The Drell-Yan process in NNLO QCD

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Introduction

The production of vector bosons in hadron collisions was historically the first application of parton model ideas to hadron collisions

Drell, Yan (1970)

Such processes are important for physics studies within and beyond the SM

- Large production rates and clean experimental signatures make these processes standard candles for detector calibration
- Background for new physics searches
- Possible use as luminosity monitor

→ It is important to have reliable theoretical predictions

State of the art

- QCD corrections:

The total cross section for the Drell-Yan process is known since long time up to NNLO in QCD perturbation theory

R.Hamberg, T.Matsuura, W.L. Van Neerven (1991)

Rapidity distributions up to NNLO and fully exclusive calculation

C.Anastasiou, L.Dixon, K.Melnikov, F.Petriello (2003)
K.Melnikov and F.Petriello (2006)

NLO corrections at large transverse momentum

K.Ellis, G.Martinelli, R.Petronzio (1983)
P.B.Arnold, M.H. Reno (1989)
R.J.Gonsalves, J.Pawlowski, C.F.Wai (1989)

- EW corrections:

Known up to $\mathcal{O}(\alpha)$ for both W and Z production

S.Dittmaier,M.Kramer (2002)
U.Baur et al. (2002)
G.Montagna et al. (2006,2007)
A.Arbuzov et al. (2006,2008)

A fully exclusive NNLO calculation

Higher order calculations in QCD are complicated by the presence of infrared (soft and collinear) singularities that enter the intermediate stages of the computation and prevent the straightforward implementation of numerical techniques

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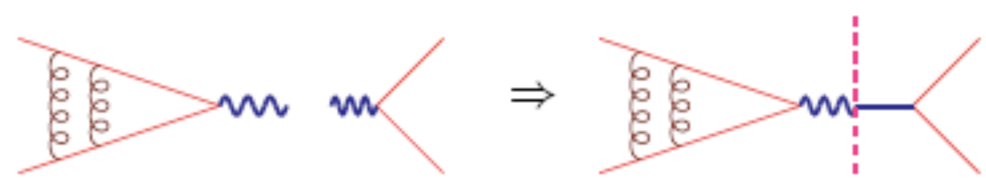
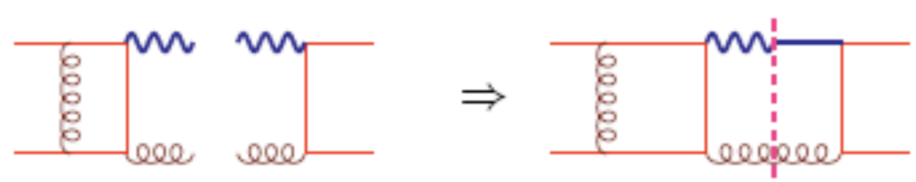
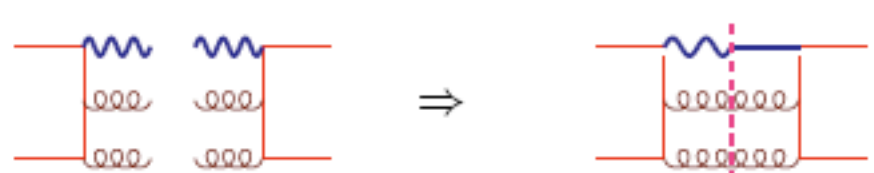
- Virtual-Virtual;



- Real-Virtual;



- Real-Real.



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Life is easier for sufficiently inclusive quantities, when phase space integrations can be carried out analytically

The total cross section for the Drell-Yan process is known since long time up to NNLO in QCD perturbation theory

R.Hamberg, T.Matsuura, W.L. Van Neerven (1991)

The first fully exclusive NNLO calculation was completed 15 years later !

K.Melnikov, F.Petriello (2006)

➡ Same Feynman diagrams but IR cancellation achieved at the fully exclusive level

A fully exclusive NNLO calculation

S.Catani, L.Cieri, G.Ferrera,
D. de Florian, MG (2009)

We have now completed an independent NNLO calculation by using a recently proposed version of the subtraction method

S.Catani, MG (2007)

Our calculation includes $\gamma - Z$ interference, finite width effects, the leptonic decay of the vector boson and the corresponding spin correlations

The calculation is implemented in a parton level event generator with which we can apply arbitrary cuts on the final state leptons and the associated jet activity

- **Possible to compute acceptances....**
- **....but also all the kinematical distributions you want !**

The method

S. Catani, MG (2007)

Let us consider a specific, though important class of processes: the production of colourless high-mass systems F in hadron collisions (F may consist of lepton pairs, vector bosons, Higgs bosons......)

