Electroweak corrections to hadronic production of gauge bosons at large transverse momentum

Anna Kulesza

in collaboration with J. H. Kühn, S. Pozzorini and M. Schulze

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Introduction

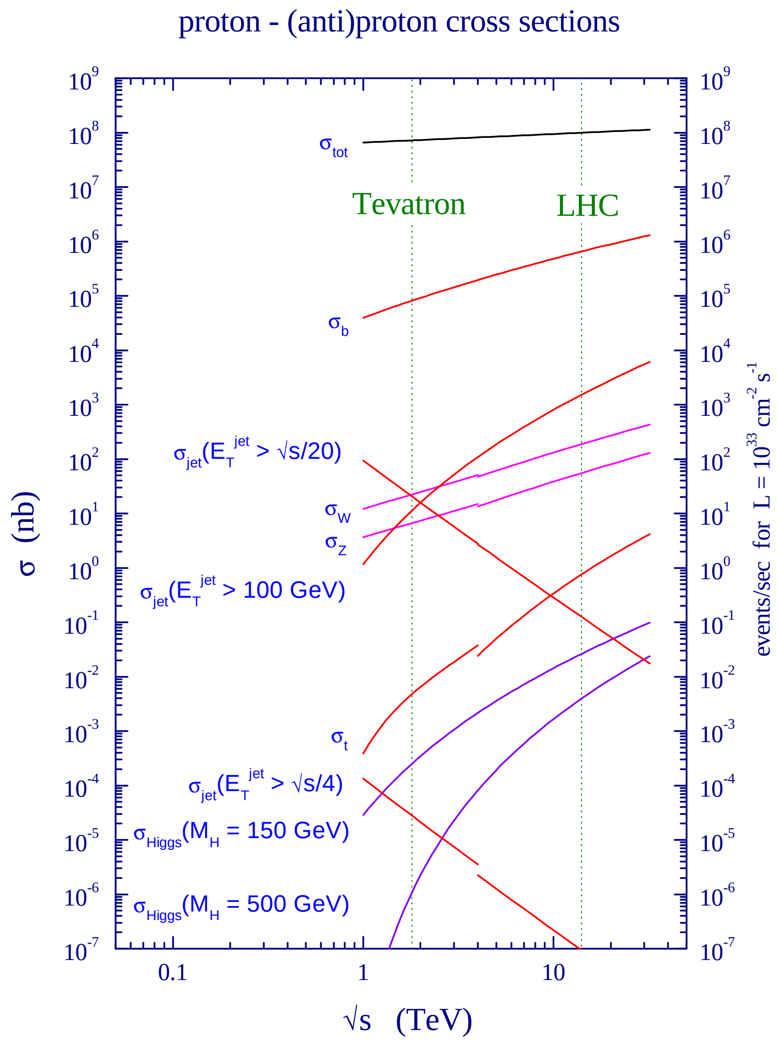
LHC:

- W/Z production: benchmark process
- Expected cross sections large

At low luminosity 10^{33} cm^{-2} s^{-1} estimate

200 W bosons
50 Z bosons per second!

$\Rightarrow$ LHC will be a W/Z factory
(→ parton luminosity monitor)
[Dittmar, Pauss, Zürcher,'97]



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Associated gauge boson production $V + \mathrm{jet}$

- Probe of the hard-scattering dynamics $\longrightarrow$ important test of the SM physics
  - clean signatures: direct γ, W/Z-boson ($\longrightarrow$ leptons)

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- $\gamma + \text{jet}$ and $Z + \text{jet}$ used for jet energy scale calibration
- Background to Higgs production

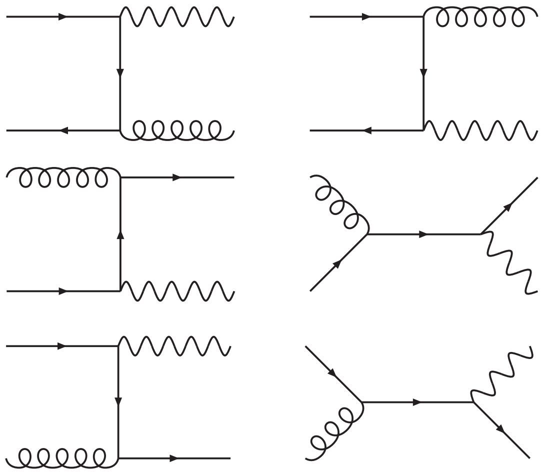
  $$(H \rightarrow \gamma\gamma,\ H \rightarrow WW^* \rightarrow l\nu l\nu,\ H \rightarrow ZZ \rightarrow ll\nu\nu, \ldots)$$

  and SUSY searches at the LHC

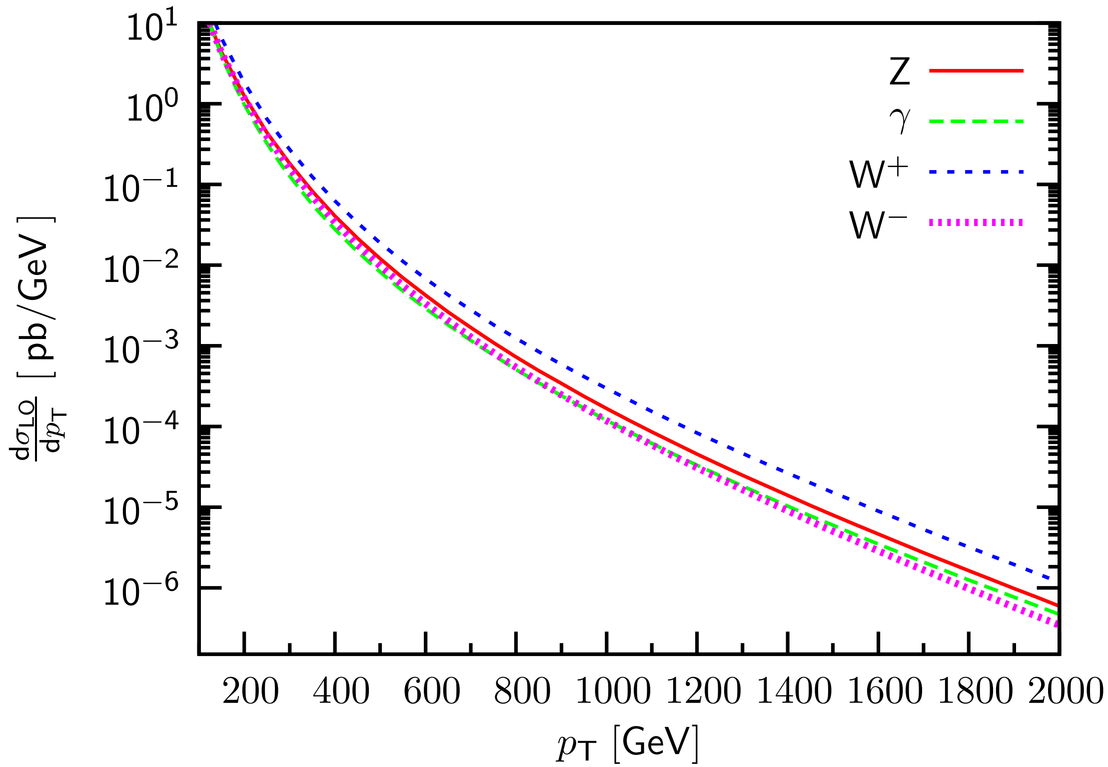
  (typical signature $E_T^{\text{miss}} + \text{jet}\ [+\ l]$)

