Precise calculation for heavy gauge boson production in the LHT model

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Outline

1. Introduction of littlest Higgs model with T-parity(LHT)
2. $W_H/Z_H + q_-$ associated production
3. W_H pair production
4. Summary

1. Introduction of littlest Higgs model with T-parity(LHT)

Symmetry breaking pattern

- $SU(5)/SO(5)$ global symmetry breaking
- local symmetry group breaking

$$[SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2$$

$$\Rightarrow SU(2)_L \times U(1)_Y$$ (identified as SM gauge group)

Gauge generators:

$$Q_1^a = \begin{pmatrix} \sigma^a/2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0_{2\times 2} \end{pmatrix}, Y_1 = \mathrm{diag}(3, 3, -2, -2, -2)/10,$$

$$Q_2^a = \begin{pmatrix} 0_{2\times 2} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma^a/2 \end{pmatrix}, Y_2 = \mathrm{diag}(2, 2, 2, -3, -3)/10.$$

Gauge and Higgs sectors

$$\mathcal{L}_{G+S} = \sum_{j=1}^{2} \left[-\frac{1}{2} Tr \left(W_{j\mu\nu} W_j^{\mu\nu} \right) - \frac{1}{4} B_{j\mu\nu} B_j^{\mu\nu} \right] + \frac{f^2}{8} Tr \left[\left(D_\mu \Sigma \right)^\dagger \left(D^\mu \Sigma \right) \right]$$

where the covariant derivative of Σ is

$$D_\mu \Sigma = \partial \Sigma - i \sum_{j=1}^{2} \left[g_j \left(W_{j\mu} \Sigma + \Sigma W_{j\mu}^T \right) + g_j' B_{j\mu} (Y_j \Sigma + \Sigma Y) \right]$$

Scalar fields: $\Sigma = e^{i\Pi/f} \Sigma_0 e^{i\Pi^T/f} = e^{2i\Pi/f} \Sigma_0$

$$\Sigma_0 = \langle \Sigma \rangle = \begin{pmatrix} & & 1_{2\times 2} \\ & 1 & \\ 1_{2\times 2} & & \end{pmatrix} \qquad \Pi = \begin{pmatrix} & \frac{H}{\sqrt{2}} & \phi \\ \frac{H^\dagger}{\sqrt{2}} & & \frac{H^T}{\sqrt{2}} \\ \phi^\dagger & \frac{H^*}{\sqrt{2}} & \end{pmatrix}$$

T-parity transformation

$$W^a_{1\mu} \longleftrightarrow W^a_{2\mu}, \qquad B_{1\mu} \longleftrightarrow B_{2\mu}$$

$$\Pi \longrightarrow -\Omega\Pi\Omega, \quad \text{where} \quad \Omega = \mathrm{diag}(1,1,-1,1,1)$$

T-party invariance: $g_1 = g_2 = \sqrt{2}g, g'_1 = g'_2 = \sqrt{2}g'$

T-even : $W^a_L = \dfrac{W^a_1 + W^a_2}{\sqrt{2}}$ and $B_L = \dfrac{B_1 + B_2}{\sqrt{2}}$

T-odd : $W^a_H = \dfrac{W^a_1 - W^a_2}{\sqrt{2}}$ and $B_H = \dfrac{B_1 - B_2}{\sqrt{2}}$

Mass eigenstates

$$W_L^{\pm} = \frac{W_L^1 \mp i W_L^2}{\sqrt{2}}, \begin{pmatrix} A_L \\ Z_L \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B_L \\ W_L^3 \end{pmatrix}, \text{(T-even)}$$

$$W_H^{\pm} = \frac{W_H^1 \mp i W_H^2}{\sqrt{2}}, \begin{pmatrix} A_H \\ Z_H \end{pmatrix} = \begin{pmatrix} \cos\theta_H & \sin\theta_H \\ -\sin\theta_H & \cos\theta_H \end{pmatrix} \begin{pmatrix} B_H \\ W_H^3 \end{pmatrix}, \text{(T-odd)}$$

mixing angle : $$S_H = \sin\theta_H \simeq \frac{5gg'}{4(5g^2 - g'^2)} \frac{v^2}{f^2}$$

T-even mass eigenstates: SM photon, W and Z bosons

T-odd mass eigenstants: heavy gauge bosons

$$m_{A_H} \simeq \frac{1}{\sqrt{5}} g' f \left(1 - \frac{5}{8}\frac{v^2}{f^2}\right), m_{Z_H} = m_{W_H} \simeq gf(1 - \frac{1}{8}\frac{v^2}{f^2}).$$