At LO it starts with $c\bar{c} \to F$

Strategy: start from NLO calculation of F+jet(s) and observe that as soon as the transverse momentum of the F $q_T \neq 0$ one can write:

$$d\sigma^F_{(N)NLO}|_{q_T \neq 0} = d\sigma^{F+\text{jets}}_{(N)LO}$$

Define a counterterm to deal with singular behaviour at $q_T \to 0$

But.....
the singular behaviour of $d\sigma^{F+\text{jets}}_{(N)LO}$ is well known from the resummation program of large logarithmic contributions at small transverse momenta

G. Parisi, R. Petronzio (1979)
J. Collins, D.E. Soper, G. Sterman (1985)
S. Catani, D. de Florian, MG (2000)

→ choose $d\sigma^{CT} \sim d\sigma^{(LO)} \otimes \Sigma^F(q_T/Q)$

where $\Sigma^F(q_T/Q) \sim \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi}\right)^n \sum_{k=1}^{2n} \Sigma^{F(n;k)} \frac{Q^2}{q_T^2} \ln^{k-1} \frac{Q^2}{q_T^2}$

Then the calculation can be extended to include the $q_T = 0$ contribution:

$$d\sigma^F_{(N)NLO} = \mathcal{H}^F_{(N)NLO} \otimes d\sigma^F_{LO} + \left[d\sigma^{F+\text{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO}\right]$$

where I have subtracted the truncation of the counterterm at (N)LO and added a contribution at $q_T = 0$ to restore the correct normalization

The function $\mathcal{H}^F$ can be computed in QCD perturbation theory

$$\mathcal{H}^F = 1 + \left(\frac{\alpha_S}{\pi}\right) \mathcal{H}^{F(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{F(2)} + \ldots\ldots$$

For a generic $pp \to F + X$ process:

- At NLO we need a LO calculation of $d\sigma^{F+\text{jet(s)}}$ plus the knowledge of $d\sigma^{CT}_{LO}$ and $\mathcal{H}^{F(1)}$
  - the counterterm $d\sigma^{CT}_{LO}$ requires the resummation coefficients $A^{(1)}, B^{(1)}$ and the one loop anomalous dimensions
  - the general form of $\mathcal{H}^{F(1)}$ is known

D. de Florian, MG (2000)
G. Bozzi, S. Catani, D. de Florian, MG (2005)

- At NNLO we need a NLO calculation of $d\sigma^{F+\text{jet(s)}}$ plus the knowledge of $d\sigma^{CT}_{NLO}$ and $\mathcal{H}^{F(2)}$
  - the counterterm $d\sigma^{CT}_{NLO}$ depends also on the resummation coefficients $A^{(2)}, B^{(2)}$ and on the two loop anomalous dimensions
  - the general form of $\mathcal{H}^{F(2)}$ is not known.....

  ....but we have computed $\mathcal{H}^{V(2)}$ for vector boson production !