Introduction

LO p_T distribution at the LHC



$|\mathcal{M}|^2$ related by crossing symmetries



- Large cross sections at LO $\Rightarrow$ good statistics;
- Reducing theoretical error requires calculation of radiative corrections: here EW

Gauge boson production at large p_{T}

Theoretical status of higher order corrections

- $\mathcal{O}(\alpha_{\mathrm{S}})$ QCD corrections [*Ellis, Martinelli, Petronzio'81*] [*Arnold, Reno'89*][*Arnold, Ellis, Reno'89*] [*Gonsalves, Pawłowski, Wai'89*] [*Giele, Glover, Kosower'93*] [*Melnikov, Petriello'06*]
  - Implementations exist (*DYRAD* [*Giele, Glover, Kosower'93*], *MCFM* [*Campbell, Ellis'02*], *FEWZ* [*Melnikov, Petriello'06*], *JETPHOX* [*Aurenche, Binoth,Fontannaz, Guillet, Heinrich, Pilon, Werlen*]. . .)

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- $\mathcal{O}(\alpha)$ EW corrections to LO $\mathcal{O}(\alpha\alpha_S)$ process (no QCD corrections)
  - γ/Z production [*Maina,Moretti, Ross'04*]
  - $\gamma/Z/W^{\pm}$ production [*Kühn, A.K., Pozzorini,Schulze'05-07*] (analytic results and numerical predictions)
  - $W^{\pm}$ production [*Hollik, Kasprzik, Kniehl '07*]

Introduction

$\longrightarrow$ see S. Pozzorini's talk

- EW corrections: naively expected to be small [$\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2)$]

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- Systematic enhancements due to logarithmic (Sudakov) terms of the structure

$\mathcal{O}(\alpha)$	$\mathcal{O}(\alpha^2)$	
$\alpha \log^2\left(\frac{\hat{s}}{M_W^2}\right)$	$\alpha^2 \log^4\left(\frac{\hat{s}}{M_W^2}\right)$	leading log (LL)
$\alpha \log\left(\frac{\hat{s}}{M_W^2}\right)$	$\alpha \log^3\left(\frac{\hat{s}}{M_W^2}\right)$	next − to − leading log (NLL)

Typically, at $\sqrt{\hat{s}} \sim 1$ TeV, one-loop corrections of $\mathcal{O}(10\%)$

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Typically, at $\sqrt{\hat{s}} \sim 1$ TeV, one-loop corrections of $\mathcal{O}(10\%)$

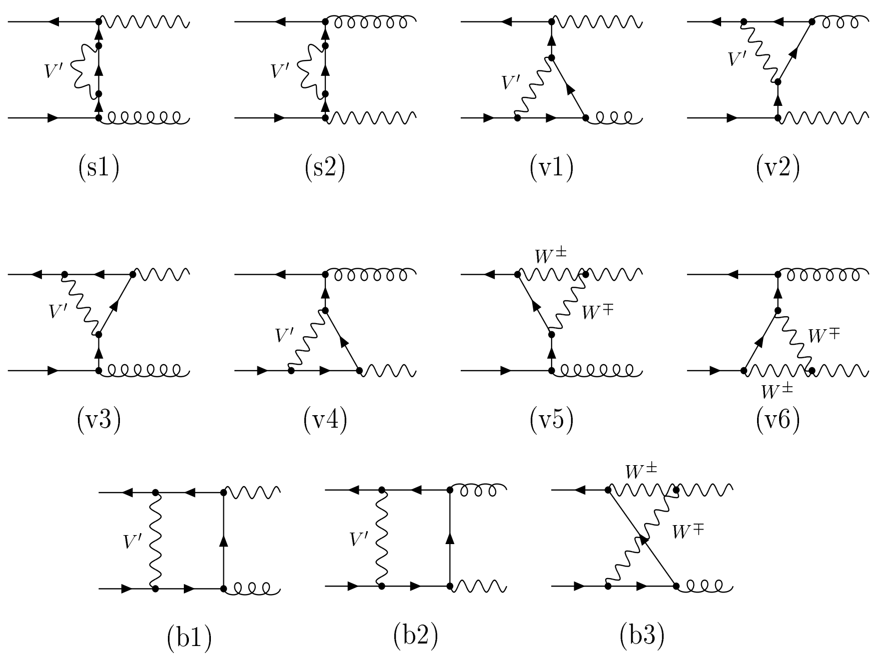
- Origin: soft/collinear emission of virtual *massive* gauge bosons (W, Z)
  - real radiation possible to observe $\Longrightarrow$ no compensation of virtual emission by real radiation
  - finite logarithmic corrections $\Longrightarrow$ different from massless gauge theories such as QCD or QED

$\mathcal{O}(\alpha)$ corrections to $q\overset{(-)}{q} \to V g$

Z/γ production

$V' = W^{\pm}, Z$

[Kühn, A.K., Pozzorini, Schulze'05-07]