Fermion sector

$$\mathcal{L}_F = -\kappa f \left(\bar{\Psi}_2 \xi + \bar{\Psi}_1 \Sigma_0 \Omega \xi^\dagger \Omega \right) \Psi_{HR} + \mathrm{h.c.}$$

where

$$\Psi_1 = \begin{pmatrix} \psi_1 \\ 0 \\ 0 \end{pmatrix}, \Psi_2 = \begin{pmatrix} 0 \\ 0 \\ \psi_2 \end{pmatrix}, \Psi_{HR} = \begin{pmatrix} \tilde{\psi}_{HR} \\ \chi_{HR} \\ \psi_{HR} \end{pmatrix}.$$

T-parity transformation:

$$\Psi_1 \longrightarrow -\Sigma_0 \Psi_2, \quad \Psi_2 \longrightarrow -\Sigma_0 \Psi_1, \quad \Psi_{HR} \longrightarrow -\Psi_{HR}$$

Fermion sector

T-even left-handed $SU(2)$ doublet:

$$\psi_{SM} = (\psi_1 - \psi_2)/\sqrt{2}$$

T-odd $SU(2)$ doublets:

$$\psi_h = (\psi_1 + \psi_2)/\sqrt{2} \quad \text{(left-handed)} \qquad \psi_{HR} \quad \text{(right-handed)}$$

After EWSB:

$$m_{u_-} \simeq \sqrt{2}\kappa f \left(1 - \frac{1}{8}\frac{v^2}{f^2}\right), \qquad m_{d_-} = \sqrt{2}\kappa f$$

Top sector

In order to avoid quadratic divergences of the Higgs mass, Yukawa intraction of the top quark must be modified.

$$
\begin{aligned}
\mathcal{L}_t^Y &= \frac{\lambda_1 f}{2\sqrt{2}} \epsilon_{ijk}\epsilon_{xy}[(\bar{Q}_1)_i \Sigma_{jx}\Sigma_{ky} - (\bar{Q}_2\Sigma_0)_i \tilde{\Sigma}_{jx}\tilde{\Sigma}_{ky}]u_R \\
& \quad +\lambda_2 f(\bar{U}_{L_1}U_{R_1} + \bar{U}_{L2}U_{R2}) + h.c.
\end{aligned}
$$

where, $\tilde{\Sigma} = \Sigma_0 \Omega \Sigma^\dagger \Omega \Sigma_0$

$$
Q_1 = \begin{pmatrix} \psi_1 \\ U_{L1} \\ 0 \end{pmatrix} \quad \text{and} \quad Q_2 = \begin{pmatrix} 0 \\ U_{L_2} \\ \psi_2 \end{pmatrix}
$$

left handed $SU(2)$ singlets: U_{L1} and U_{L2}
right handed $SU(2)$ singlets: U_{R1} and U_{R2}

Top sector

T-parity transformation: $U_{L1} \longleftrightarrow -U_{L2}, \quad U_{R1} \longleftrightarrow -U_{R2}$
T-parity eigenstates:

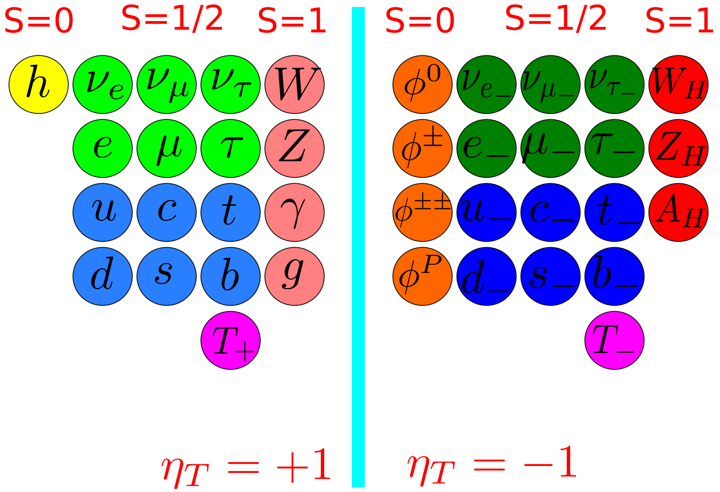
$$U_{L\pm} = \frac{U_{L1} \mp U_{L_2}}{\sqrt{2}} \quad \text{and} \quad U_{R\pm} = \frac{U_{R1} \mp U_{R_2}}{\sqrt{2}}$$

$$\begin{pmatrix} t_L \\ (T_+)_L \end{pmatrix} = \begin{pmatrix} \cos\,\theta_L & -\sin\,\theta_L \\ \sin\,\theta_L & \cos\,\theta_L \end{pmatrix} \begin{pmatrix} u_{SM} \\ U_{L+} \end{pmatrix}$$

$$\begin{pmatrix} t_R \\ (T_+)_R \end{pmatrix} = \begin{pmatrix} \cos\,\theta_R & -\sin\,\theta_R \\ \sin\,\theta_R & \cos\,\theta_R \end{pmatrix} \begin{pmatrix} u_R \\ U_{R+} \end{pmatrix}$$

$$\begin{aligned} m_{T_-} &= \lambda_2 f \\ m_{T_+} &= f\sqrt{\lambda_1^2 + \lambda_2^2} \\ m_t &\simeq \frac{\lambda_1 \lambda_2 v_{SM}}{\sqrt{\lambda_1^2 + \lambda_2^2}} \end{aligned}$$