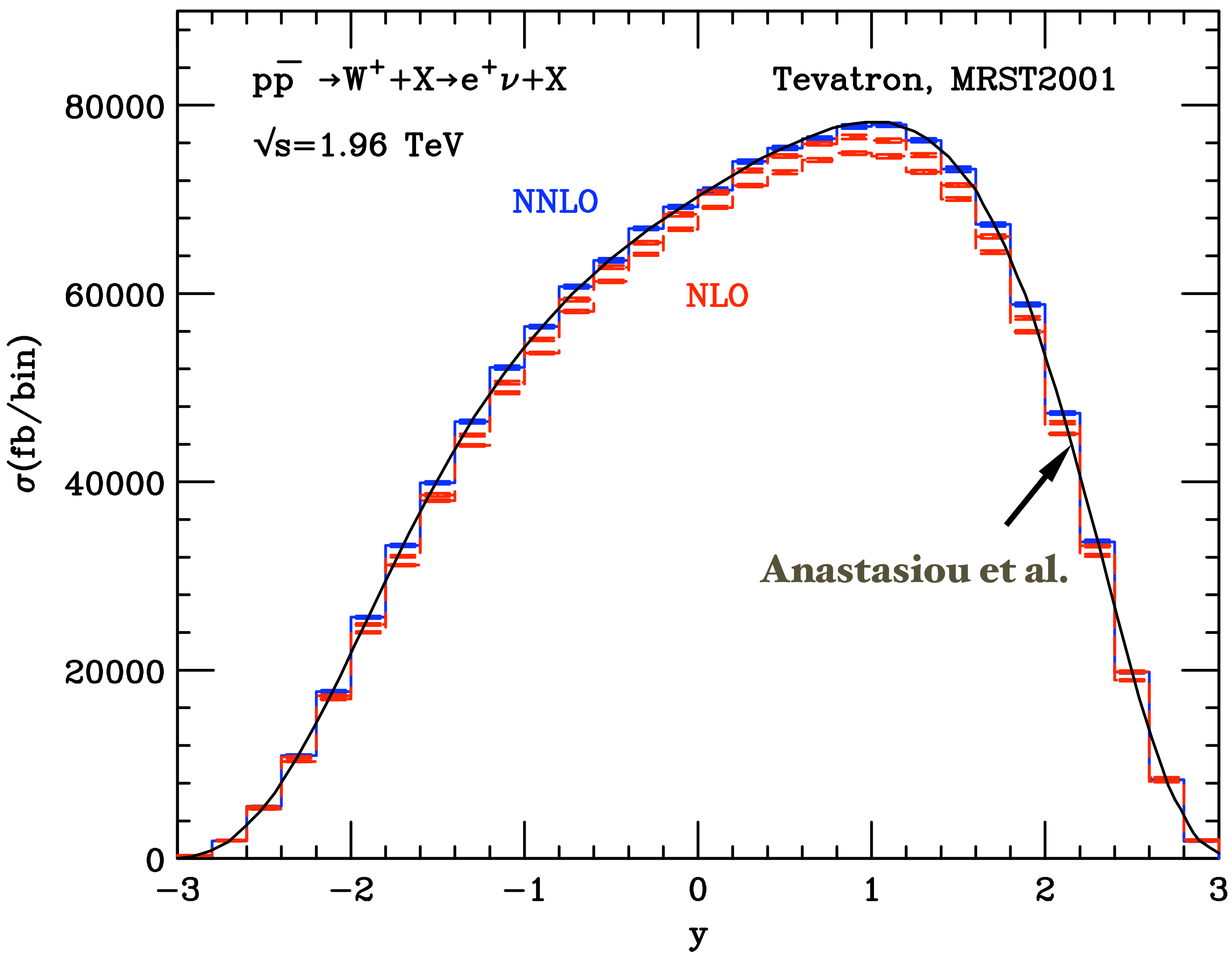
L.Cieri, S. Catani, G.Ferrera, D. de Florian, MG (2009)

→ **since V+1 jet is known to NLO we have all the necessary ingredients to go to NNLO**

W production: rapidity distribution

When no cuts are applied our numerical program provides the first independent check of the vector boson rapidity distribution up to NNLO

