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“W Boson Production at Large Transverse Momentum”

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Main Idea:

• To study the production of W bosons at large transverse momentum in $p\bar{p}$ collisions

• The exact NLO differential cross sections predictions can be improved if higher order threshold soft–gluon corrections are taken into account.

Results:

• The transverse momentum distribution of the W at the Tevatron is slightly enhanced and the factorisation and renormalisation scale dependence is reduced.

Motivation:

• W boson production in hadron colliders as a test of the Standard Model and to estimate backgrounds to new physics.
(e.g. $Wb\bar{b}$ production as background to the associated Higgs boson production $p\bar{p} \to H(\to b\bar{b})W$ at the Tevatron Ellis–Veseli(1999))

Background:

• The NLO cross section for W hadroproduction at large transverse momentum done by Arnold–Reno(1989) Gonsalves–Pawlowski–Wai(1989).

Threshold Resummation:

Near partonic threshold limited phase space for real gluon emission. Large logarithms arising from incomplete cancellations between real emission and virtual graphs.

Threshold corrections, in the eikonal approximation, exponentiate as a result of the factorization properties of the cross section .

Kidonakis–Sterman(1996) Kidonakis–Oderda–Sterman (1998)

Laenen–Oderda–Sterman(1998)

The cross section is factorized into functions that describe gluons collinear to the incoming partons, hard quanta, and noncollinear soft-gluons.

The renormalization group properties of these functions result in resummation. Threshold corrections have been resummed for many processes.

In this talk:

Phenomenological analysis of the results in Kidonakis–Del Duca (2000) where threshold logarithms where resummed for electroweak boson hadroproduction at NNLL accuracy.

NNLO soft–gluon corrections for W-boson production at large transverse momentum are studied.

It is possible to go beyond NNLL as shown in N. Kidonakis (2003).

Kinematics and notation:

Hadronic production of W boson with m_W:

$$h_A(P_A) + h_B(P_B) \longrightarrow W(Q) + X$$

Factorisation:

$$E_Q \frac{d\sigma_{h_A h_B \to W(Q)+X}}{d^3Q} = \sum_f \int dx_1\, dx_2\; \phi_{f_a/h_A}(x_1, \mu_F^2)\; \phi_{f_b/h_B}(x_2, \mu_F^2) \times E_Q \frac{d\widehat{\sigma}_{f_a f_b \to W(Q)+X}}{d^3Q}(s, t, u, Q, \mu_F, \alpha_s(\mu_R^2))$$

$E_Q = Q^0$
$\phi_{f/h}$: parton distribution
$\widehat{\sigma}$: perturbative parton-level cross section
Initial-state collinear singularities
factorized into $\phi_{f/h}$at factorization scale μ_F
μ_R: renormalization scale.

Parton level, lowest-order subprocesses:

$$\begin{aligned} q(p_a) + g(p_b) &\longrightarrow W(Q) + q(p_c)\,, \\ q(p_a) + \bar{q}(p_b) &\longrightarrow W(Q) + g(p_c) \end{aligned}$$

Hadronic & partonic kinematical invariants:

$$\begin{aligned} S &= (P_A + P_B)^2 \\ T &= (P_A - Q)^2 \\ U &= (P_B - Q)^2 \\ S_2 &= S + T + U - Q^2 \end{aligned}$$

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S_2, s_2: invariant mass recoiling against the W.

$s_2 = (p_a + p_b - Q)^2$: inelasticity parton scatterg.
$s_2 = 0$ for one-parton production.

$p_a = x_1 P_A$ and $p_b = x_2 P_B$, therefore relations:

$$\begin{aligned} s &= x_1 x_2 S \\ t - Q^2 &= x_1 (T - Q^2) \\ u - Q^2 &= x_2 (U - Q^2) \end{aligned} \tag{1}$$

Partonic $\hat{\sigma}$ includes + distributions at α_s^n remnants of cancellations between real and virtual contributions:

$$\left[\frac{\ln^m(s_2/Q_T^2)}{s_2}\right]_+ , \qquad m \le 2n-1$$

defined by:

$$\int_0^{s_{2\,max}} ds_2\, f(s_2) \left[\frac{\ln^m(s_2/Q_T^2)}{s_2}\right]_+ \equiv$$
$$\int_0^{s_{2\,max}} ds_2 \frac{\ln^m(s_2/Q_T^2)}{s_2} \left(f(s_2) - f(0)\right) + \frac{1}{m+1} \ln^{m+1}\left(\frac{s_{2\,max}}{Q_T^2}\right) f(0)$$

In this work use of Q_T instead of Q.

Terminology at order α_s^n:

LL $\to m = 2n-1$
NLL $\to m = 2n-2$
NNLL $\to m = 2n-3$
NNNLL $\to m = 2n-4$

• $qg \longrightarrow Wq$ **subprocess:** $\overline{\text{MS}}$ scheme.

Born differential cross section:

$$E_Q \frac{d\sigma^B_{qg\to Wq}}{d^3Q} = F^B_{qg\to Wq}\,\delta(s_2)$$

where

$$F^B_{qg\to Wq} = \frac{\alpha\,\alpha_s(\mu_R^2) C_F}{s(N_c^2-1)} A^{qg} \sum_f |L_{ff_a}|^2$$

$$A^{qg} = -\left(\frac{s}{t} + \frac{t}{s} + \frac{2uQ^2}{st}\right)$$

L: left-handed couplings of W to quarks

$\sum_f$: flavour sum allowed by CKM mixing & energy threshold.