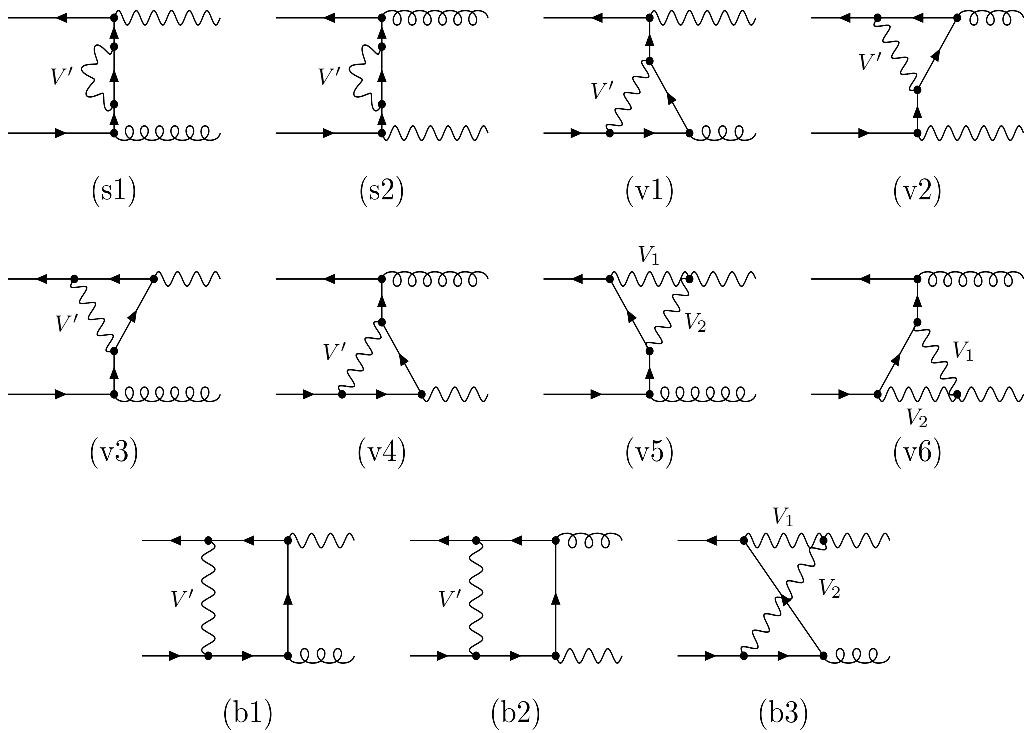


- Loop corrections: IR-finite
- Real corrections: W, Z emission assumed possible to be observed $\to$ not calculated

$\mathcal{O}(\alpha)$ corrections to $q\overset{(-)}{q} \rightarrow V g$

$W^{\pm}$ production [Kühn, A.K., Pozzorini, Schulze'05-07]

$(V_1, V_2) = (V'', W^{\pm})$ with $V'' = (\gamma, Z)$, $V' = (\gamma, Z, W^{\pm})$ or $V' = (\gamma, Z)$



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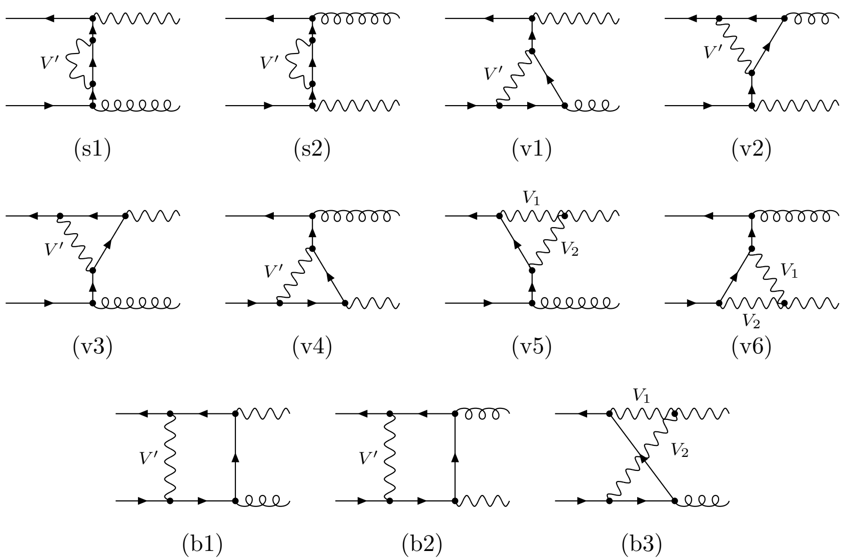

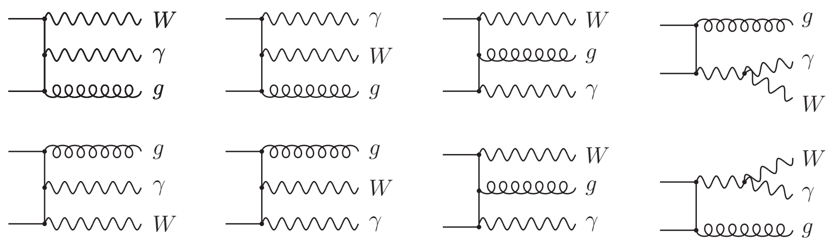

- Loop corrections: IR-singular (photons)
- Real corrections: W, Z emission assumed possible to be observed $\to$ not calculated
  photon emission IR-singular $\to$ needs to be calculated

Results for $\mathcal{O}(\alpha)$ corrections to $q\overset{(-)}{q} \to Vg$

[*Kühn, A.K., Pozzorini, Schulze'05-07*]

- Analytical one-loop result (Passarino - Veltman tensor reduction)

Schematically

coupling factor

$$\overline{\sum}|\mathcal{M}_{1,\mathrm{v}}^{q_i q_j \to Vg}|^2 \sim \sum_{i=1}^{N_V} \sum_{V'=A,Z,W^\pm} C_i^{V\,V'} H_V^i(M_{V'})$$

$N_V = 2$ for $V = A, Z$, $\quad N_V = 4$ for $V = W^\pm$

$$H_V^i(M_{V'}^2) = \mathrm{Re}\left[\sum_{j=0} K_{V,j}^i(M_{V'}^2)\, J_j(M_{V'}^2)\right]$$