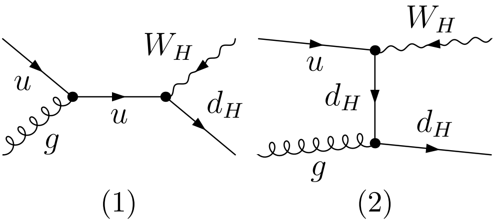
Particles list



2. $W_H/Z_H + q_-$ production

LO partonic processes

$$g(p_1) + q(p_2) \to V_H(p_3) + q'_-(p_4), (V_H = W_H, Z_H),$$
$$(q = u, d, c, s, \bar{u}, \bar{d}, \bar{c}, \bar{s}),\ (q'_- = u_-, d_-, c_-, s_-, \bar{u}_-, \bar{d}_-, \bar{c}_-, \bar{s}_-).$$



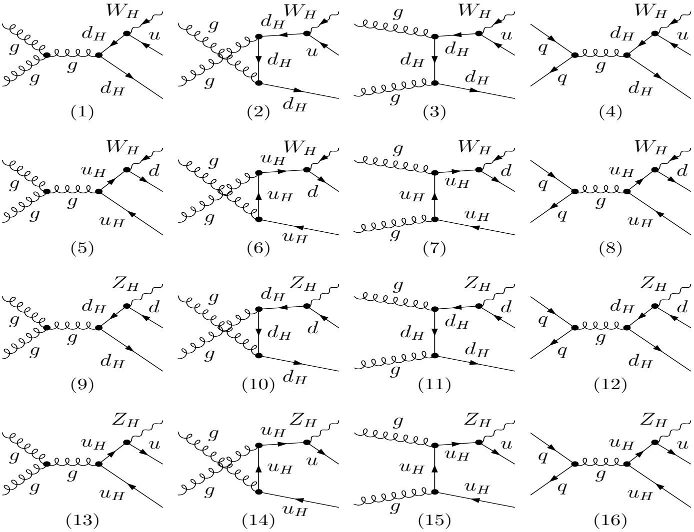
The LO Feynman diagrams for the partonic process $gu \to W_H^+ d_-$.

NLO QCD corrections

1. The QCD one-loop virtual corrections to the partonic processes $gq \to W_H(Z_H)q'_-$.
2. The contributions of the real gluon emission partonic processes $gq \to W_H(Z_H)q'_- + g$.
3. The contributions of the real light-quark emission partonic processes $gg \to W_H(Z_H)q'_- + \bar{q}$, $q''\bar{q}'' \to W_H(Z_H)q'_- + \bar{q}$ and $qq'' \to W_H(Z_H)q'_- + q''$.
4. The corresponding contributions of the PDF counterterms.

where the q_- will be resonant in light-quark emission processes. The widths should be added to the propagators, we got the total widths:

$$\boxed{\mathrm{Br}(q_- \to W_H q') + \mathrm{Br}(q_- \to Z_H q) + \mathrm{Br}(q_- \to A_H q) \simeq 100\%}$$



The Feynman diagrams for the real light-quark emission partonic processes via intermediate on-shell T-odd quarks.

Three schemes for NLO corrections

1. Include all NLO QCD corrections
2. Exclude the real light-quark emission contributions
3. PROSPINO scheme

$$\frac{|\mathcal{M}|^2(s_{V_H q})}{(s_{V_H q}-m_{q_-}^2)^2+m_{q_-}^2\Gamma_{q_-}^2} \to \frac{|\mathcal{M}|^2(s_{V_H q})}{(s_{V_H q}-m_{q_-}^2)^2+m_{q_-}^2\Gamma_{q_-}^2}$$

$$-\frac{|\mathcal{M}|^2(m_{q_-}^2)}{(s_{V_H q}-m_{q_-}^2)^2+m_{q_-}^2\Gamma_{q_-}^2}\Theta(\hat{s}-4m_{q_-}^2)\Theta(m_{q_-}-m_{V_H})$$