NLO soft + virtual corrections:

$$E_Q \frac{d\hat{\sigma}^{(1)}_{qg\to Wq}}{d^3Q} = F^B_{qg\to Wq} \frac{\alpha_s(\mu_R^2)}{\pi} \left\{ c_3^{qg} \left[\frac{\ln(s_2/Q_T^2)}{s_2}\right]_+ + c_2^{qg} \left[\frac{1}{s_2}\right]_+ + c_1^{qg}\,\delta(s_2)\right\}$$

$$c_3^{qg} = C_F + 2\,C_A$$

$$c_2^{qg} = -(C_F + C_A)\ln\left(\frac{\mu_F^2}{Q_T^2}\right) - \frac{3}{4}C_F - C_A \ln\left(\frac{tu}{sQ_T^2}\right)$$

$$c_1^{qg} = \frac{1}{2A^{qg}}\left[B_1^{qg} + B_2^{qg} n_f + C_1^{qg} + C_2^{qg} n_f\right] + \frac{c_3^{qg}}{2}\ln^2\left(\frac{Q_T^2}{Q^2}\right) + c_2^{qg}\ln\left(\frac{Q_T^2}{Q^2}\right)$$

NNLO soft + virtual: $E_Q\frac{d\hat{\sigma}^{(2)}_{qg\to Wq}}{d^3Q}=F^B_{qg\to Wq}\frac{\alpha_s^2(\mu_R^2)}{\pi^2}\,\hat{\sigma'}^{(2)}_{qg\to Wq}$

$$
\begin{aligned}
\hat{\sigma'}^{(2)}_{qg\to Wq} \;=\; & \frac{1}{2}(c_3^{qg})^2\left[\frac{\ln^3(s_2/Q_T^2)}{s_2}\right]_+ + \left[\frac{3}{2}c_3^{qg}\,c_2^{qg}-\frac{\beta_0}{4}c_3^{qg}+C_F\frac{\beta_0}{8}\right]\left[\frac{\ln^2(s_2/Q_T^2)}{s_2}\right]_+ \\
& +\left\{c_3^{qg}\,c_1^{qg}+(c_2^{qg})^2-\zeta_2\,(c_3^{qg})^2-\frac{\beta_0}{2}T_2^{qg}+\frac{\beta_0}{4}c_3^{qg}\ln\left(\frac{\mu_R^2}{s}\right)+(C_F+C_A)\,K\right. \\
& \left.\quad + C_F\left[-\frac{K}{2}+\frac{\beta_0}{4}\ln\left(\frac{Q_T^2}{s}\right)\right]-\frac{3}{16}\beta_0 C_F\right\}\left[\frac{\ln(s_2/Q_T^2)}{s_2}\right]_+ \\
& +\left\{c_2^{qg}\,c_1^{qg}-\zeta_2\,c_2^{qg}\,c_3^{qg}+\zeta_3\,(c_3^{qg})^2-\frac{\beta_0}{2}T_1^{qg}+\frac{\beta_0}{4}\,c_2^{qg}\ln\left(\frac{\mu_R^2}{s}\right)+\mathcal{G}^{(2)}_{qg}\right. \\
& \quad +(C_F+C_A)\left[\frac{\beta_0}{8}\ln^2\left(\frac{\mu_F^2}{s}\right)-\frac{K}{2}\ln\left(\frac{\mu_F^2}{s}\right)\right]-C_F\,K\ln\left(\frac{-u}{Q_T^2}\right)-C_A\,K\ln\left(\frac{-t}{Q_T^2}\right) \\
& \left.\quad + C_F\left[\frac{\beta_0}{8}\ln^2\left(\frac{Q_T^2}{s}\right)-\frac{K}{2}\ln\left(\frac{Q_T^2}{s}\right)\right]-\frac{3}{16}\beta_0 C_F\ln\left(\frac{Q_T^2}{s}\right)\right\}\left[\frac{1}{s_2}\right]_+ \\
& +\left\{\frac{1}{2}({c'}^{qg}_{1\,\mu})^2+{c'}^{qg}_{1\,\mu}{T'}^{qg}_1+\frac{\beta_0}{4}{c'}^{qg}_{1\,\mu}\ln\left(\frac{Q_T^2}{s}\right)+\frac{\beta_0}{4}c_1^{qg}\ln\left(\frac{\mu_R^2}{Q_T^2}\right)-(C_F+C_A)^2\frac{\zeta_2}{2}\ln^2\left(\frac{\mu_F^2}{Q_T^2}\right)\right. \\
& \quad +(C_F+C_A)\ln\left(\frac{\mu_F^2}{Q_T^2}\right)\left(\zeta_2 T_2^{qg}-\zeta_2(C_F+C_A)\ln\left(\frac{Q_T^2}{s}\right)-\zeta_3 c_3^{qg}\right) \\
& \quad -\frac{\beta_0^2}{32}\ln^2\left(\frac{\mu_R^2}{Q_T^2}\right)-\frac{\beta_0^2}{16}\ln\left(\frac{\mu_R^2}{Q_T^2}\right)\ln\left(\frac{Q_T^2}{s}\right)+\frac{\beta_1}{16}\ln\left(\frac{\mu_R^2}{Q_T^2}\right) \\
& +\frac{\beta_0}{8}\left[\frac{3}{4}C_F+\frac{\beta_0}{4}-C_F\ln\left(\frac{-u}{Q_T^2}\right)-C_A\ln\left(\frac{-t}{Q_T^2}\right)\right]\left[\ln^2\left(\frac{\mu_F^2}{Q_T^2}\right)+2\ln\left(\frac{\mu_F^2}{Q_T^2}\right)\ln\left(\frac{Q_T^2}{s}\right)\right] \\
& +C_F\frac{K}{2}\ln\left(\frac{-u}{Q_T^2}\right)\ln\left(\frac{\mu_F^2}{Q_T^2}\right)+C_A\frac{K}{2}\ln\left(\frac{-t}{Q_T^2}\right)\ln\left(\frac{\mu_F^2}{Q_T^2}\right)-({\gamma'}^{(2)}_{q/q}+{\gamma'}^{(2)}_{g/g})\ln\left(\frac{\mu_F^2}{Q_T^2}\right) \\
& \left.\quad + R^{(2)}_{qg}\right\}\delta(s_2)
\end{aligned}
$$

$K = C_A(67/18 - \zeta_2) - 5n_f/9$ Kodaira–Trentadue (1982)