Basis of 14 scalar integrals

$J_0(M_{V'}^2) = 1$ $\qquad J_2(M_{V'}^2) \ldots J_6(M_{V'}^2) = B_0(\ldots)$ $\qquad J_{12}(M_{V'}^2) \ldots J_{14}(M_{V'}^2) =$

$J_1(M_{V'}^2) = A_0(M_{V'}^2)$ $\qquad J_7(M_{V'}^2) \ldots J_{11}(M_{V'}^2) = C_0(\ldots)$ $\qquad$ comb. of $C_0(\ldots)$ & $D_0(\ldots)$

- Compact expressions for coefficients $K_{V,j}^i$ (rational functions of kin. variables)

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$\Rightarrow$ mass regularization: small quark mass m and photon mass λ

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- Real corrrections for $W^{\pm}$ production
  - Subtraction formalism

$$\sigma^{\mathsf{NLO}} = \int_{m+1} \left(d\sigma^{\mathsf{R}} - d\sigma^{\mathsf{A}} \right) + \int_{m} \left(d\sigma^{\mathsf{V}} + \int_{1} d\sigma^{\mathsf{A}} \right)$$

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  - Dipole subtraction method

$\Rightarrow$ photon radiation off massless or massive fermions: mass regularization [*Dittmaier '00*]

$\Rightarrow$ QCD radiation off massless or massive partons: dimensional regularization, easily adopted to QED radiation [*Catani, Seymour '97; Catani, Dittmaier, Seymour, Trócsanyi '02*]

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- Results always obtained with two independent codes within the collaboration

Results for $\mathcal{O}(\alpha)$ corrections to $q\overset{(-)}{q} \rightarrow Vg$

- Final state $W + \mathrm{jet}$ with $p_T^{\mathrm{jet}} > p_T^{\mathrm{jet,c}}$
  Collinear singularity ($q\gamma W$ state)
  - Here: recombination of momenta for collinear $q\gamma$ configurations
    if $R(q,\gamma) = \sqrt{(n_q - n_\gamma)^2 + (\phi_q - \phi_\gamma)^2} < R_{\mathrm{sep}}$ then $\boldsymbol{p}_{\text{jet}} = \boldsymbol{p}_q + \boldsymbol{p}_\gamma$

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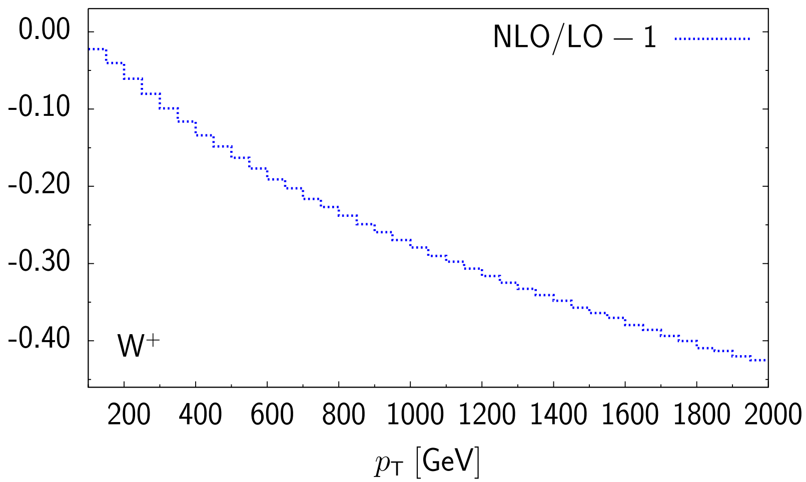
- Initial state collinear singularities absorbed in the pdfs
  - $\mathcal{O}(\alpha)$ effects in MRST2004QED (NLO QCD evolution)
  - This is a LO calculation in QCD $\rightarrow$ MRST2001 LO pdfs
  - $\mathcal{O}(\alpha)$ effects known to be small [*Roth, Weinzierl '04*]
  - Photon-induced contributions suppressed by α/α_s wrt $\mathcal{O}(\alpha^2\alpha_s) \Rightarrow$ not included here; found to be non-negligible numerically [*Hollik, Kasprzik, Kniehl '07*]

$\mathcal{O}(\alpha)$ corrections to $pp \to W^+ + 1$ jet at the LHC

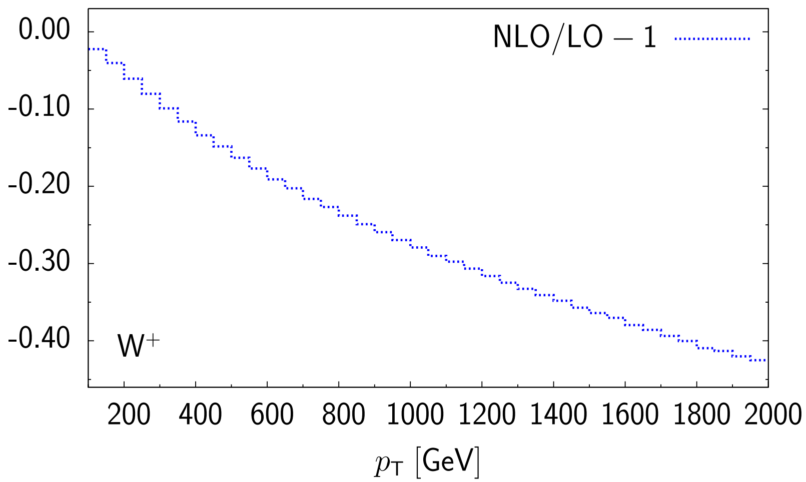


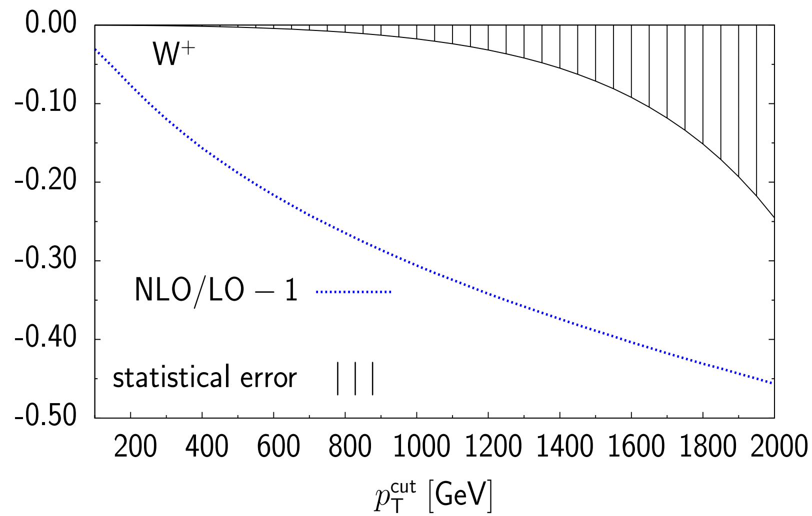
- Corrections negative; range from -15% at 500 GeV up to -42% at 2 TeV

