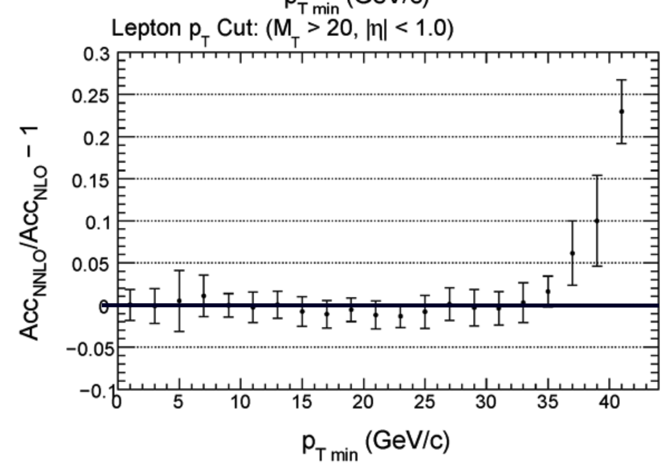
cross section





acceptance

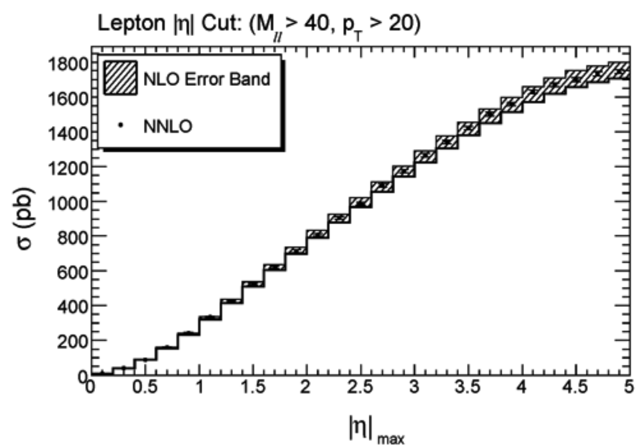


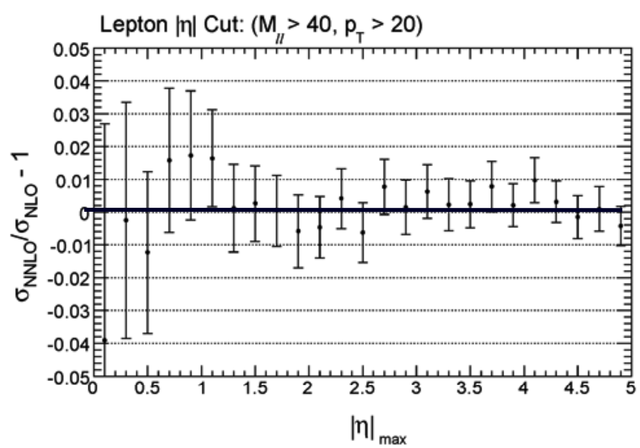


NNLO Dependence on η Cut: Z

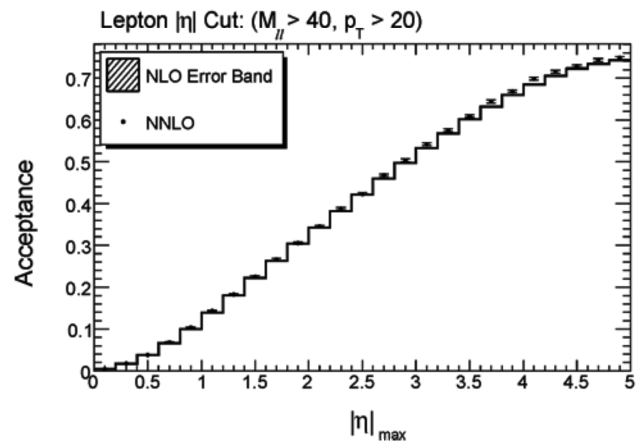
NNLO contribution dependence on lepton η cuts for Z production