$\beta_1 = 34C_A^2/3 - 2n_f(C_F + 5C_A/3)$

$$\gamma'^{(2)}_{q/q} = C_F^2\left(\frac{3}{32} - \frac{3}{4}\zeta_2 + \frac{3}{2}\zeta_3\right) + C_F C_A\left(-\frac{3}{4}\zeta_3 + \frac{11}{12}\zeta_2 + \frac{17}{96}\right) + n_f C_F\left(-\frac{\zeta_2}{6} - \frac{1}{48}\right)$$

$$\gamma'^{(2)}_{g/g} = C_A^2\left(\frac{2}{3} + \frac{3}{4}\zeta_3\right) - n_f\left(\frac{C_F}{8} + \frac{C_A}{6}\right)$$

Two-loop parton anomalous dimensions
Gonzalez-Arroyo–Lopez–Yndurain (1979)
Curci–Furmanski–Petronzio(1980)

$\mathcal{G}^{(2)}_{qg}$ in the NNNLL term:
A set of two-loop contributions

$$\mathcal{G}^{(2)}_{qg} = C_F^2\left(-\frac{3}{32} + \frac{3}{4}\zeta_2 - \frac{3}{2}\zeta_3\right) + C_F C_A\left(\frac{3}{4}\zeta_3 - \frac{11}{12}\zeta_2 - \frac{189}{32}\right) + C_A^2\left(\frac{7}{4}\zeta_3 + \frac{11}{3}\zeta_2 - \frac{41}{216}\right) + n_f C_F\left(\frac{1}{6}\zeta_2 + \frac{17}{16}\right) + n_f C_A\left(-\frac{2}{3}\zeta_2 - \frac{5}{108}\right)$$

No two-loop process-dependent contributions
In top hadroproduction & direct photon production small.

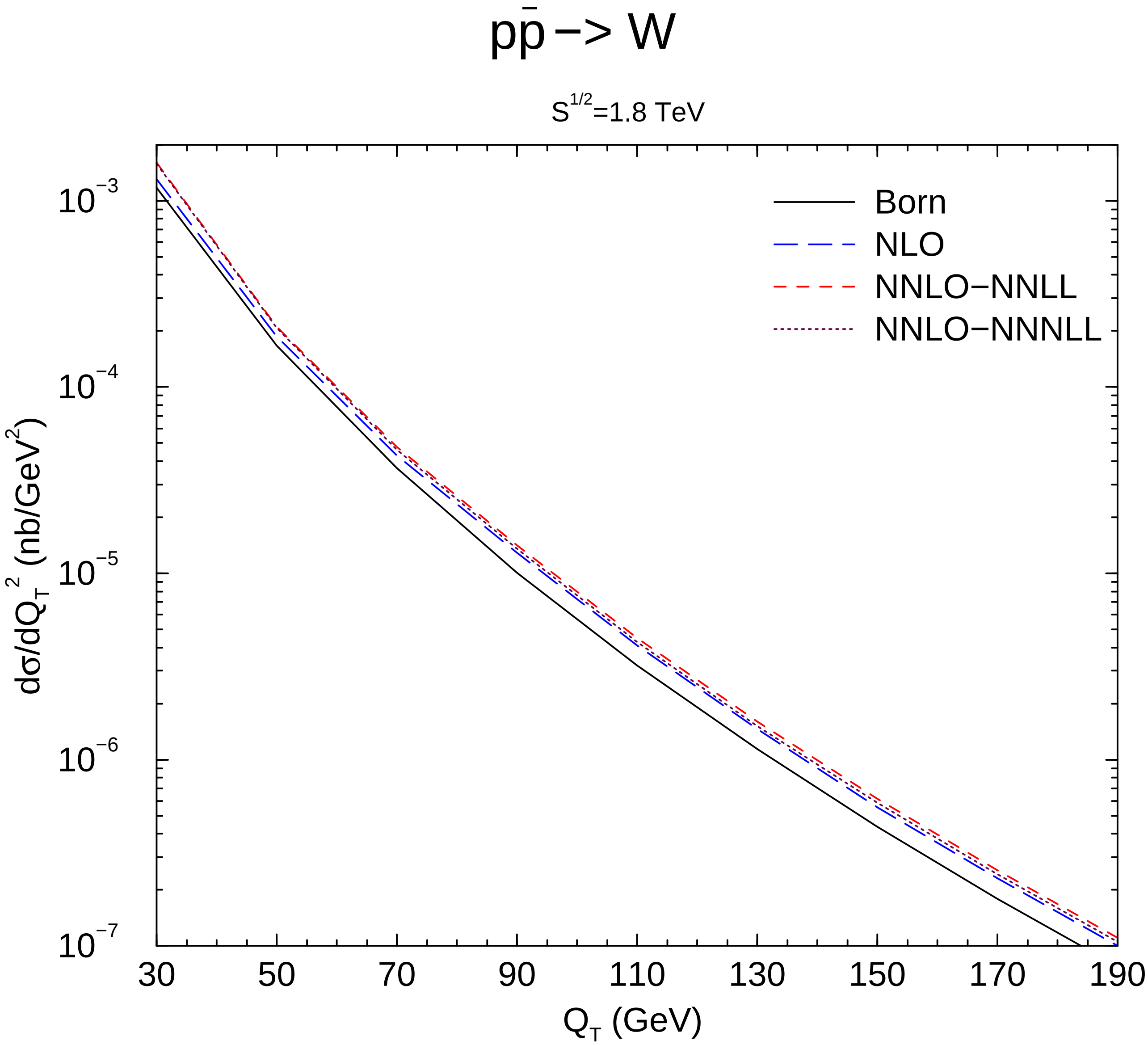
$-\zeta_2 c_2^{qg} c_3^{qg} + \zeta_3 (c_3^{qg})^2$ dominates.

In $\delta(s_2)$ not full virtual corrections
No $R^{(2)}_{qg}$: scale-independent virtual corrections
All scale–dependent terms are included.