LO MRST2001 pdf's, $R_{\mathrm{sep}} = 0.4$, $p_T^{\mathrm{jet,c}}$=100 GeV,$\alpha_s(M_Z) = 0.13$, $\mu_F^{QCD} = \mu_R^{QCD} = p_T$, $\mu_F^{QED} = M_W$, G_μ scheme, $\alpha(M_Z)$=1/127.9, ${s_W}^2 = 0.231$, M_Z= 91.19 GeV, $M_W = c_W M_Z$, $m_t = 175$ GeV, $m_H = 130$ GeV

$\mathcal{O}(\alpha)$ corrections to $pp \to W^+ + 1$ jet at the LHC

Integrated $\Delta\sigma(p_T^{cut})$ vs. $\Delta\sigma_{stat} = \frac{\sigma}{\sqrt{N}}$
$N = \mathcal{L} \times \mathrm{BR}(Z \to l,\ \nu_l) \times \sigma_{LO}$
$\mathrm{BR}(W^+ \to l,\ \nu_l) = 30.6\%$, $\mathcal{L} = 300$ fb^{-1}





- Corrections negative; range from -15% at 500 GeV up to -42% at 2 TeV
- Size of the integrated corrections much bigger than the statistical error!

$\mathcal{O}(\alpha)$ corrections to $pp \to W^- + 1$ jet at the LHC

Integrated $\Delta\sigma(p_T^{\rm cut})$ vs. $\Delta\sigma_{\rm stat} = \frac{\sigma}{\sqrt{N}}$
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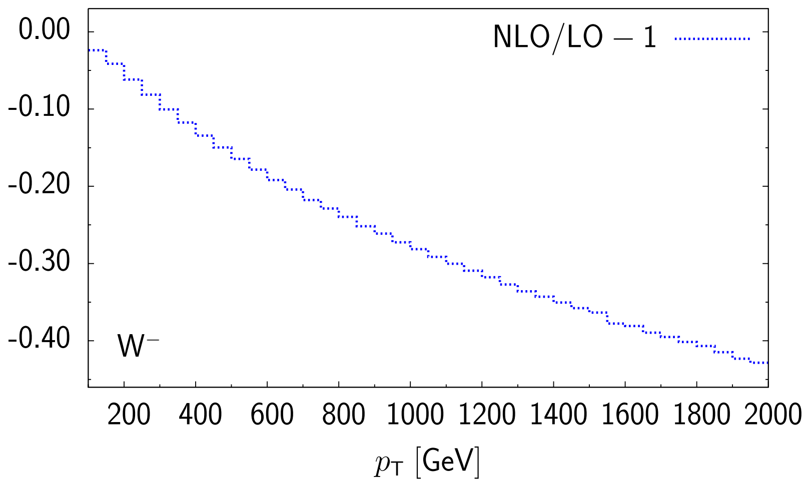
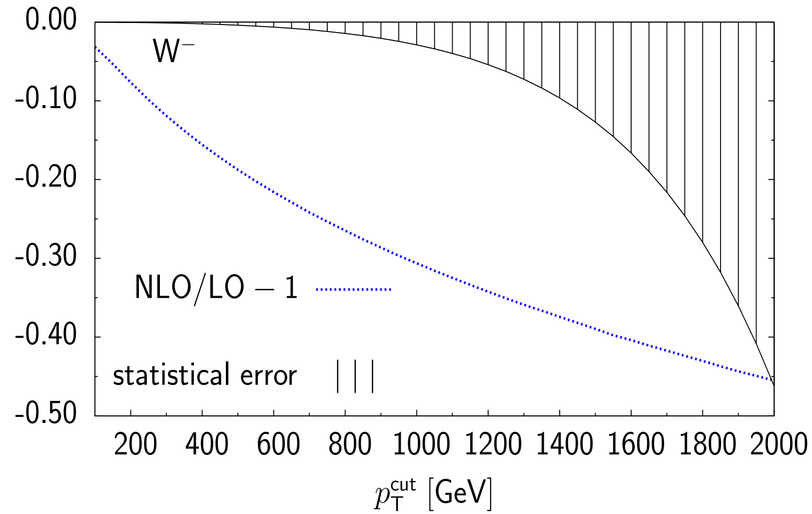
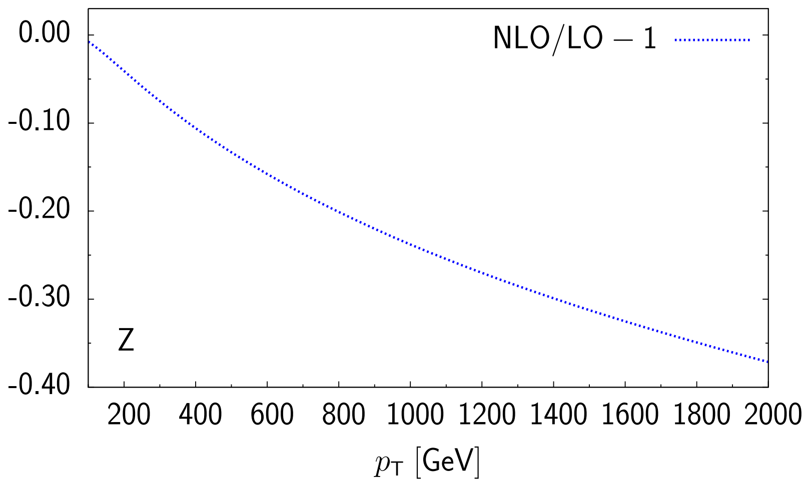




- Corrections negative; behaviour quantitatively very similar to W^+
- Size of the integrated corrections much bigger than the statistical error!