- keep the convergence of the perturbation theory
- aviod the double counting

PDF counterterms

$$\delta G_{q(g)/P}(x,\mu_f) = \delta G^{(gluon)}_{q(g)/P}(x,\mu_f) + \delta G^{(quark)}_{q(g)/P}(x,\mu_f), \quad (q = u, \bar{u}, d, \bar{d}, c, \bar{c}, s, \bar{s})$$

$$\delta G^{(gluon)}_{q(g)/P}(x,\mu_f) = \frac{1}{\epsilon}\left[\frac{\alpha_s}{2\pi}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\left(\frac{4\pi\mu_r^2}{\mu_f^2}\right)^{\epsilon}\right]\int_x^1 \frac{dz}{z} P_{qq(gg)}(z) G_{q(g)/P}(x/z,\mu_f)$$

$$\delta G^{(quark)}_{q/P}(x,\mu_f) = \frac{1}{\epsilon}\left[\frac{\alpha_s}{2\pi}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\left(\frac{4\pi\mu_r^2}{\mu_f^2}\right)^{\epsilon}\right]\int_x^1 \frac{dz}{z} P_{qg}(z) G_{g/P}(x/z,\mu_f)$$

$$\delta G^{(quark)}_{g/P}(x,\mu_f) = \frac{1}{\epsilon}\left[\frac{\alpha_s}{2\pi}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\left(\frac{4\pi\mu_r^2}{\mu_f^2}\right)^{\epsilon}\right]\sum_{q=u,\bar{u}}^{d,\bar{d},c,\bar{c},s,\bar{s}} \int_x^1 \frac{dz}{z} P_{gq}(z) G_{q/P}(x/z,\mu_f)$$

Virtual corretions (CT)

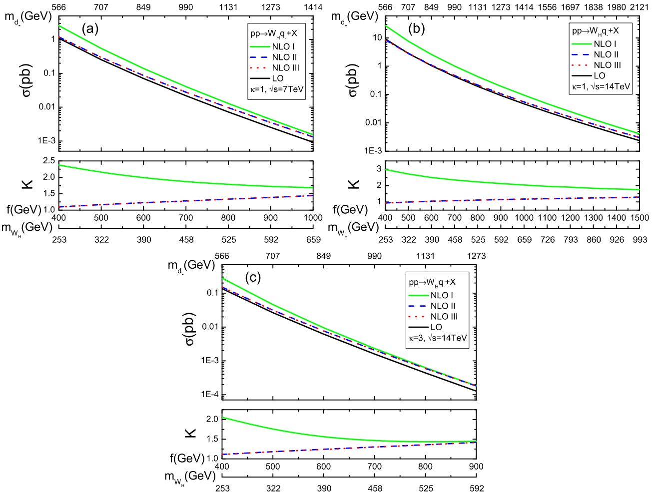
$$\mathcal{M}_{CT} = \left(\frac{\delta g_s}{g_s} + \frac{1}{2}\delta Z_g + \frac{1}{2}\delta Z_q + \frac{1}{2}\delta Z_{q'_-}\right)\mathcal{M}_{LO} + \delta m_{q'_-}\mathcal{M}_t\Big|_{\frac{i}{(\not{p}_{q'_-} - m_{q'_-})} \to \frac{i}{(\not{p}_{q'_-} - m_{q'_-})^2}}$$

$$\begin{aligned}
\delta Z_q^{L,R} &\equiv \delta Z_q = -\frac{\alpha_s(\mu_r)}{3\pi}\Big[\Delta_{UV} - \Delta_{IR}\Big], \\
\delta Z_{q_-}^{L,R} &\equiv \delta Z_{q_-} = -\frac{\alpha_s(\mu_r)}{3\pi}\left[\Delta_{UV} + 2\Delta_{IR} + 4 + 3\ln\left(\frac{\mu_r^2}{m_{q_-}^2}\right)\right], \\
\frac{\delta m_{q_-}}{m_{q_-}} &= -\frac{\alpha_s(\mu_r)}{3\pi}\left\{3\left[\Delta_{UV} + \ln\left(\frac{\mu_r^2}{m_{q_-}^2}\right)\right] + 4\right\}, \\
\frac{\delta g_s}{g_s} &= -\frac{\alpha_s(\mu_r)}{4\pi}\left[\frac{3}{2}\Delta_{UV} + \frac{1}{3}\ln\frac{m_t^2}{\mu_r^2} + \frac{1}{3}\sum_{T=T_+}^{T_-}\ln\frac{m_T^2}{\mu_r^2} + \frac{1}{3}\sum_{q_-}\ln\frac{m_{q_-}^2}{\mu_r^2}\right], \\
\delta Z_g &= -\frac{\alpha_s(\mu_r)}{2\pi}\left\{\frac{3}{2}\Delta_{UV} + \frac{5}{6}\Delta_{IR} + \frac{1}{3}\ln\left(\frac{\mu_r^2}{m_t^2}\right) + \frac{1}{3}\sum_{T=T_+}^{T_-}\ln\left(\frac{\mu_r^2}{m_T^2}\right)\right. \\
&\quad \left. + \frac{1}{3}\sum_{q_-}\ln\frac{\mu_r^2}{m_{q_-}^2}\right\}, \qquad (q_- = u_-, d_-, c_-, s_-, t_-, b_-),
\end{aligned}$$