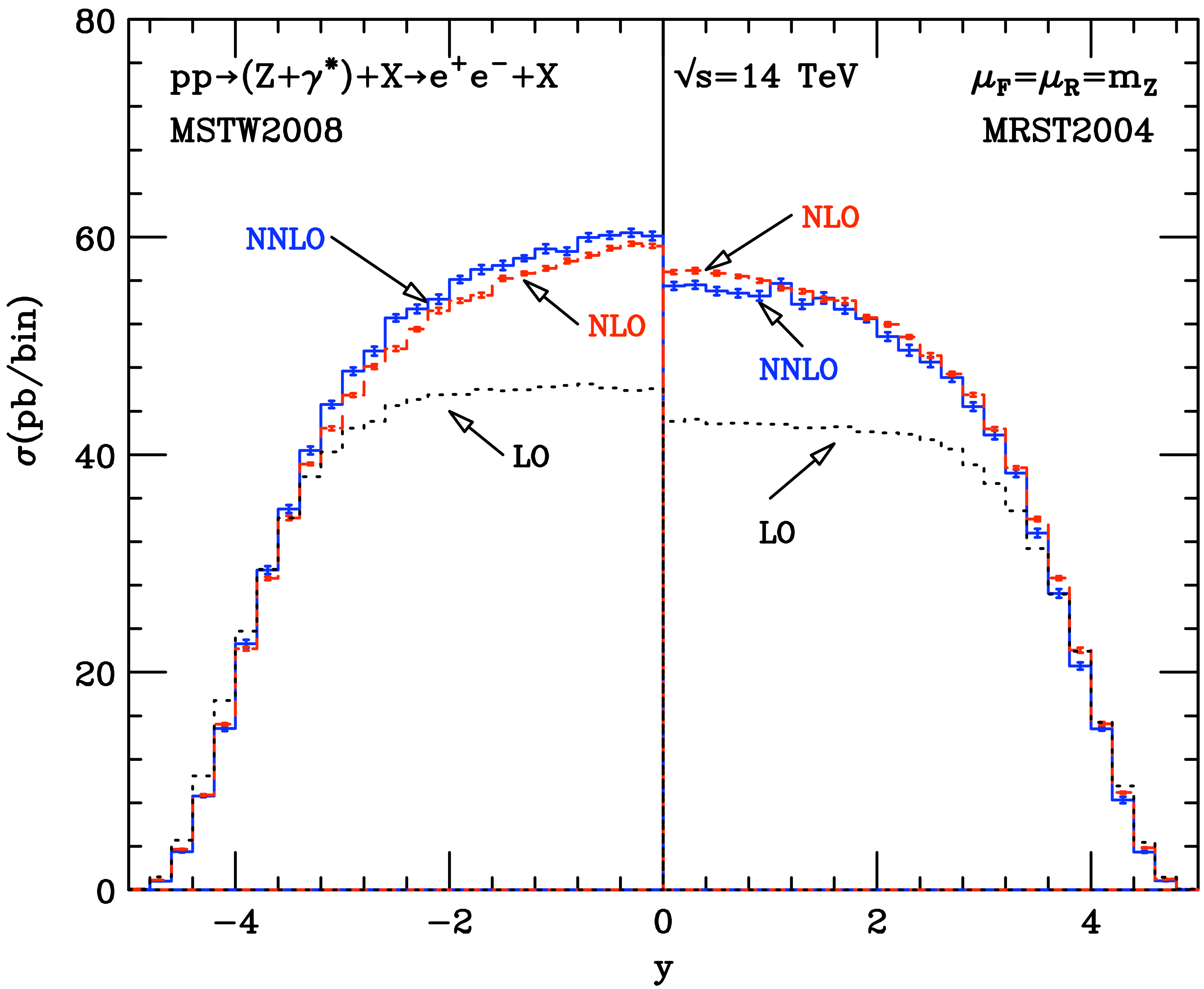
C.Anastasiou et al. (2003)



In this plot I compare the NNLO result with the NLO band (obtained by varying $\mu_F = \mu_R$ between $0.5\, m_W$ and $2\, m_W$) and with the (scaled) result by Anastasiou et al.