$\mathcal{O}(\alpha)$ corrections to $pp \to Z + 1\ \mathrm{jet}$ at the LHC



- Corrections negative; range from -13% at 500 GeV up to -37 % at 2 TeV

LO MRST2001 pdf's, $\alpha_s(M_Z) = 0.13$, $\mu_F = \mu_R = p_T$, $\overline{MS}$ scheme, $\alpha(M_Z)$=1/127.9, ${s_W}^2 = 0.231$, M_Z= 91.19 GeV, $M_W = c_W M_Z$, $m_t = 175$ GeV, $m_H = 130$ GeV

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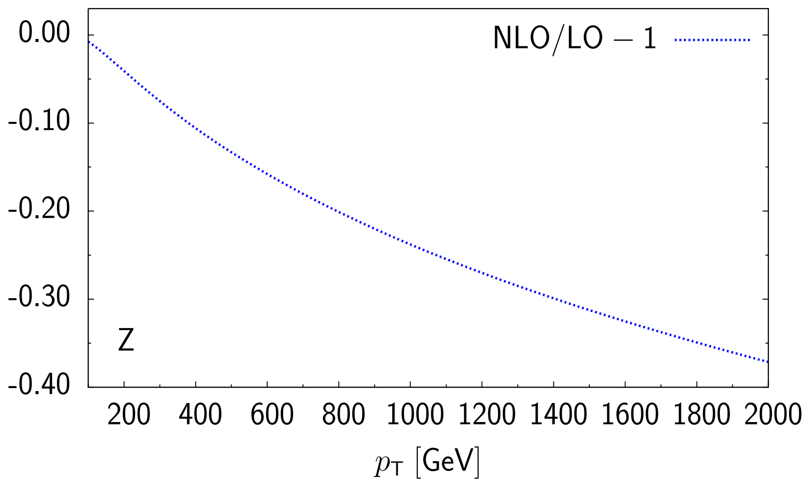

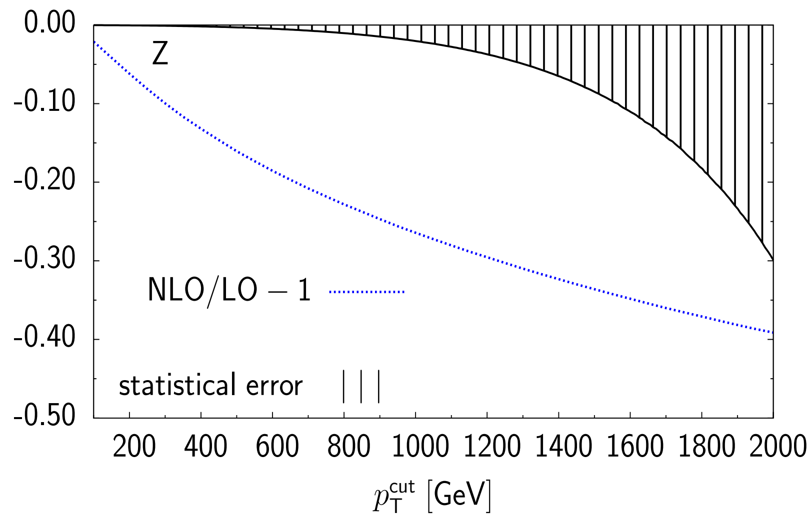

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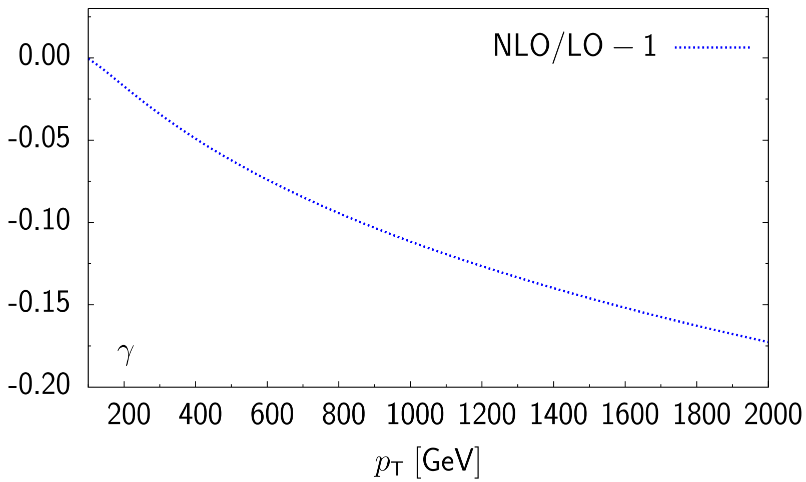

- Corrections negative; range from -6% at 500 GeV up to -17 % at 2 TeV

LO MRST2001 pdf's, $\alpha_s(M_Z^2) = 0.13$, $\mu_F = \mu_R = p_T$
OS scheme, $\alpha(0) = 1/137$, $s_W^2 = 1 - M_W^2/M_Z^2$, $M_Z = 91.19$ GeV, $M_W = 80.39$ GeV

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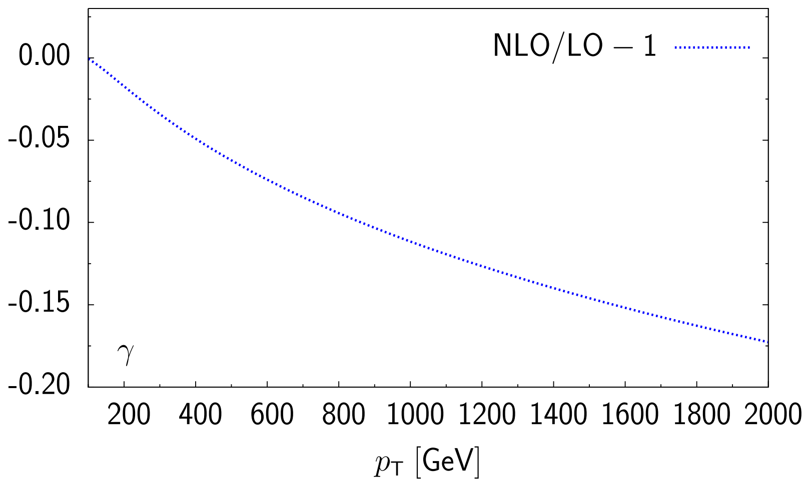