Masses of W_H, Z_H and q_-

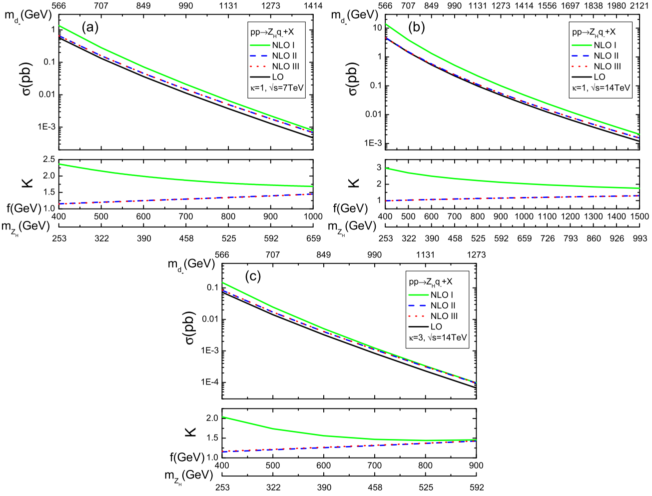
κ	f (GeV)	$m_{W_H} = m_{Z_H}$ (GeV)	$m_{u_-} = m_{c_-}$ (GeV)	$m_{d_-} = m_{s_-}$ (GeV)
1	500	322.1	685.7	707.1
	700	457.8	974.7	989.9
	900	592.3	1260.9	1272.8
	1000	659.3	1403.5	1414.2
	1100	726.1	1545.9	1555.6
	1300	859.7	1830.3	1838.5
3	500	322.1	2057.1	2121.3
	700	457.8	2924.0	2969.9
	900	592.3	3782.7	3818.4

Numerical results



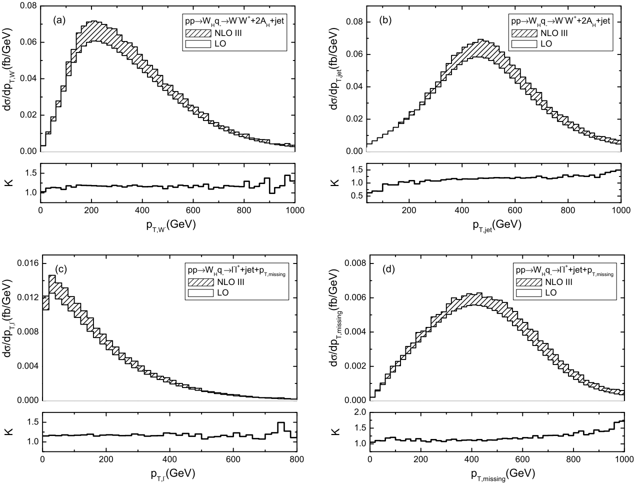
The cross sections and the corresponding K-factors for the $pp \to W_H q_- + X$ process as the functions of the LHT parameter f at the LHC

Numerical results



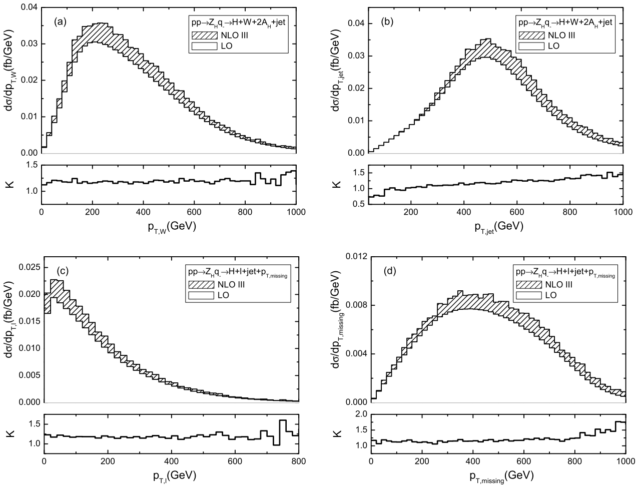
The cross sections and the corresponding K-factors for the $pp \to Z_H q_- + X$ process as the functions of the LHT parameter f at the LHC

Distributions



The LO and QCD NLO corrected p_T distributions of final particles for the $pp \to W_H q_- + X$ process at the LHC by taking $f = 1\ TeV$, $\kappa = 1$ and $\sqrt{s} = 14\ TeV$.

