WZ and W+jets production at large transverse momenta beyond NLO

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Introduction and motivation

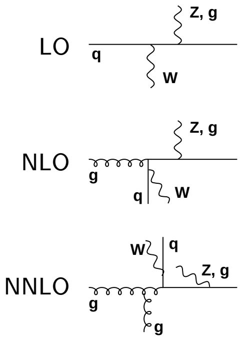
$$pp \to W^\pm Z + X \to \ell_1^\pm \overset{(-)}{\nu_1} \ell_2^+ \ell_2^- + X$$

$$pp \to W^\pm + \text{jet} + X \to \ell^\pm \overset{(-)}{\nu} + \text{jet} + X$$

Beyond NLO in QCD: motivation

- NLO QCD corrections for WZ and W+jets processes turned out to be sizable
  - new production channels
  - new topologies
- further new subprocesses and topologies expected at NNLO

Using only the NLO results is risky and may lead to misinterpretation of data!



The method: LoopSim

[Mathieu Rubin, Gavin Salam and SS (2010)]

LoopSim (brief summary)

The general idea: use unitarity to simulate the divergent part of 2-loop diagrams

LoopSim procedure

input: event with n final state particles	LoopSim →	output: all $n-k$ final state particle events (i.e. all k-loop events)

- notation:

$$\bar{n}\textbf{LO} \quad - \quad \text{simulated 1-loop}$$
$$\bar{n}\textbf{NLO} \quad - \quad \text{simulated 2-loop and exact 1-loop}$$

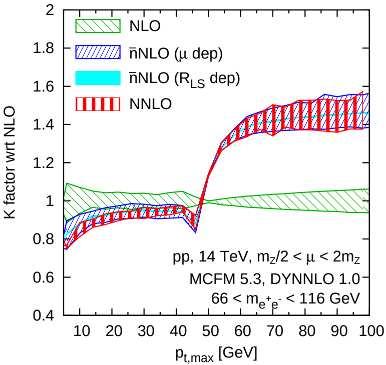
- this will work very well for the processes with large K factors e.g.

$$\sigma_{\bar{n}\mathrm{NLO}} = \sigma_{\mathrm{NNLO}}\left(1+\mathcal{O}\left(\frac{\alpha_s^2}{K_{\mathrm{NNLO}}}\right)\right), \quad K_{\mathrm{NNLO}} \gtrsim K_{\mathrm{NLO}} \gg 1$$

- LoopSim has one parameter R_{LS} (we vary it to probe uncertainties of the method related to nonsingular terms of the loop diagrams)

LoopSim has been shown to work

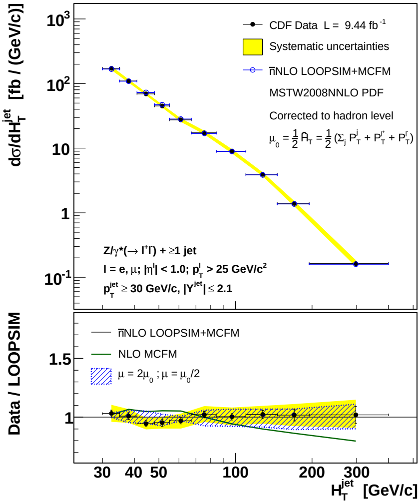
Drell-Yan at NNLO



- excellent agreement with DY at NNLO
- accounts very well for H_T distributions at Tevatron

Z+jets at Tevatron

[courtesy to Stefano Camarda]



WZ

[F. Campanario and SS, Phys.Lett. B718 (2012) 100-104]

WZ at $\bar{n}$NLO: details of the computation

To compute approximate NNLO QCD correction to WZ we used:

VBFNLO + LoopSim

- The former provides WZ at NLO and WZj at NLO, the latter, consistent way to supplement them with approximate 2-loop corrections.

All results correspond to:

- both W^+Z and W^-Z production channels
- two unlike-flavour decay channels: $ee\mu\nu_\mu$ and $\mu\mu e\nu_e$
- MSTW NNLO 2008 at all orders
- $\mu_{F,R} = \frac{1}{2}\left\{\sum p_{T,\text{partons}} + \sqrt{p_{T,W}^2 + m_W^2} + \sqrt{p_{T,Z}^2 + m_Z^2}\right\}$

Cuts:

- $|y_\ell| \leq 2.5,\ p_{T,\ell} \geq 15\,(20)$, for ℓ coming from Z (W)
- $E_{T,\text{miss}} > 30\,\text{GeV}$
- $60 < m_{\ell^+\ell^-} < 120\,\text{GeV}$
- jets from anti-k_t, $R = 0.45$,
- for observables involving jets: $|y_\text{jet}| \leq 4.5, p_{T,\text{ jet}} \geq 30\,\text{GeV}$
- $\Delta R_{\ell\,(\ell,j)} > 0.3,\ \Delta R = \sqrt{\Delta\phi^2 + \Delta y^2}$