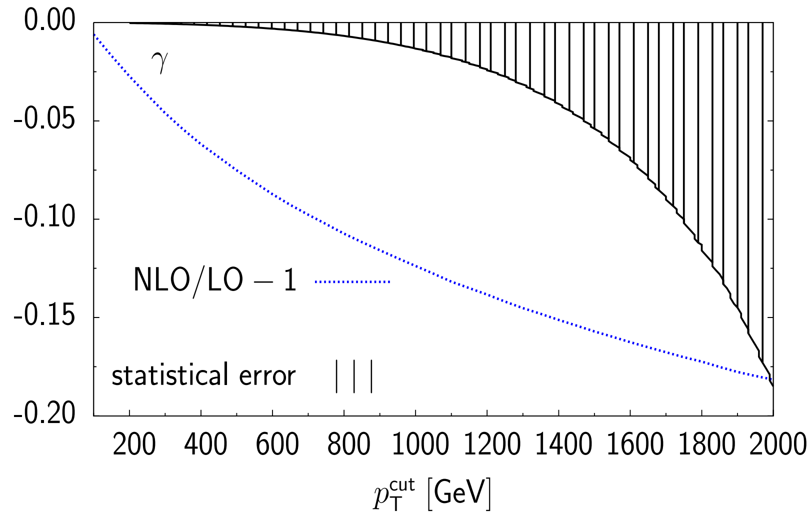

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High-energy approximation of the one-loop result

NNLL approximation: high energy limit of the NLO result for $\overline{\sum}|\mathcal{M}^{q_i q_j}|^2$

$M_W^2/\hat{s} \to 0$ ($\hat{t}/\hat{s}$, $\hat{u}/\hat{s}$ constant) [*Roth, Denner'96*]

terms with $\alpha \ln^2(\frac{\hat{s}}{M_W^2})$, $\alpha \ln(\frac{\hat{s}}{M_W^2})$ and constants

$(V = \gamma, Z)$ LL NLL NNLL

$$H_1^{V,\mathrm{A/N}}(M_{V'}^2) \overset{\mathrm{NNLL}}{=} \mathrm{Re}\left[g_0^{V,\mathrm{A/N}}(M_{V'}^2)\,\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}} + g_1^{V,\mathrm{A/N}}(M_{V'}^2)\,\frac{\hat{t}^2-\hat{u}^2}{\hat{t}\hat{u}} + g_2^{V,\mathrm{A/N}}(M_{V'}^2)\right]$$

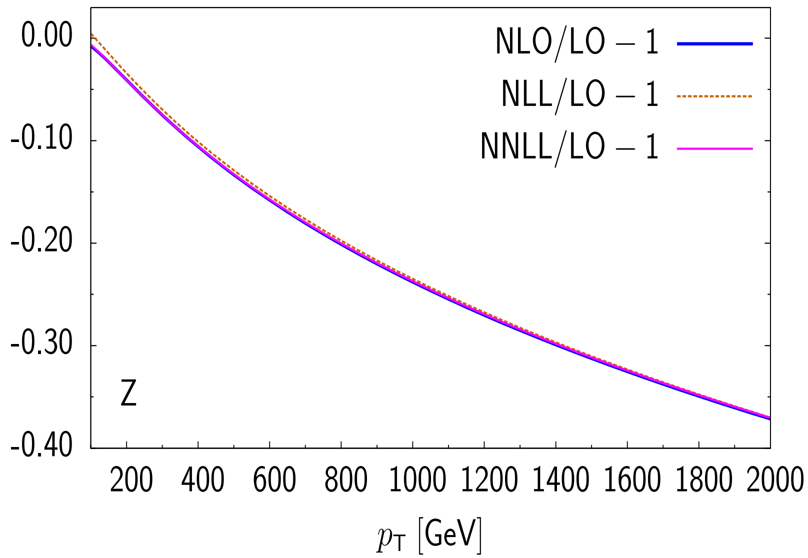
$$\begin{aligned}
g_0^{V,\mathrm{A}}(M_{V'}^2) &= -\log^2\left(\frac{-\hat{s}}{M_{V'}^2}\right) + 3\log\left(\frac{-\hat{s}}{M_{V'}^2}\right) + \frac{3}{2}\left[\log^2\left(\frac{\hat{t}}{\hat{s}}\right) + \log^2\left(\frac{\hat{u}}{\hat{s}}\right) + \log\left(\frac{\hat{t}}{\hat{s}}\right) + \log\left(\frac{\hat{u}}{\hat{s}}\right)\right] + \frac{7\pi^2}{3} - \frac{5}{2} \\
g_0^{V,\mathrm{N}}(M_W^2) &= 2\left[2/(4-D) - \gamma_\mathrm{E} + \log\left(\frac{4\pi\mu^2}{M_Z^2}\right) - \delta_{V\gamma}\log\left(\frac{M_W^2}{M_Z^2}\right)\right] + \log^2\left(\frac{-\hat{s}}{M_W^2}\right) - \log^2\left(\frac{-\hat{t}}{M_W^2}\right) - \log^2\left(\frac{-\hat{u}}{M_W^2}\right) \\
&\quad + \log^2\left(\frac{\hat{t}}{\hat{u}}\right) - \frac{3}{2}\left[\log^2\left(\frac{\hat{t}}{\hat{s}}\right) + \log^2\left(\frac{\hat{u}}{\hat{s}}\right)\right] - 2\pi^2 + 2\delta_{VZ}\left(-\frac{\pi^2}{9} - \frac{\pi}{\sqrt{3}} + 2\right) \\
g_1^{V,\mathrm{N}}(M_{V'}^2) &= -g_1^{V,\mathrm{A}}(M_{V'}^2) + \frac{3}{2}\left[\log\left(\frac{\hat{u}}{\hat{s}}\right) - \log\left(\frac{\hat{t}}{\hat{s}}\right)\right] = \frac{1}{2}\left[\log^2\left(\frac{\hat{u}}{\hat{s}}\right) - \log^2\left(\frac{\hat{t}}{\hat{s}}\right)\right] \\
g_2^{V,\mathrm{N}}(M_{V'}^2) &= -g_2^{V,\mathrm{A}}(M_{V'}^2) = -2\left[\log^2\left(\frac{\hat{t}}{\hat{s}}\right) + \log^2\left(\frac{\hat{u}}{\hat{s}}\right) + \log\left(\frac{\hat{t}}{\hat{s}}\right) + \log\left(\frac{\hat{u}}{\hat{s}}\right)\right] - 4\pi^2
\end{aligned}$$