The two results appear to be in good agreement

Z production: rapidity distribution



No cuts: rapidity distribution of the vector boson

left: MSTW2008

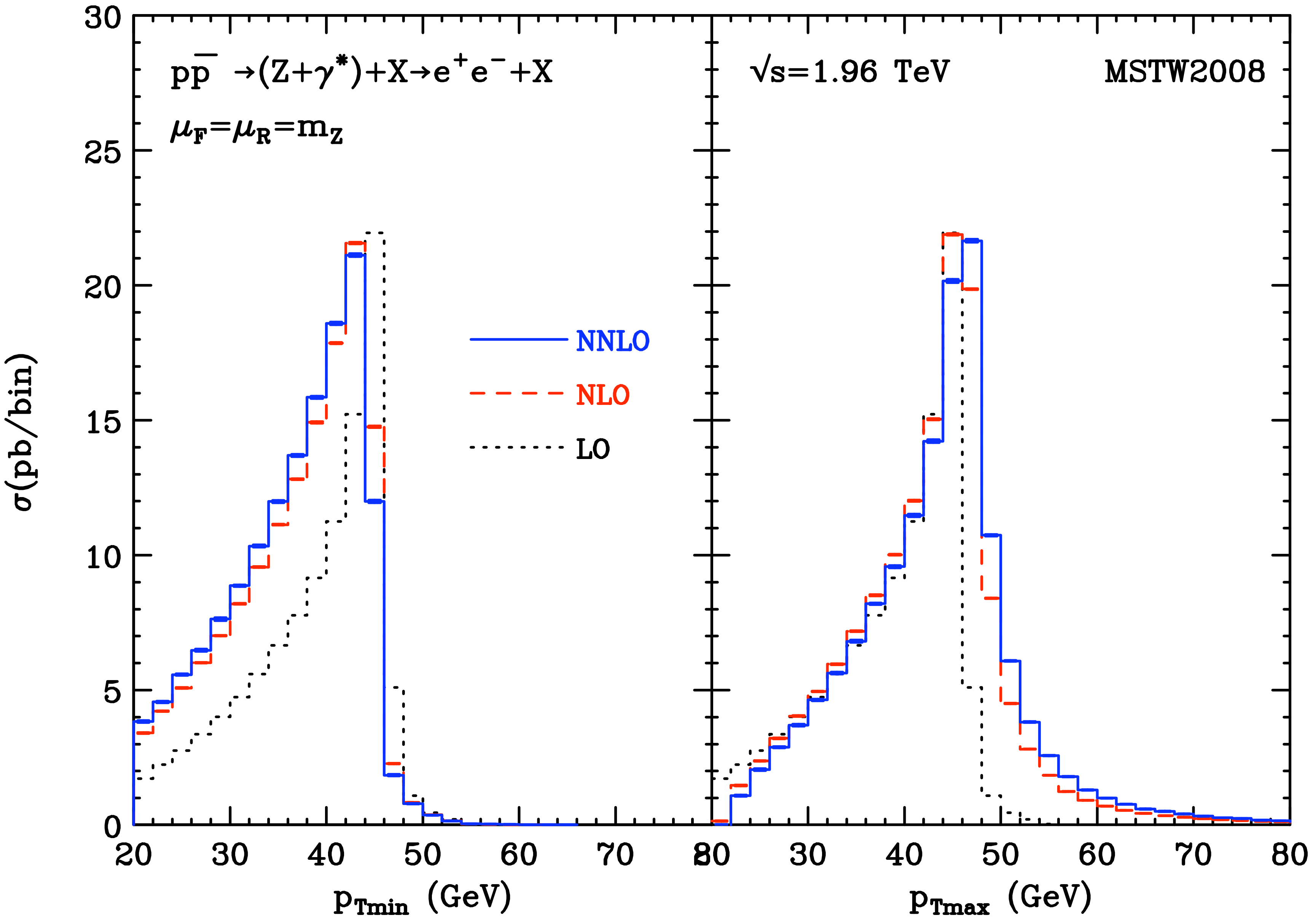
from NLO to NNLO the cross section is increased by about 3%

right: MRST2004

from NLO to NNLO the cross section is decreased by about 2%

MSTW2008 includes more refined treatment of heavy quark thresholds

Z production at the Tevatron



Cuts:

$p_{\mathrm{Tmin}} \geq 20\,\mathrm{GeV} \quad |\eta| < 2$

$70\,\mathrm{GeV} \leq m_{e^+e^-} \leq 110\,\mathrm{GeV}$

NNLO corrections make the p_{Tmin} distribution softer and the p_{Tmax} harder

Accepted cross sections:

$\sigma_{LO} = 103.37 \pm 0.04$ pb, $\sigma_{NLO} = 140.43 \pm 0.07$ pb $\sigma_{NNLO} = 143.86 \pm 0.12\,\mathrm{pb}$