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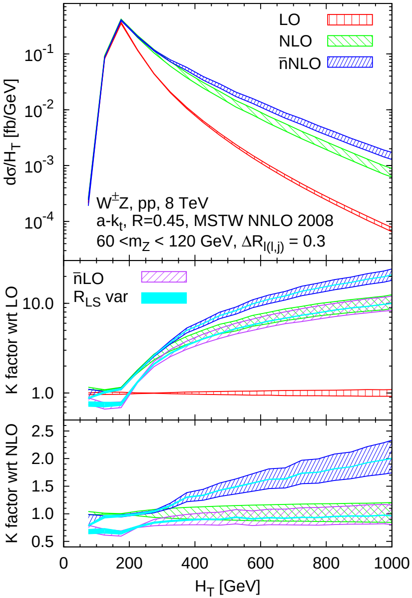
Total cross section
[take it with a pinch of salt]

Increases from 25.7 $\pm$ 1.0 (scale) fb at NLO to 26.9 $\pm$ 0.9 (scale) $\pm$ 0.4 (R_{LS}) fb at $\bar{n}$NLO, which is about 5%.

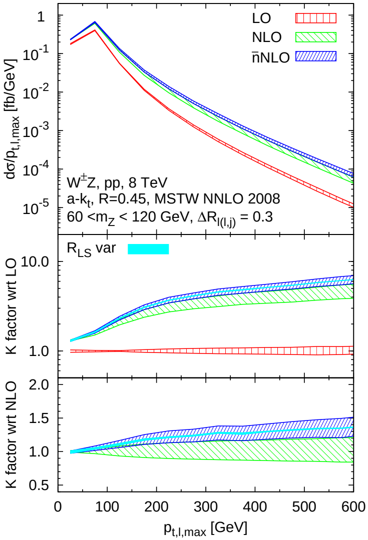
H_T distribution

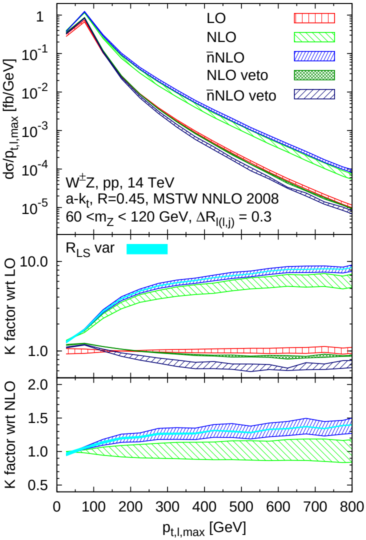


$$H_T = \sum p_{T,\mathrm{jets}} + \sum p_{T,\ell} + E_{T,\mathrm{miss}}$$

- huge K-factor from LO to NLO, distribution very sensitive to new channels and new topologies
- very good agreement between $\bar{n}$LO and NLO at large H_T
- $\bar{n}$NLO corrections as large as 100% w.r.t. NLO
- small R_{LS} uncertainties at large H_T
- marginal reduction of scale uncertainties at $\bar{n}$NLO (new topologies which dominate computed only at LO)

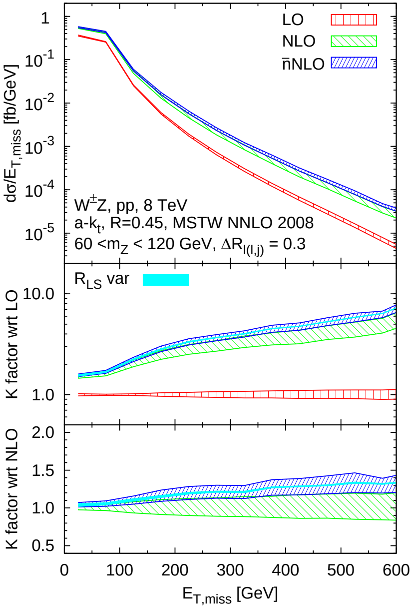
p_t of the hardest lepton





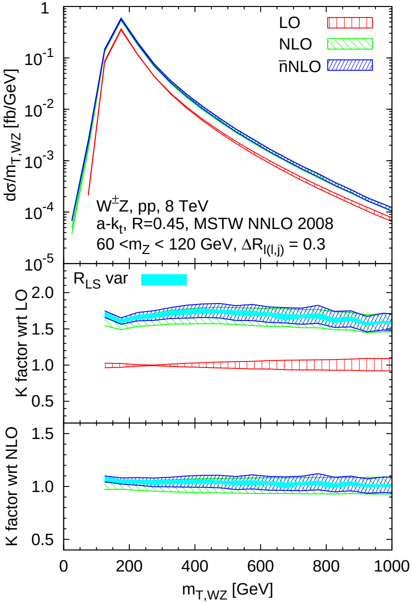
- $\bar{n}$NLO corrections beyond NLO scale uncertainties for $p_t > 200$ GeV
- $\bar{n}$NLO with $p_{t,\mathrm{veto}} = 50$ GeV: large corrections, larger scale uncertainties