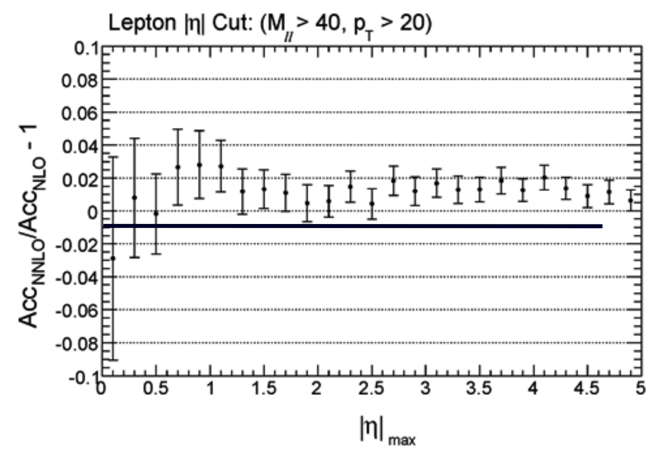
cross section





acceptance

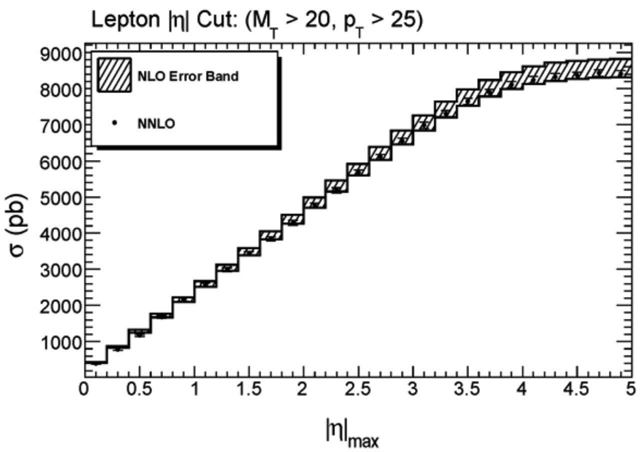


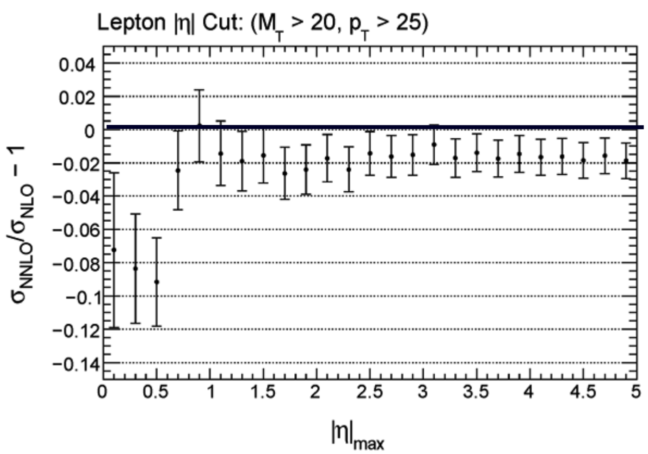


NNLO Dependence on η Cut: W^+

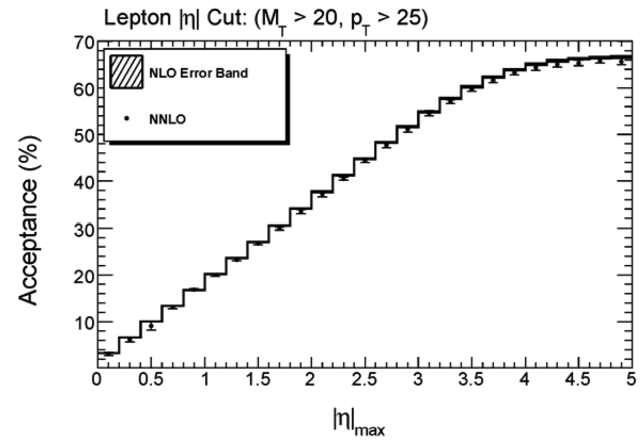
NNLO contribution dependence on lepton η cuts for W^+ production