W production at the Tevatron

Define $m_T = \sqrt{2 p_T^l p_T^{\rm miss}(1-\cos\phi)}$

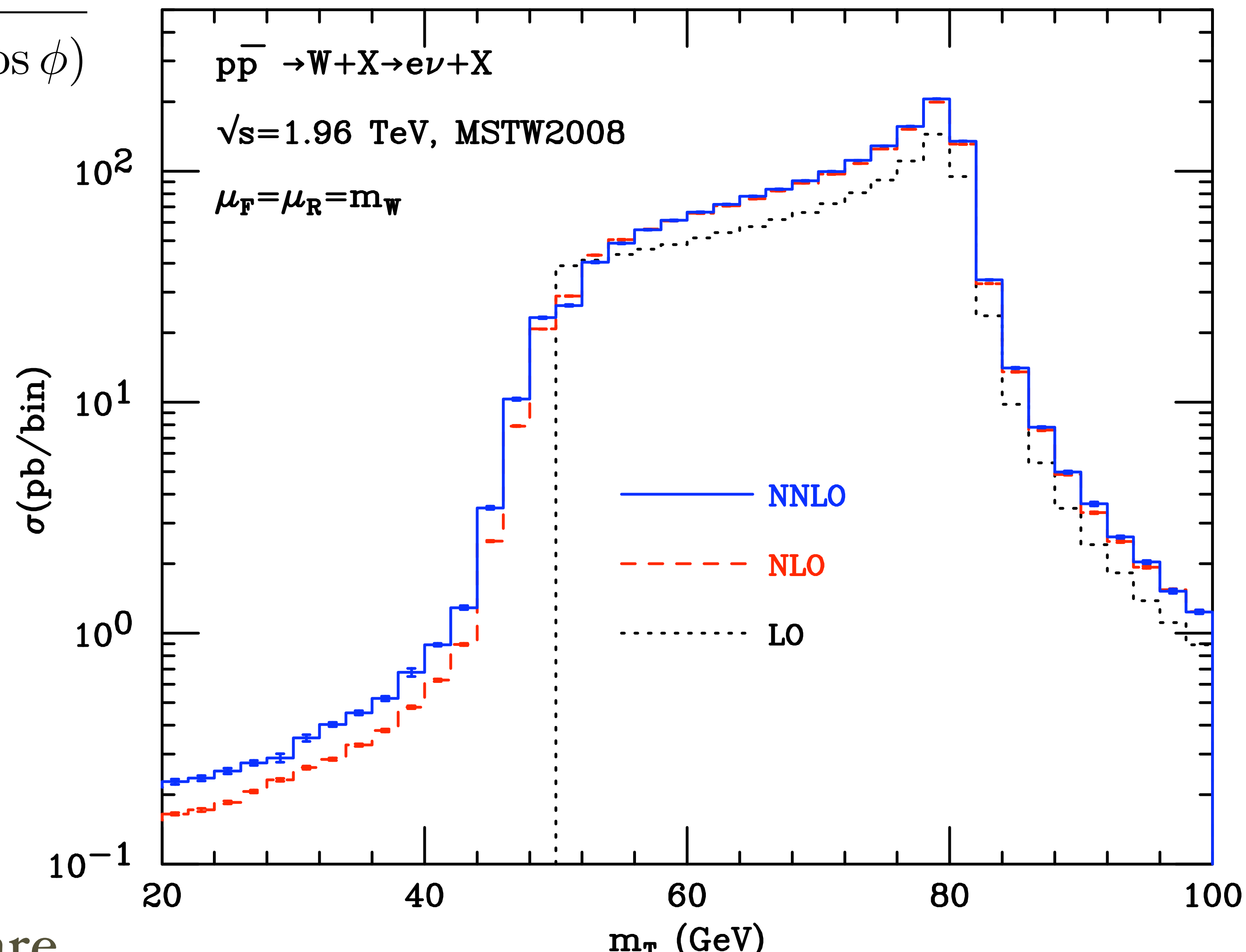
Cuts: $p_T^{\rm miss} > 25\,{\rm GeV}$

$p_T^l > 20\,{\rm GeV}$ $|\eta| < 2$

Note that at LO $\phi = \pi$

➡ $p_T^{\rm miss} > 25\,{\rm GeV}$

gives $m_T > 50\,{\rm GeV}$



In the presence of such a kinematical boundary there are perturbative instabilities at NLO and NNLO

$\sigma_{LO} = 1.161 \pm 0.001$ nb $\sigma_{NLO} = 1.550 \pm 0.001$ nb

$\sigma_{NNLO} = 1.586 \pm 0.002$ nb

Below the boundary the NNLO effects is large $+40\%$ at $m_T \sim 30\,{\rm GeV}$ ➡ **This is because in this region the calculation is NLO !**

Summary & Outlook

- Vector boson production is a benchmark process for physics studies within and beyond the SM
- We have recently completed a fully exclusive QCD calculation at NNLO for this process
- Spin correlations and finite-width effects are included
- Our calculation is implemented in a parton level event generator that allows the user to apply arbitrary cuts on the final state leptons and the associated jet activity
- The program also allows the user to plot all the desired distributions in the form of bin histograms

PUBLIC CODE AVAILABLE SOON !