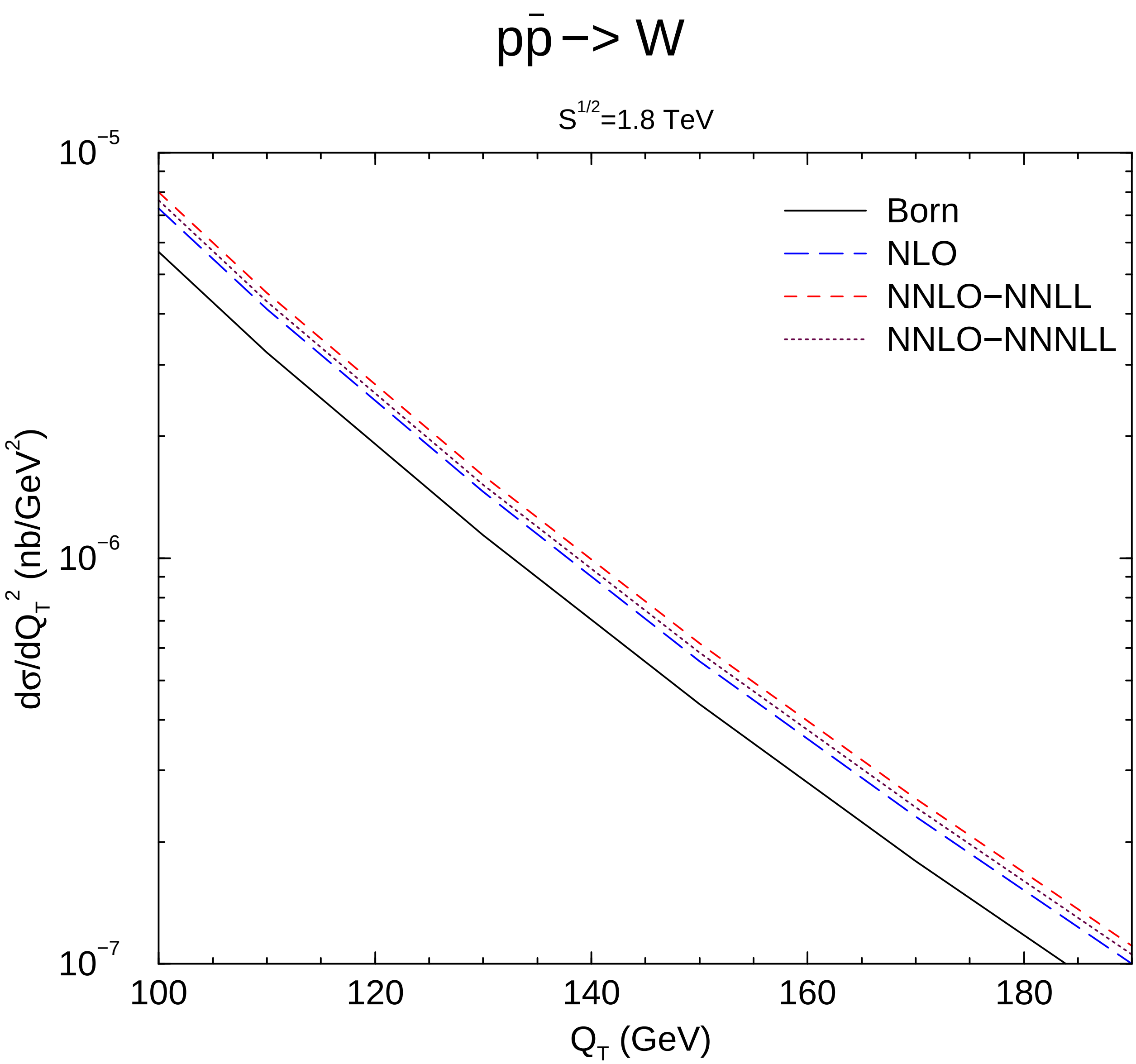
- $q\bar{q} \longrightarrow Wg$ **subprocess:**

Similar expressions.