Distributions



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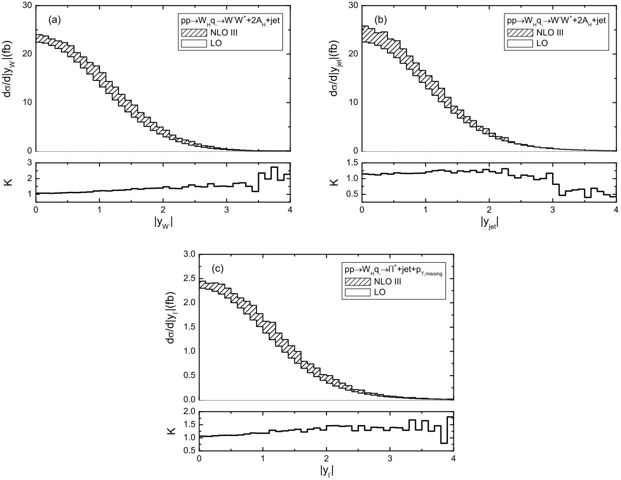
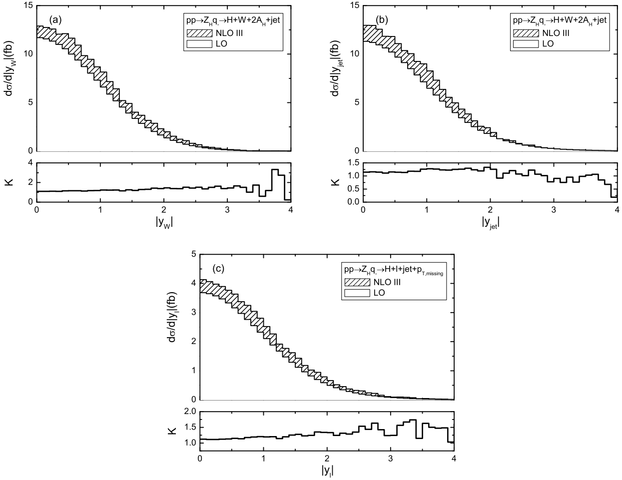
Distributions



The LO and QCD NLO corrected rapidity distributions of final particles for the $pp \to W_H q_- + X$ process at the LHC by taking $f = 1\ TeV$, $\kappa = 1$ and $\sqrt{s} = 14\ TeV$.

Distributions

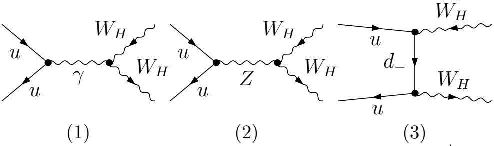


The LO and QCD NLO corrected rapidity distributions of final particles for the $pp \to Z_H q_- + X$ process at the LHC by taking $f = 1\ TeV$, $\kappa = 1$ and $\sqrt{s} = 14\ TeV$.

3. W_H pair production

LO partonic processes

$$q(p_1) + \bar{q}(p_2) \to W_H^+(p_3) + W_H^-(p_4), \quad (q = u, d, c, s, b).$$



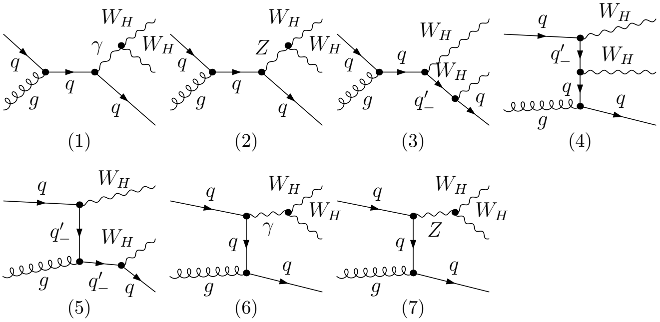
The LO Feynman diagrams for the partonic process $u\bar{u} \to W_H^+ W_H^-$