missing E_T distribution



- again, huge K-factor from LO to NLO
- large $\bar{n}$NLO of the order of 30%
- $\bar{n}$NLO correction exceeds NLO scale uncertainty
- reduced scale uncertainty at $\bar{n}$NLO

transverse mass of the WZ system



$$m_{T,WZ}^2 = (E_T^W + E_T^Z)^2 - (p_x^W + p_x^Z)^2 - (p_y^W + p_y^Z)^2$$

- example of an observable for which $\bar{n}$NLO corrections are small
- finite loop terms of large importance (hence larger $R_{\rm LS}$ uncertainty)
- favoured configurations with W and Z back-to-back and both with sizable p_t; those do not have logarithmic enhancements

W + jets

[Daniel Maitre, Gavin Salam and SS (in preparation)]

W+jets at $\bar{n}$NLO: details of the computation

To compute approximate NNLO QCD correction to W+jets we used:

MCFM (or BlackHat+Sherpa) + LoopSim

- The former provides W+1j at NLO and W+2j at NLO, the latter, consistent way to supplement them with approximate 2-loop corrections.

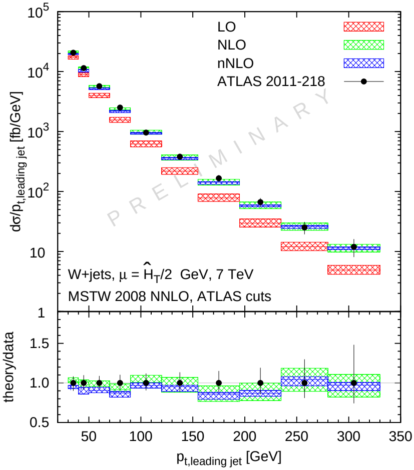
All results correspond to:

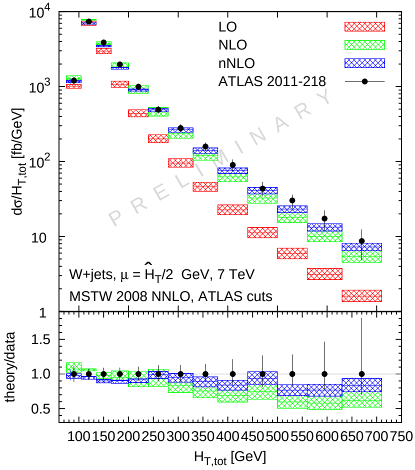
- both W^+ and W^- production channels
- MSTW NNLO 2008 at all orders
- $\mu_{F,R} = \frac{1}{2}\hat{H}_T \equiv \frac{1}{2}\left\{\sum p_{T,\text{partons}} + \sum p_{T,\ell}\right\}$

Cuts (as in ATLAS 2010 data):

- $|y_\ell| \leq 2.5$, $p_{T,\ell} \geq 20$ $E_{T,\text{miss}} > 25\,\mathrm{GeV}$
- $m_{T,W} = \sqrt{2p_{T,\ell}p_{T,\nu}\left(1 - \cos\Delta\phi_{\ell,\nu}\right)} > 40\,\mathrm{GeV}$
- jets from anti-k_t, $R = 0.4$,
- for observables involving jets: $|y_{\text{jet}}| \leq 4.4$, $p_{T,\text{jet}} \geq 30\,\mathrm{GeV}$
- $\Delta R_{\ell,j} > 0.5$, $\Delta R = \sqrt{\Delta\phi^2 + \Delta y^2}$