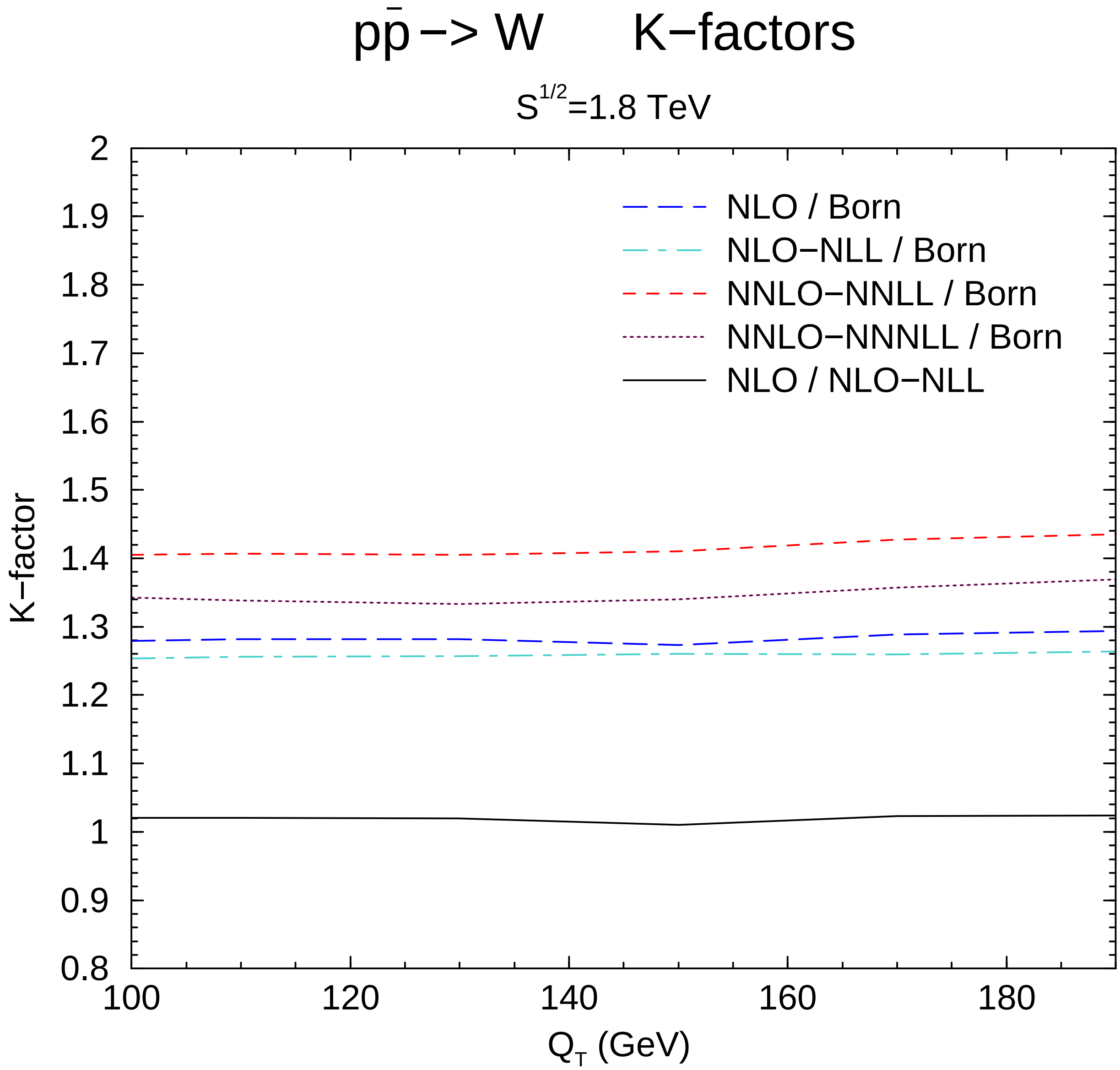
- **Numerical results:**



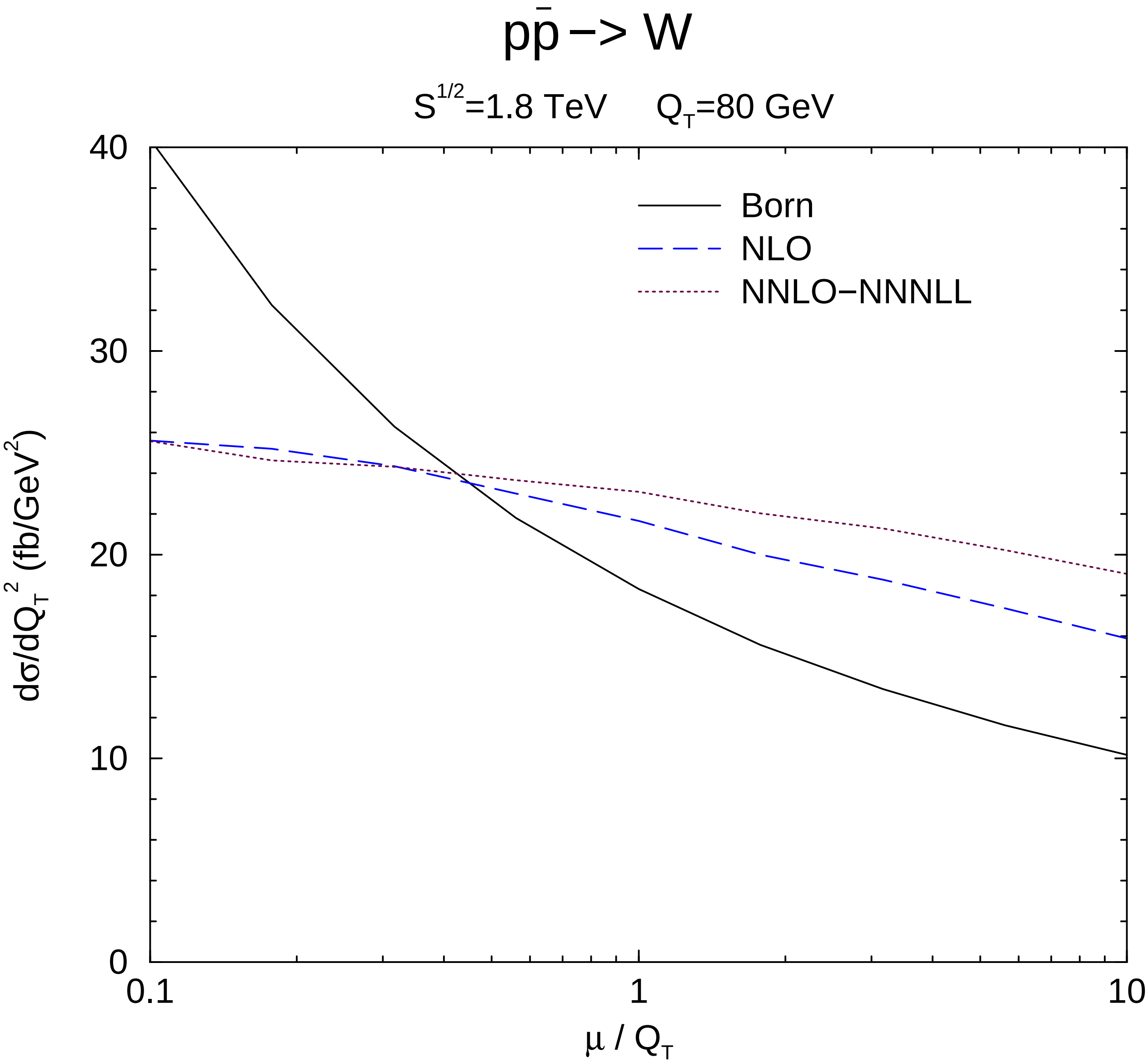
The differential cross section, $d\sigma/dQ_T^2$, for W hadroproduction in $p\bar{p}$ collisions at the Tevatron with $\sqrt{S} = 1.8$ TeV and $\mu_F = \mu_R = Q_T$. Shown are the Born (solid line), NLO (long-dashed line), NNLO-NNLL (short-dashed line), and NNLO-NNNLL (dotted line) results.