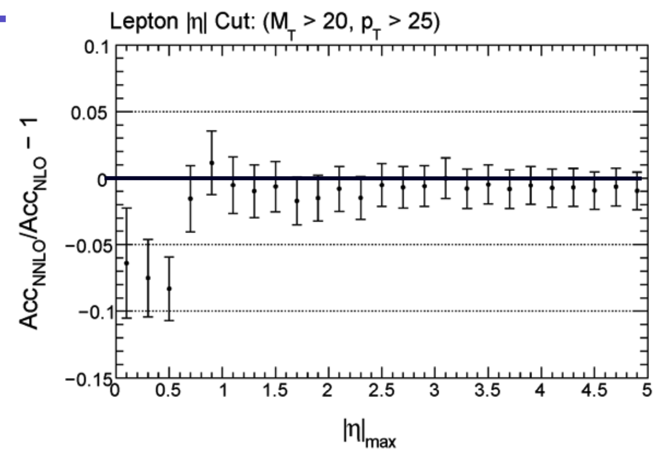
cross section





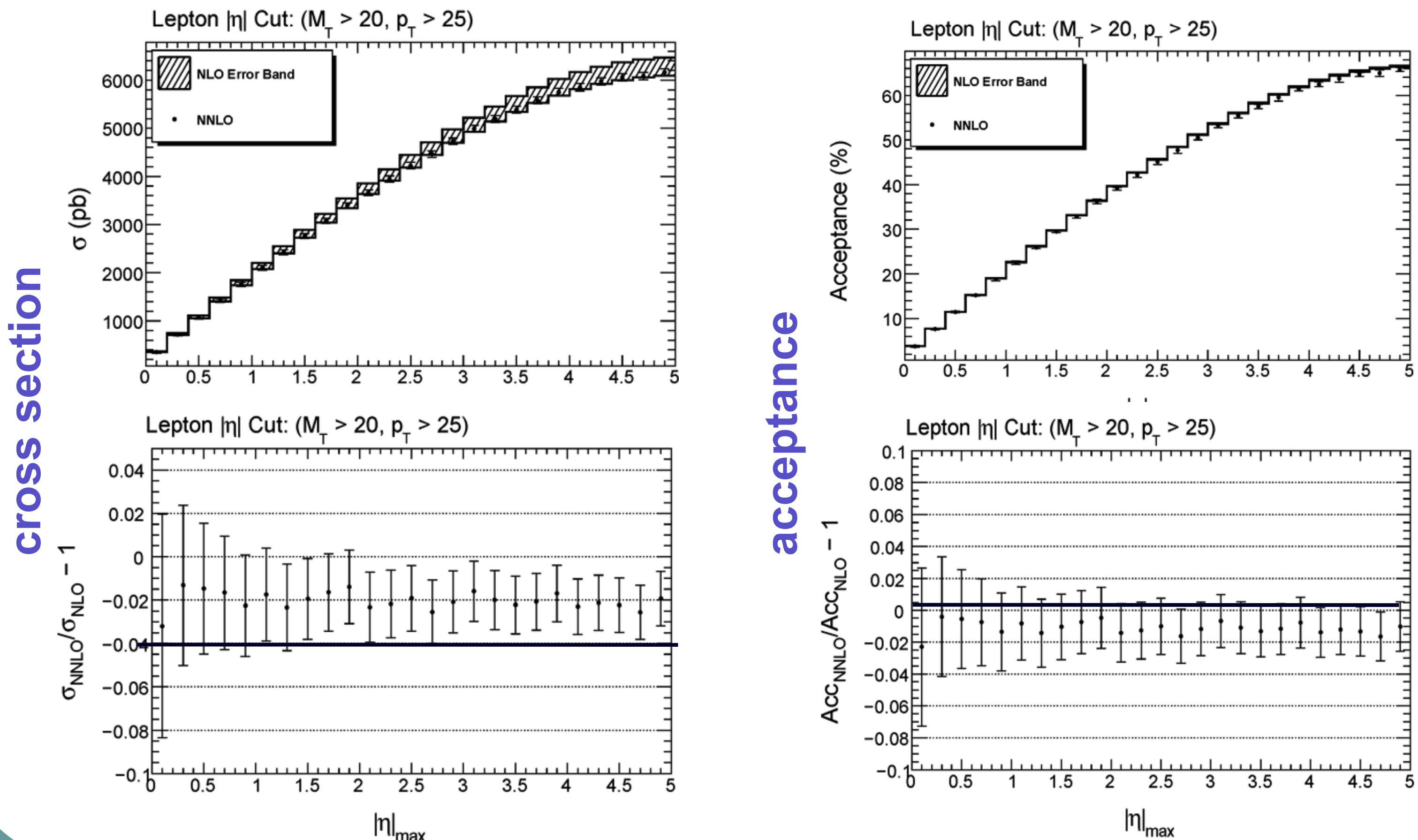
acceptance





NNLO Dependence on η Cut: W⁻

NNLO contribution dependence on lepton η cuts for W^- production

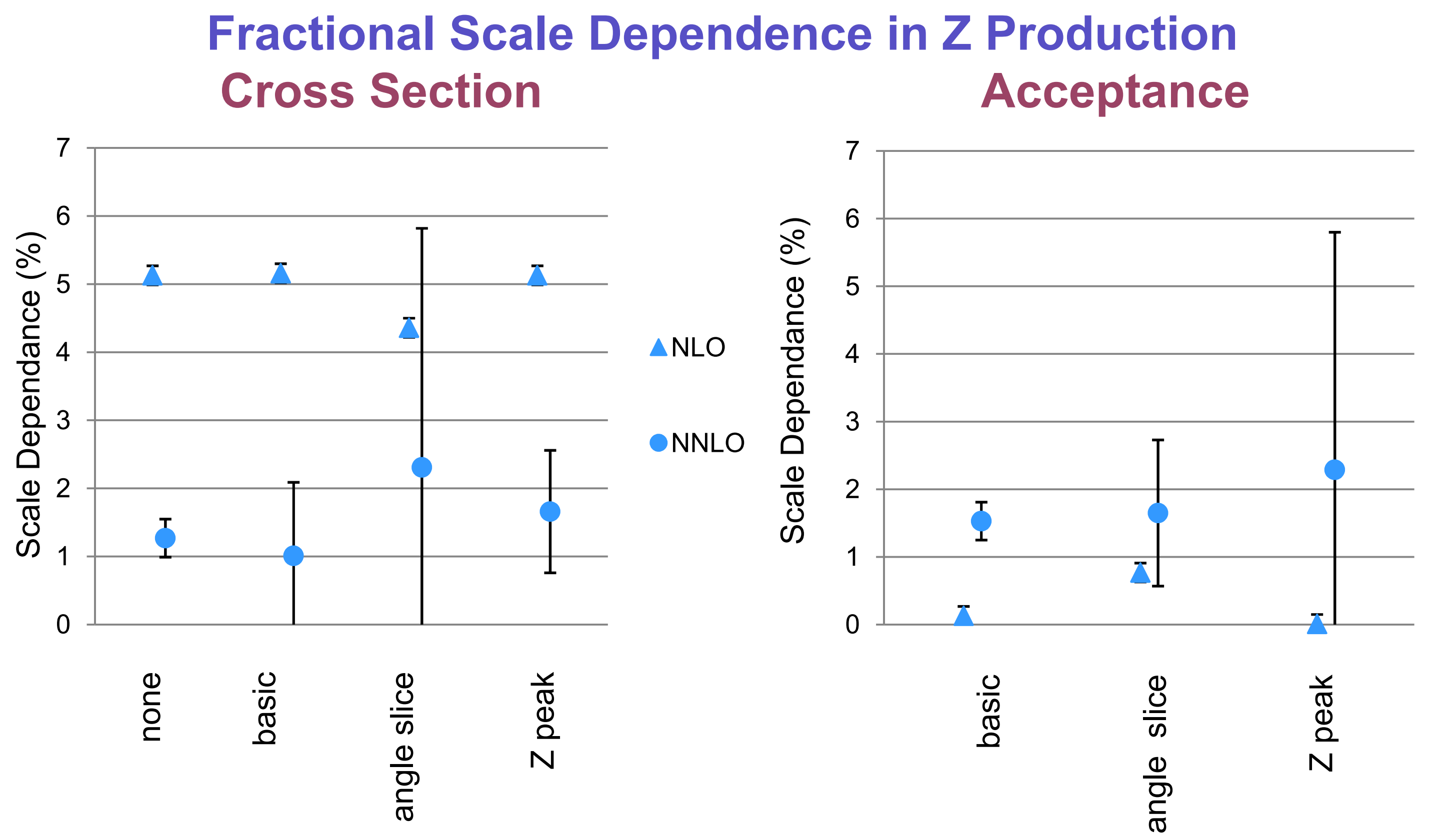


QCD Scale Dependence

- The QCD calculations depend on two arbitrary scales: the factorization scale and renormalization scale. These scales are fictitious, and would cancel in a complete all-order calculation. At finite order, they must be chosen.
- We have chosen these to be M_Z or M_W in our calculations, but need to check the dependence on them.
- We varied them by a factor of 2 or ½ to see how the cross-sections and acceptances change with scale.
- NNLO calculations reduce scale dependence in the cross section, but not necessarily in acceptances.