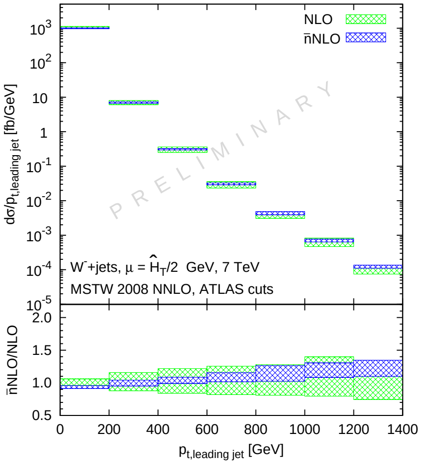
W+jets at $\bar{n}$NLO: data comparison

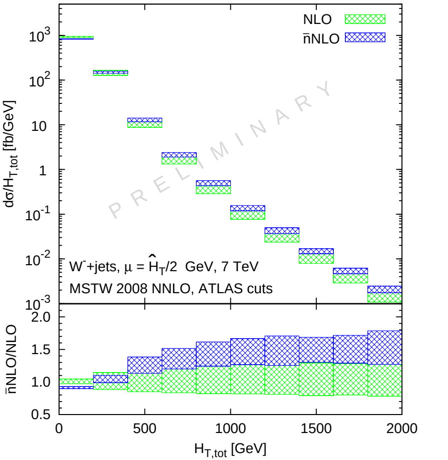




- no further corrections for $p_{t,\text{leading jet}}$, some reduction of scale uncertainty
- further corrections for $H_{T,\text{tot}}$ bringing the QCD prediction closer to data

W^-+jets at $\bar{n}$NLO: large p_t





- $p_{t,\text{leading jet}}$ converges well at $\bar{n}$NLO which stays within the NLO band, substantial reduction of uncertainties (similar conclusion for $p_{t,W}$)
- $H_{T,\text{tot}}$ receives further corrections at $\bar{n}$NLO with the $\bar{n}$NLO/NLO K factor reaching 1.5-1.7 (similar conclusion for $H_{T,\text{jet}}$)

Summary

- We used LoopSim + VBFNLO to compute approximate NNLO QCD corrections to the process $pp \to WZ \to \ell_1^{\pm} \overset{(-)}{\nu}_1 \ell_2^{+} \ell_2^{-} + X$
- We found that these corrections are sizable for a number of observables at high p_t, that is: H_T, $p_{T,\ell,\max}$ and $E_{T,\text{miss}}$
- It is therefore important to take them into account in physics analyses within and beyond the Standard Model

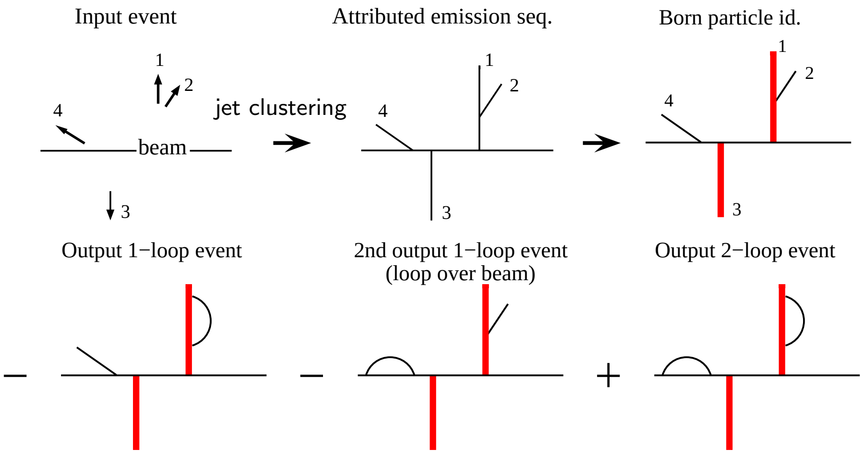
- We also showed preliminary results for W+jets at $\bar{n}$NLO obtained with LoopSim combined with MCFM (or BlackHat + Sherpa)
- We observed good convergence of $p_{t,\text{leading jet}}$ and $p_{t,W}$ while $H_{T,\text{tot}}$ and $H_{T,\text{jets}}$ receive further corrections at $\bar{n}$NLO that should definitely be used in background estimations

Outlook:

- Ongoing computations of Z+jets and W+jets/Z+jets ratios at $\bar{n}$NLO as well as $\bar{n}\bar{n}$NLO
- Then W^+W^- and anomalous coupling studies

BACKUP SLIDES

The LoopSim method: $\bar{n}$LO, $\bar{n}\bar{n}$LO etc.



- jet clustering $ij \to k$ is reinterpreted as the splitting $k \to ij$
- weight of an event $\sim (-1)^{\text{nb. of loops}}$ and all weights sum up to zero (unitarity)
- beware: the loops above are just a shortcut notation!

Including exact loops

$E_{n,l}$	–	input event with n final state particles and l loops
U_l^b	–	operator producing event with b Born particles and l loops
$U_\forall^b$	–	operator generating all necessary loop diagrams at given order

How to introduce exact loop contributions?

$$U_\forall^b(E_{n,0}) \quad + \quad U_\forall^b(E_{n-1,1}) \quad - \quad U_\forall^b(U_1^b(E_{n,0}))$$

- generate all diagrams from the tree level event
- generate all diagrams from the 1-loop event
- remove all approximate diagrams from $U_\forall^b(E_{n,0})$ that have exact counterparts provided by $U_\forall^b(E_{n-1,1})$

- inclusion of exact loops helps reducing scale uncertainties
- straightforward generalization to arbitrary number of exact loops