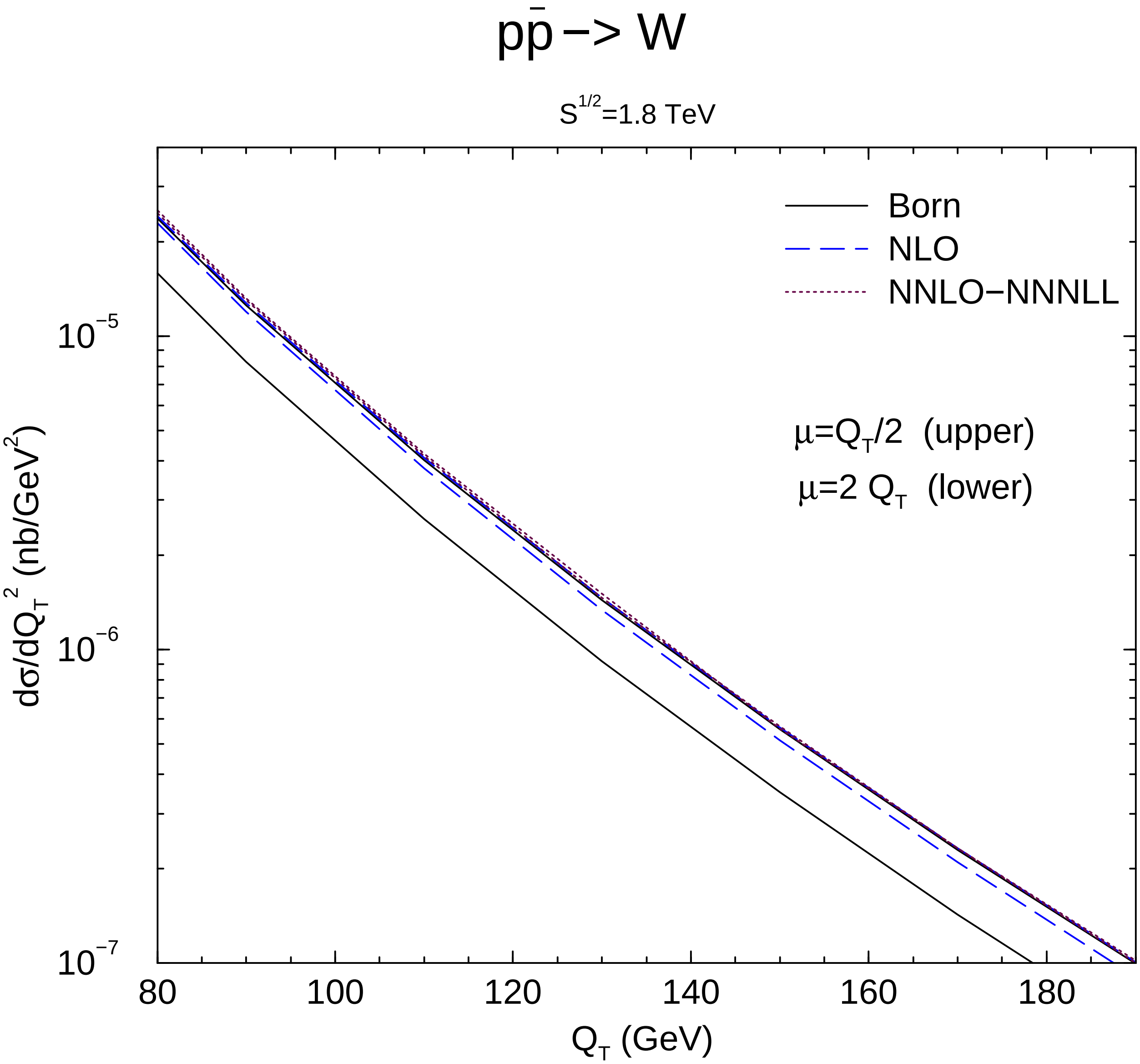
The differential cross section, $d\sigma/dQ_T^2$ at high Q_T