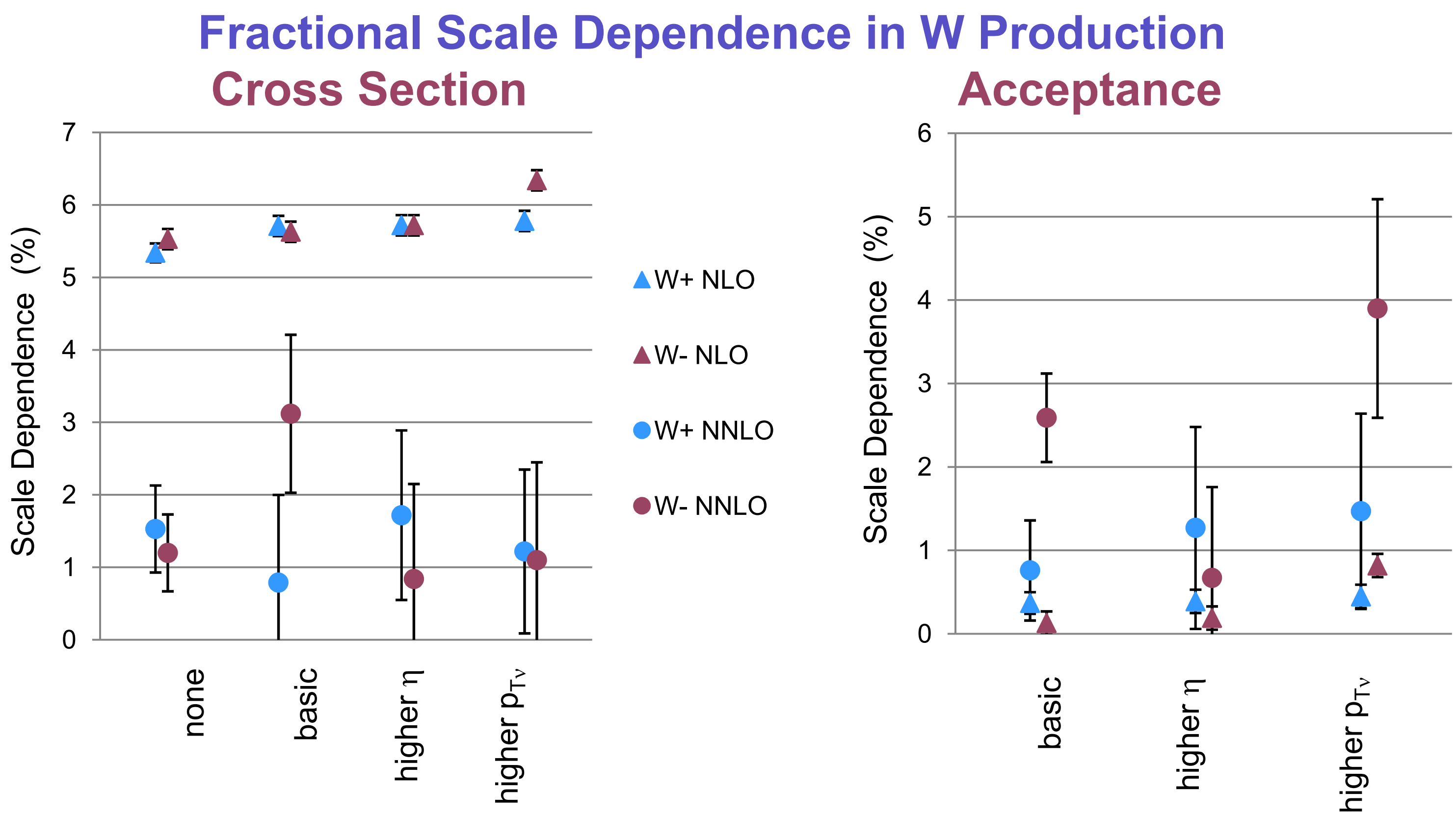
QCD Scale Dependence: Z

Change by varying QCD scales by a factor of 2 or ½ :



QCD Scale Dependence: W

The same calculation for W production:

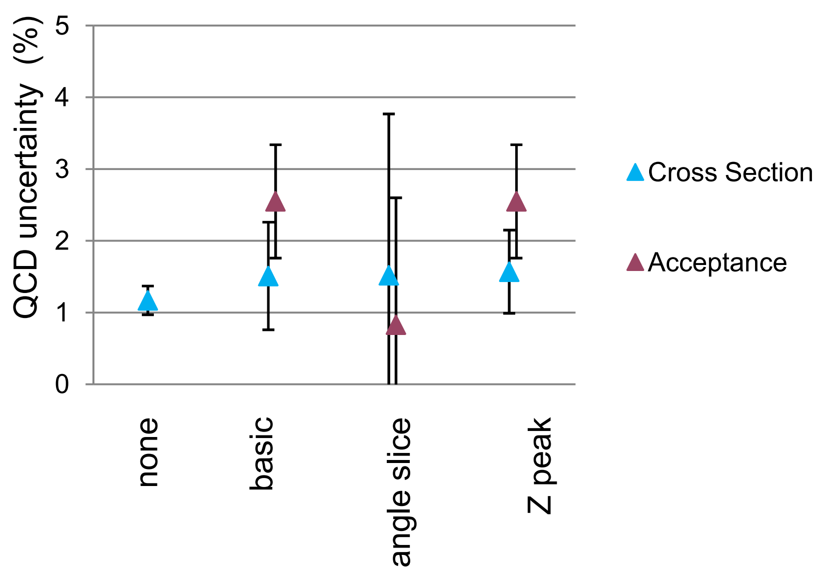


Total QCD Uncertainty

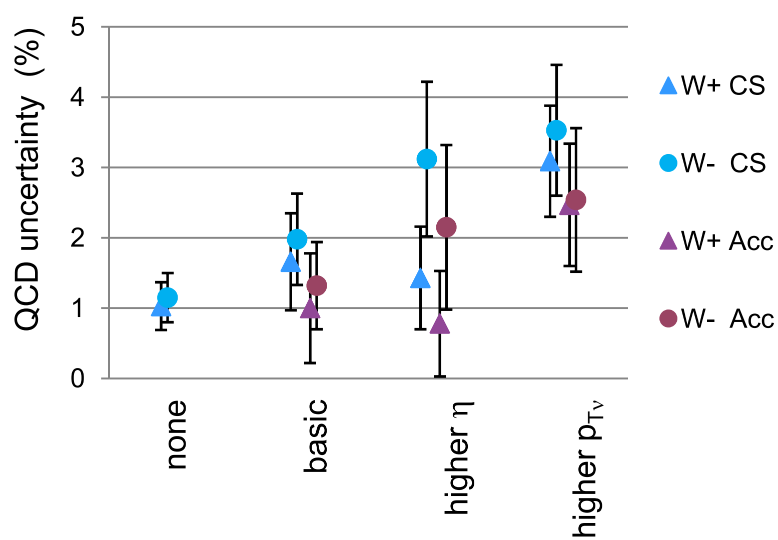
This combined QCD uncertainty includes the error for not including NNLO, with the residual scale dependence inferred at NNLO.

Estimate of Total QCD Uncertainty

Cross Section



Acceptance



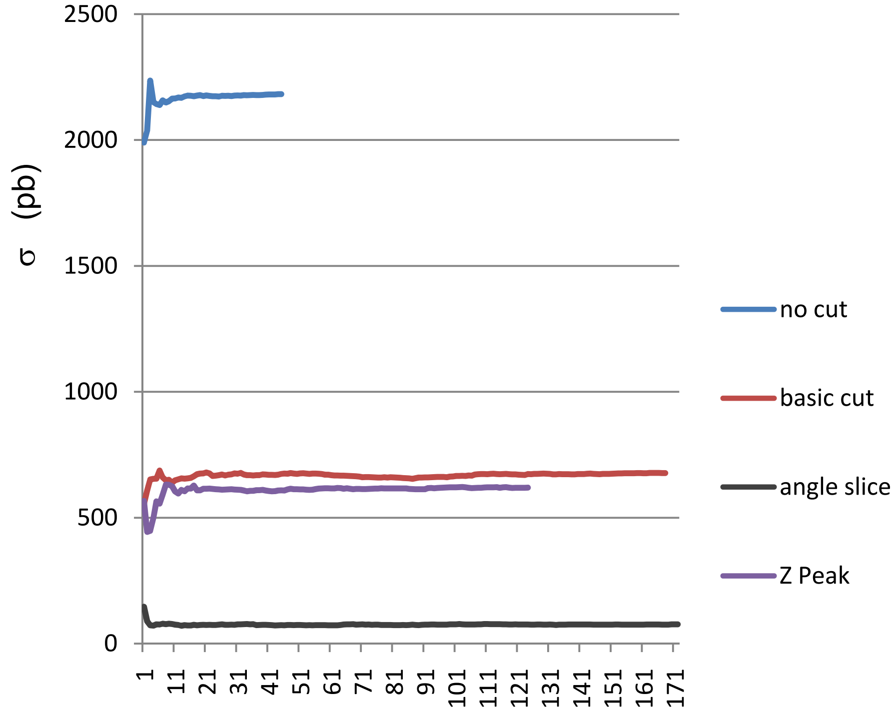
Convergence Issues

- Convergence is a limiting factor in calculating the NNLO corrections. FEWZ uses an 11-dimensional Vegas integral which converges slowly for some cuts.
- The results shown here typically took a month or longer for narrow cuts.
- Still, some results could not converge to better than 4%. Attaining 1% is difficult except for relatively inclusive cuts.
- W production converged somewhat better.
- Separating different classes of terms in FEWZw and calculating them on different nodes of the clusters helped to make the W calculation manageable.