NLO QCD corrections

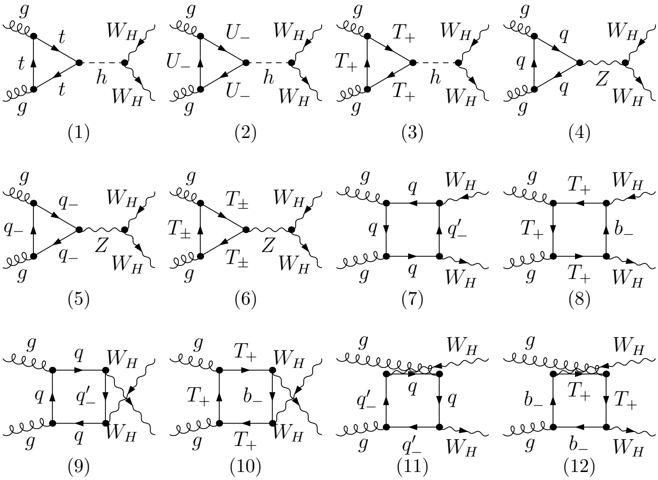
1. The QCD one-loop virtual corrections to the partonic processes $q\bar{q} \to W_H^+ W_H^-$.
2. The contribution of the real gluon emission partonic process $q\bar{q} \to W_H^+ W_H^- + g$.
3. The contribution of the real light-(anti)quark emission partonic process $q(\bar{q})g \to W_H^+ W_H^- + q(\bar{q})$.
4. The corresponding collinear counterterms of the PDFs.

Addtional:

5. The gluon-gluon fusion partonic process $gg \to W_H^+ W_H^-$.



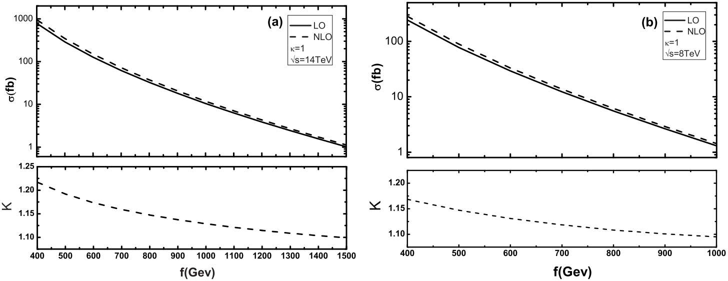
The tree-level Feynman diagrams for real light-quark emission partonic process $qg \to W_H^+ W_H^- + q$, $(q = u, d, c, s, b)$.



The representative lowest order Feynman diagrams for the partonic process $gg \to W_H^+ W_H^-$, where

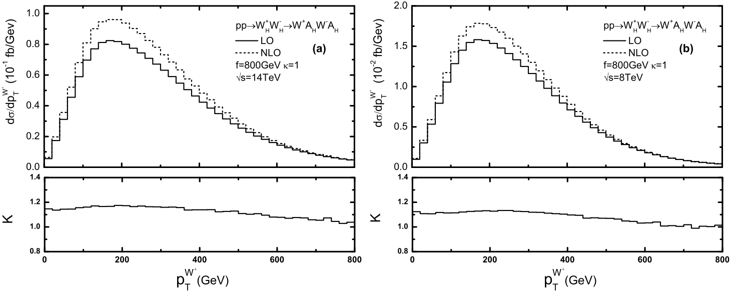
$U_- = u_-, c_-, t_-$, $q, q' = u, d, c, s, b, t$ and $q_-, q'_- = u_-, d_-, c_-, s_-, b_-, t_-$.

Numerical results



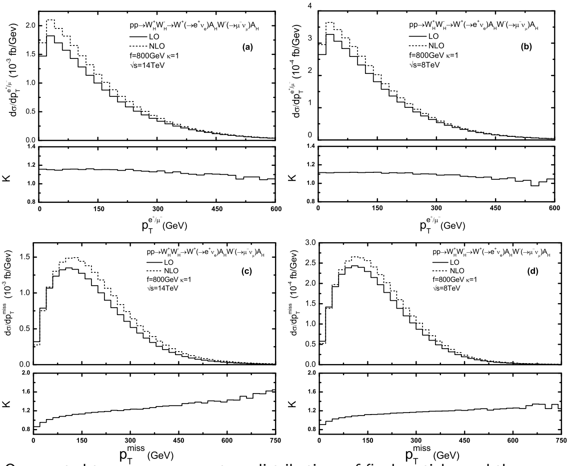
The LO, QCD NLO corrected integrated cross sections and the corresponding K-factors for the $pp \to W_H^+ W_H^- + X$ process as the functions of the global symmetry breaking scale f at the LHC with $\kappa = 1$ and $s_\alpha = c_\alpha = \frac{\sqrt{2}}{2}$.