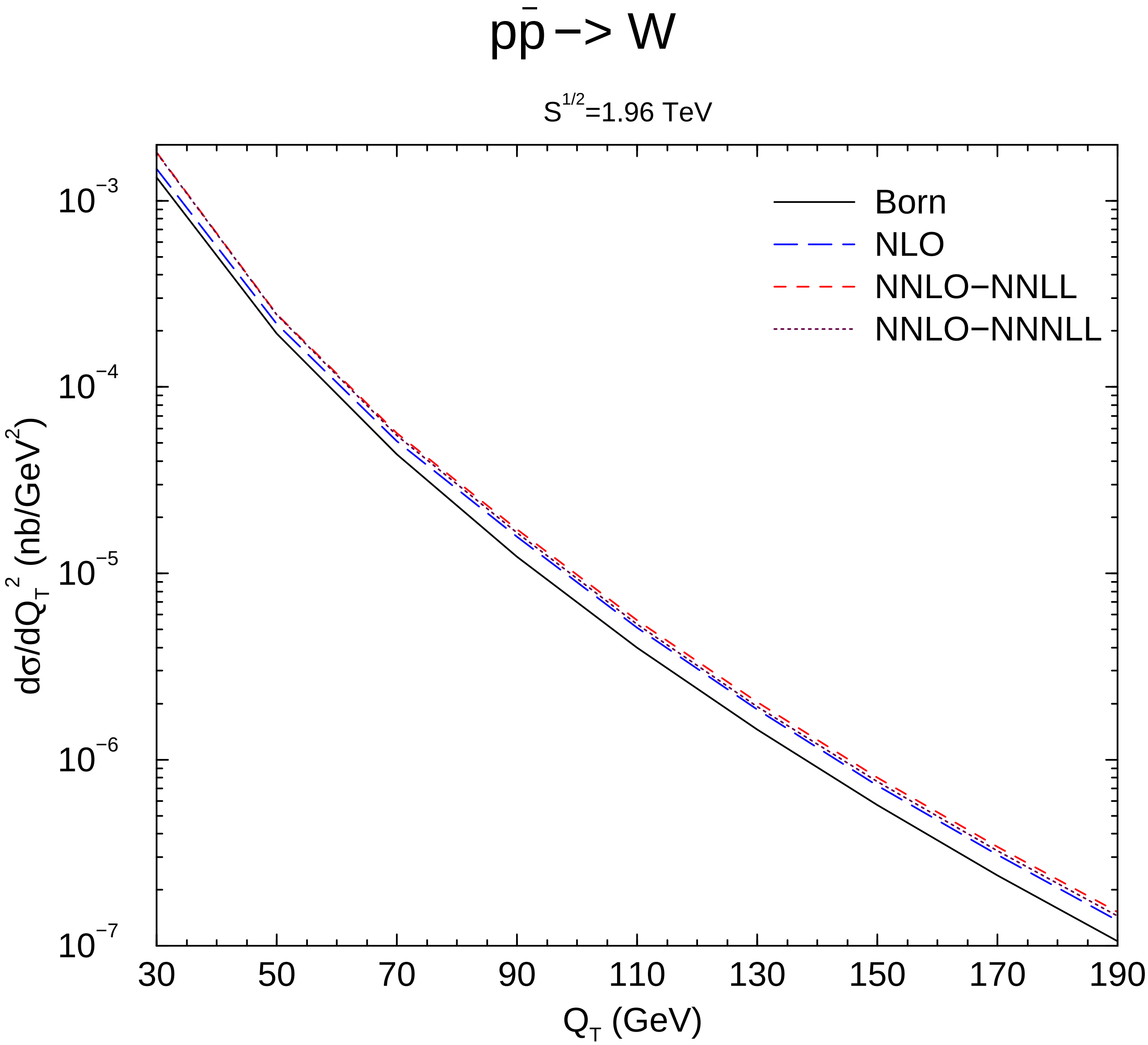
K-factors for $d\sigma/dQ_T^2$, for W hadroproduction with $\sqrt{S}=1.8$ TeV and $\mu_F=\mu_R=Q_T$. Shown are the K- factors for exact NLO/Born (long-dashed line), NLO-NLL/Born (dash-dotted line), NNLO-NNLL/Born (short-dashed line), and approximate NNLO-NNNLL/Born (dotted line) results. Also shown is the ratio of the exact NLO to the NLO-NLL cross section (solid line).



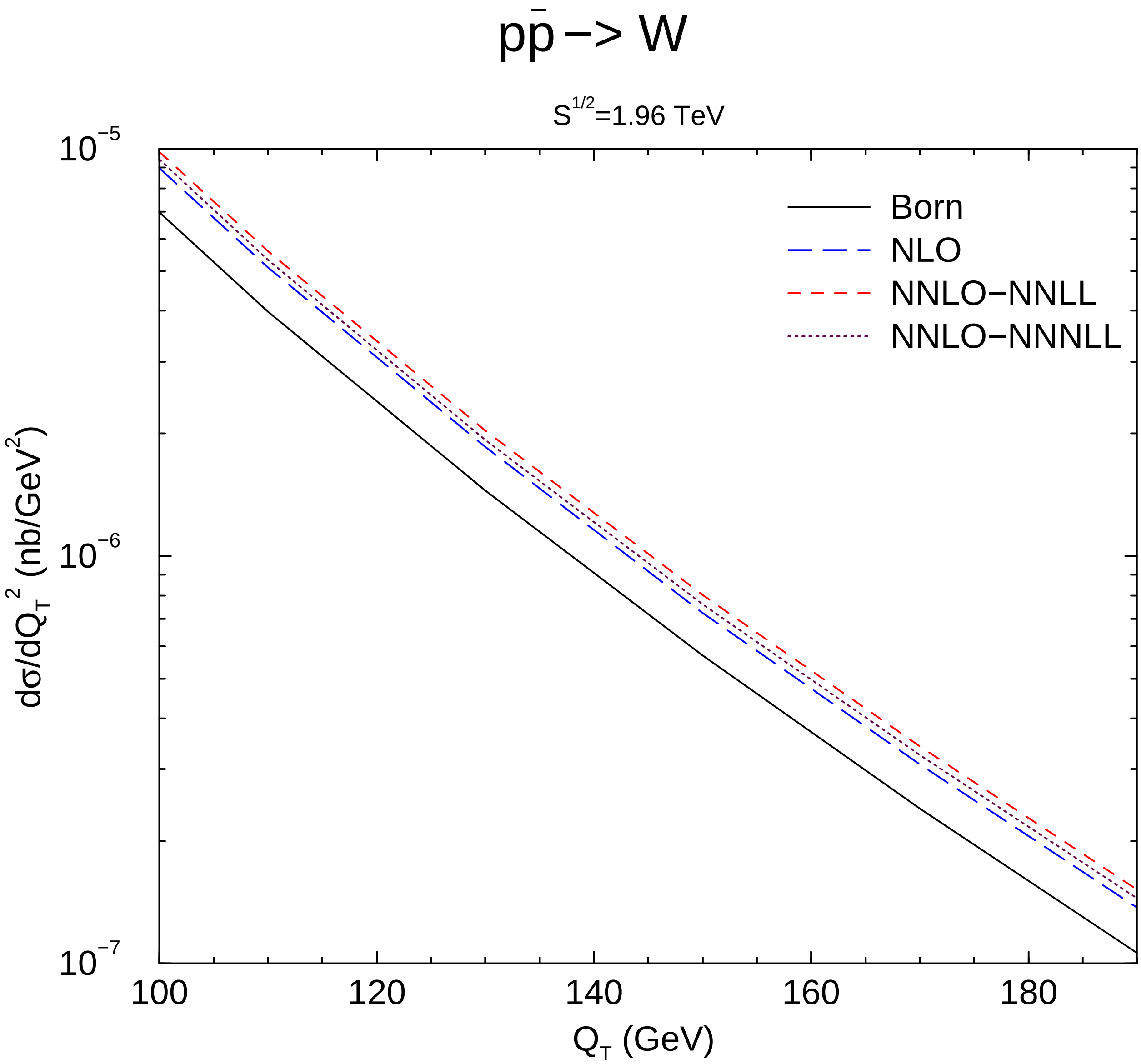
The differential cross section, $d\sigma/dQ_T^2$, for W hadroproduction in $p\bar{p}$ collisions at the Tevatron with $\sqrt{S} = 1.8$ TeV, $Q_T = 80$ GeV, and $\mu \equiv \mu_F = \mu_R$. Shown are the Born (solid line), exact NLO (long-dashed line), and NNLO-NNNLL (dotted line) results.