Convergence for Z Production

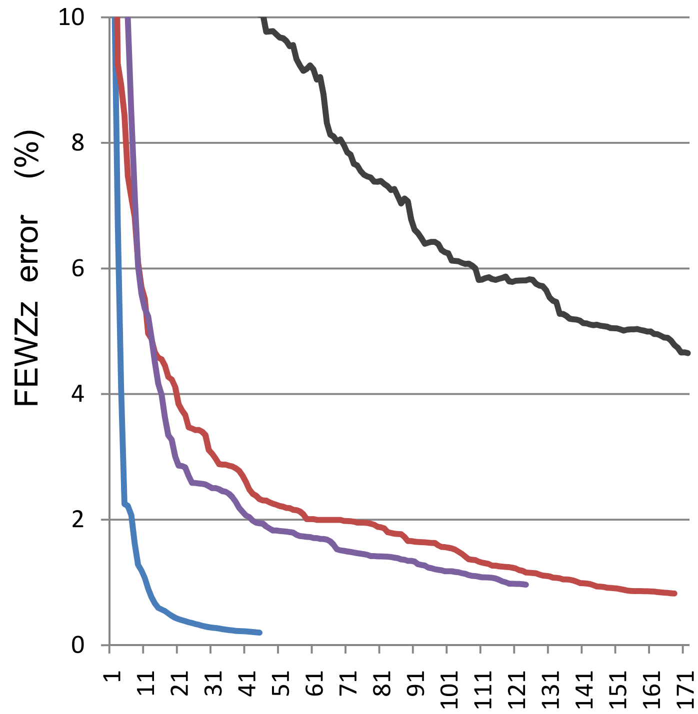
FEWZz Run Time ≈ 1 month per data point (narrow cuts)

Cross Section



Vegas iteration

Relative Error



Vegas iteration

PDF Contribution to Error

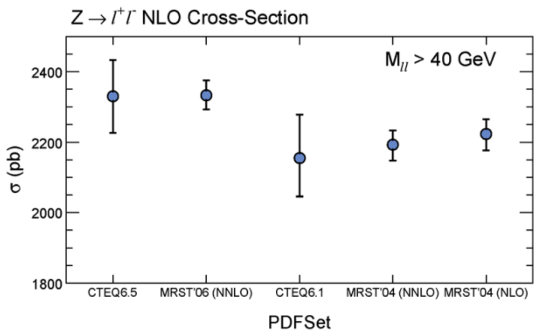
- To estimate the error due to the PDFs, we calculated the error in the NLO cross section and acceptance for a range of PDF sets using the eigenvector sets provided and using the asymmetric Hessian method to calculate the error in the cross section.

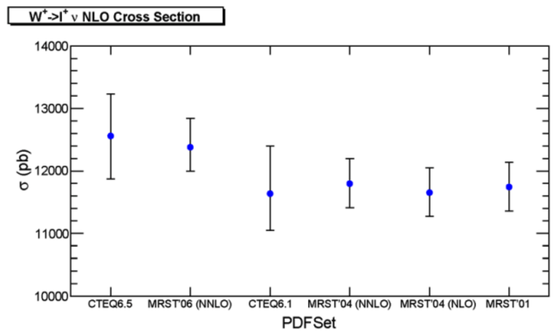
- Errors within a PDF set tend to be greater than the difference between sets, as seen in the following plots for Z, W^+, and W^- production.

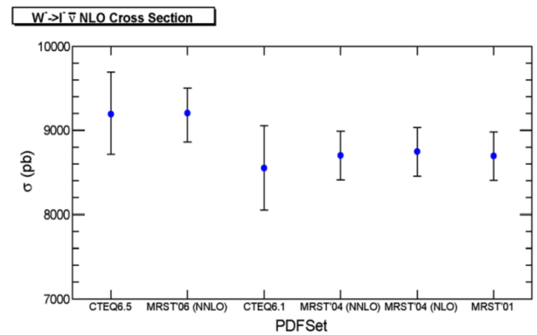
- PDF errors tend to cancel in acceptances.