Distributions



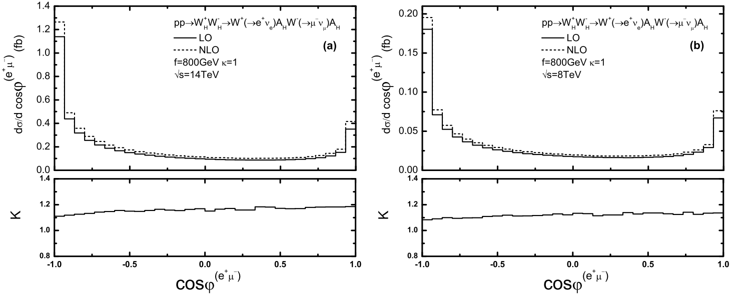
The LO, QCD NLO corrected $p_T^{W^+}$ distributions and the corresponding K-factors of final W^+ boson for the $pp \to W_H^+ W_H^- + X$ process at the LHC by taking $f = 800\ GeV$, $\kappa = 1$ and $s_\alpha = c_\alpha = \frac{\sqrt{2}}{2}$.

Distributions



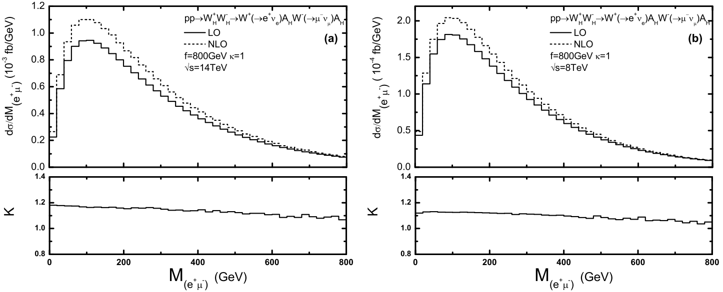
The LO, QCD NLO corrected transverse momentum distributions of final particles and the corresponding K-factors of the $pp \to W_H^+ W_H^- \to e^+ \mu^- A_H A_H \nu_e \bar{\nu}_\mu$ process at the LHC by taking $f = 800\ GeV$, $\kappa = 1$ and $s_\alpha = c_\alpha = \frac{\sqrt{2}}{2}$.

Distributions



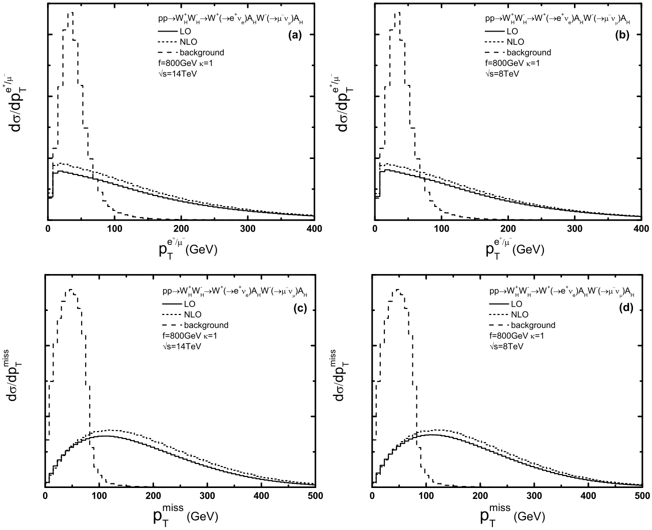
The LO, QCD NLO distributions of $\cos\varphi^{(e^+\mu^-)}$, where $\varphi^{(e^+\mu^-)}$ is the azimuthal angle between leptons e^+ and μ^-, and the corresponding K-factors of the $pp \to W_H^+ W_H^- \to e^+\mu^- A_H A_H \nu_e \bar{\nu}_\mu$ process at the LHC by taking $f = 800\ GeV$, $\kappa = 1$ and $s_\alpha = c_\alpha = \frac{\sqrt{2}}{2}$.

Distributions

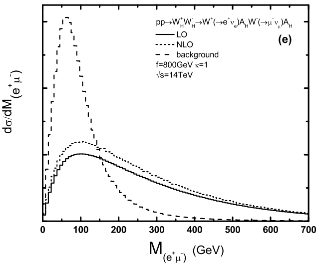


The LO, QCD NLO distributions of invariant mass of final positron and μ^-, $M_{(e^+\mu^-)}$, and the corresponding K-factors for the $pp \to W_H^+ W_H^- \to e^+\mu^- A_H A_H \nu_e \bar{\nu}_\mu$ process at the LHC by taking $f = 800\ GeV$, $\kappa = 1$ and $s_\alpha = c_\alpha = \frac{\sqrt{2}}{2}$.

Distributions



Distributions



The compare between The LO, QCD NLO corrected distributions and SM background. All curves are normalized by their total cross sections.

Summary

- Heavy gauge boson production in the LHT model can be detected in LHC.
- QCD correction can not be neglected.
- The distributions of final state particles in LHT model are different with the SM background.

Thanks!