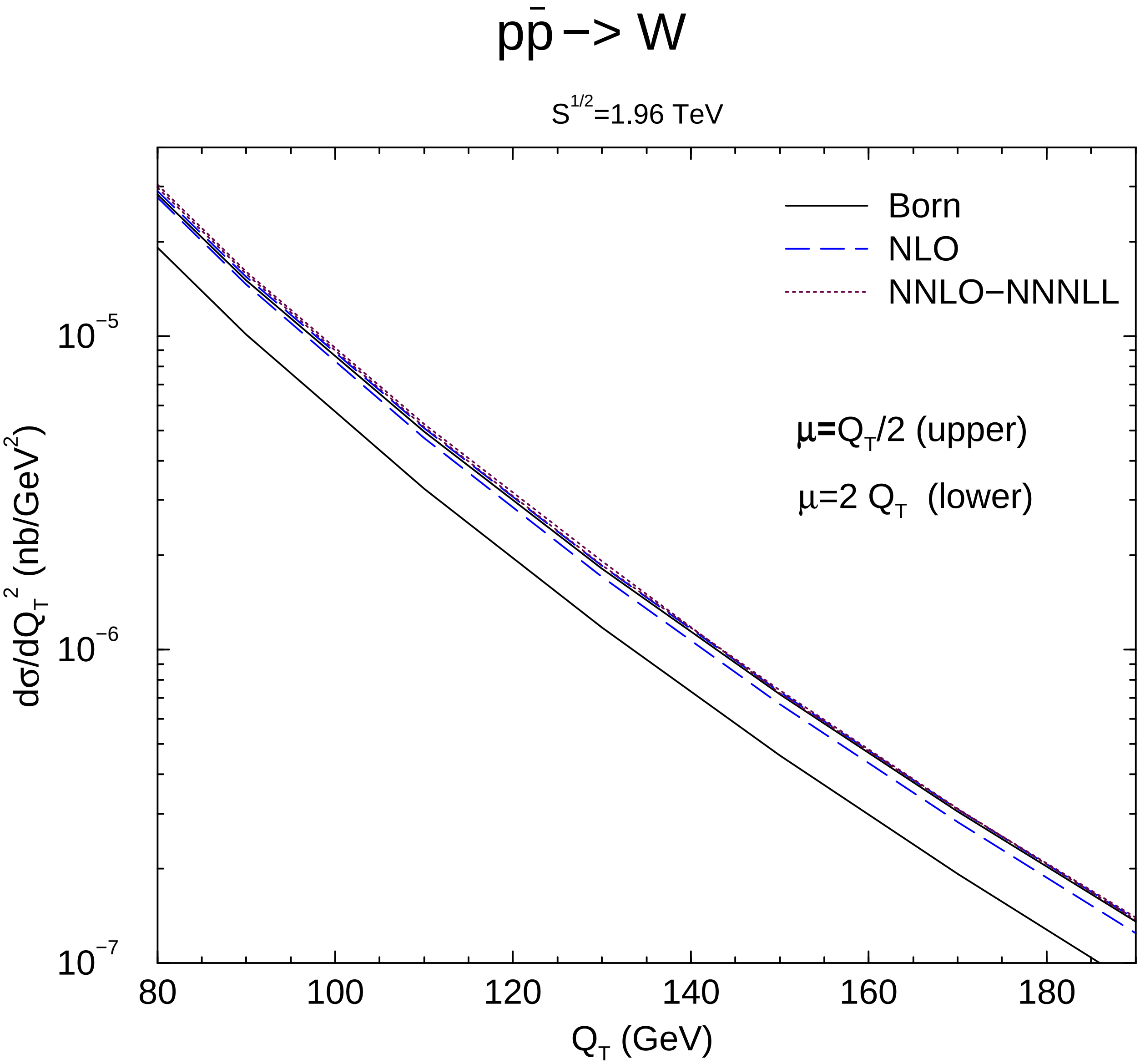
The differential cross section, $d\sigma/dQ_T^2$, for W hadroproduction in $p\bar{p}$ collisions at the Tevatron with $\sqrt{S} = 1.8$ TeV and $\mu \equiv \mu_F = \mu_R = Q_T/2$ or $2Q_T$. Shown are the Born (solid lines), NLO (long-dashed lines), and NNLO-NNNLL (dotted lines) results. The upper lines are with $\mu = Q_T/2$, the lower lines with $\mu = 2Q_T$.



The differential cross section, $d\sigma/dQ_T^2$, for W hadroproduction in $p\bar{p}$ collisions at the Tevatron Run II with $\sqrt{S} = 1.96$ TeV and $\mu_F = \mu_R = Q_T$. Shown are the Born (solid line), exact NLO (long-dashed line), NNLO-NNLL (short-dashed line), and NNLO-NNNLL (dotted line) results.



The differential cross section, $d\sigma/dQ_T^2$ at high Q_T.



The differential cross section, $d\sigma/dQ_T^2$, for W hadroproduction in $p\bar{p}$ collisions at the Tevatron with $\sqrt{S} = 1.96$ TeV and $\mu \equiv \mu_F = \mu_R = Q_T/2$ or $2Q_T$. Shown are the Born (solid lines), NLO (long-dashed lines), and NNLO-NNNLL (dotted lines) results. The upper lines are with $\mu = Q_T/2$, the lower lines with $\mu = 2Q_T$.