PDF Contribution to Error

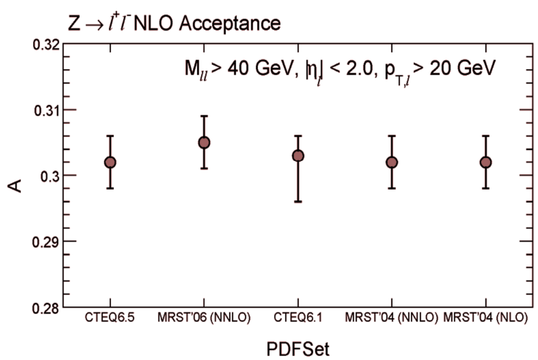
Z | **W+** | **W-**

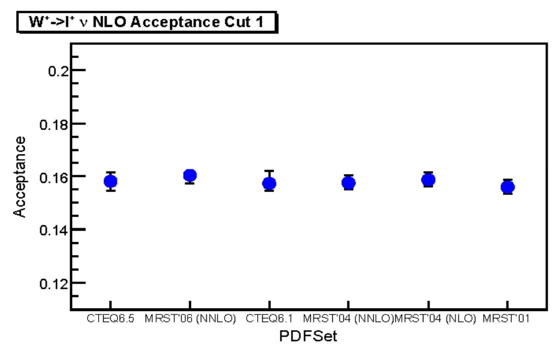


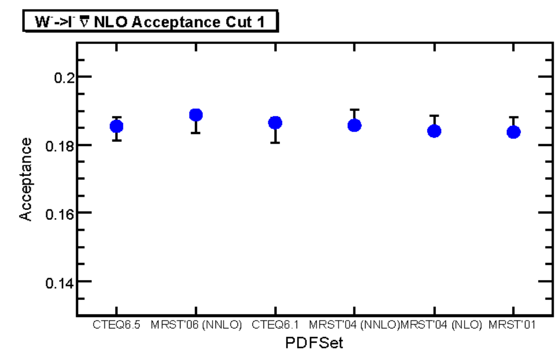




cross sections (“basic” cuts)







acceptances (“basic” cuts)

Summary of Uncertainties

Cross Section

Uncertainty	Z	W^+	W^-
Missing EW	0.4 ± 0.3	1.8 ± 0.6	1.7 ± 0.6
Total QCD	1.5 ± 0.8	1.7 ± 0.7	1.3 ± 0.6
PDF	3.8	4.0	3.3
Total	**4.1 ± 0.3**	**4.7 ± 0.5**	**3.9 ± 0.5**

Acceptance

Uncertainty	Z	W^+	W^-
Missing EW	1.0 ± 0.2	2.0 ± 0.5	2.1 ± 0.6
Total QCD	2.6 ± 0.8	1.3 ± 0.6	1.0 ± 0.8
PDF	1.3	2.2	2.3
Total	**3.0 ± 0.7**	**3.2 ± 0.3**	**3.3 ± 0.3**

"BASIC" CUT

Z:
M_{ll} > 40 GeV
P_{Tl}> 20 GeV

W:
$M_{l\nu}$ > 40 GeV
P_{Tl} > 25 GeV
$P_{T\nu}$> 20 GeV

The missing EW correction for W is based on HORACE alone. For the Z, the HORACE – PHOTOS difference is used.

The HERWIRI Project

High Energy Radiation With InfraRed Improvement

Toward a new event generator based on YFS-like non-abelian exponentiation. [My Loopfest VIII talk, Friday]

- HERWIRI 1.0 (available now) [Joseph, Majhi, Ward, Yost]
  - HERWIG with exponentiated DGLAP kernels
- HERWIRI 2.0 (this summer) [Halyo, Hejna, Ward, Yost]
  - HERWIG + YFS3 exponentiated QCD for Z production

Hypergeometric function-based reduction techniques are being developed to facilitate better convergence of higher order corrections. [Kalmykov, Ward, Yost]

Summary

- There is still work to do to calculate the W and Z production for desired cuts at the 1% level.
- Convergence of FEWZ is a limiting factor in estimating the missing NNLO contribution.
- An NNLO event generator is needed.
- For Z production, MC@NLO + Photos provides a good solution. NNLO can be small for certain cuts and acceptances.
- Horace is good for estimating the size of EW corrections. An event generator is needed.
- One approach: the HERWIRI Project. Many others are working on this too.