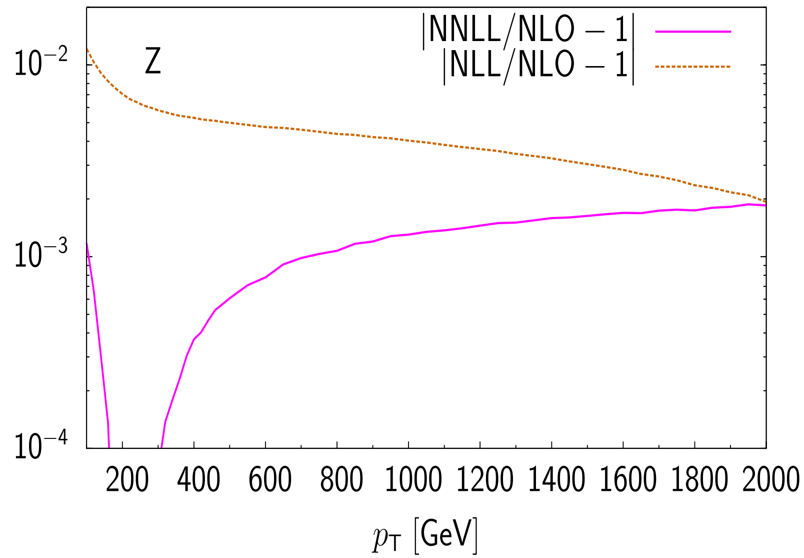
$$g_i^{\gamma,\mathrm{A}} = g_i^{Z,\mathrm{A}} \text{ for } i = 0,1,2 \quad g_j^{\gamma,\mathrm{N}} = g_j^{Z,\mathrm{N}} \text{ for } j = 1,2$$

$\longrightarrow$ extremely compact analytic formulae for NNLL approximation (also for $W^\pm$)

High-energy approximation of the one-loop result

Z production at the LHC





- NLL approximation: percent (or better) level

  $\sim$ 1% deviation from NLO at low p_T

  $\sim$ 0.2% deviation from NLO at $p_T = 2$ TeV

- NNLL approximation: permille level
- Similar behaviour for $W^{\pm}$ and γ production

NLL approximation at two loops

Phys. Lett. B 609 (2005) 277, JHEP 0603 (2006) 059, Phys. Lett B 651 (2007) 160

- Electroweak corrections in the high energy region: $|\hat{r}| \gg M_W^2 \sim M_Z^2$ for $\hat{r} = \hat{s},\ \hat{t},\ \hat{u}$

NLL approximation at two loops

Phys. Lett. B 609 (2005) 277, JHEP 0603 (2006) 059, Phys. Lett B 651 (2007) 160

- Electroweak corrections in the high energy region: $|\hat{r}| \gg M_W^2 \sim M_Z^2$ for $\hat{r} = \hat{s},\ \hat{t},\ \hat{u}$

$\longrightarrow$ Calculations based on results available in the literature:

1- loop

factorization and universality of 1-loop EW corrections at the LL and NLL level $\alpha \log^2\left(\frac{|\hat{r}|}{M_W^2}\right)$, $\alpha \log\left(\frac{\hat{s}}{M_W^2}\right)$ for arbitrary processes [*Denner, Pozzorini'01*]

2- loop

LL $\alpha^2 \log^4\left(\frac{\hat{s}}{M_W^2}\right)$ and NLL "angular" $\alpha^2 \log^3\left(\frac{\hat{s}}{M_W^2}\right)\left(\frac{|\hat{r}|}{M_W^2}\right)$ terms for arbitrary processes [*Denner, Melles, Pozzorini'03*] + remaining NLL terms with $\alpha^2 \log^3\left(\frac{\hat{s}}{M_W^2}\right)$ from general resummation formula [*Melles'02,'03*]

[*Denner,Janzen, Pozzorini'06*]

NLL approximation

W production

$$\overline{\sum}|\mathcal{M}_2^{\bar{q}q'\to W^\sigma g}|^2 \overset{NLL}{=} \overline{\sum}|\mathcal{M}_0^{\bar{q}q'\to W^\sigma g}|^2 \left[1 + \left(\frac{\alpha}{2\pi}\right) A^{(1)} + \left(\frac{\alpha}{2\pi}\right)^2 A^{(2)}\right]$$

$$A^{(1)} = -\left[C^{\mathrm{ew}}_{q_L}\left(L^2_{\hat{s}} - 3L_{\hat{s}}\right) + \frac{1}{{s_W}^2}\left(L^2_{\hat{t}} + L^2_{\hat{u}} - L^2_{\hat{s}}\right)\right]$$

$$L_{\hat{r}} = \log\left(\frac{|\hat{r}|}{M_W^2}\right), \ \hat{r} = \hat{s}, \hat{t}, \hat{u}; \qquad C^{\mathrm{ew}}_{q_L} = \frac{Y^2_{q_L}}{4{c_W}^2} + \frac{3}{(4{s_W}^2)}$$

$\Rightarrow$ agreement with the NLL limit of the full one-loop result

NLL approximation

W production

$$\overline{\sum}|\mathcal{M}_2^{\bar{q}q'\to W^\sigma g}|^2 \overset{NLL}{=} \overline{\sum}|\mathcal{M}_0^{\bar{q}q'\to W^\sigma g}|^2 \left[1+\left(\frac{\alpha}{2\pi}\right)A^{(1)}+\left(\frac{\alpha}{2\pi}\right)^2 A^{(2)}\right]$$

$$A^{(1)} = -\left[C^{\text{ew}}_{q_L}\left(L^2_{\hat{s}}-3L_{\hat{s}}\right)+\frac{1}{{s_W}^2}\left(L^2_{\hat{t}}+L^2_{\hat{u}}-L^2_{\hat{s}}\right)\right]$$

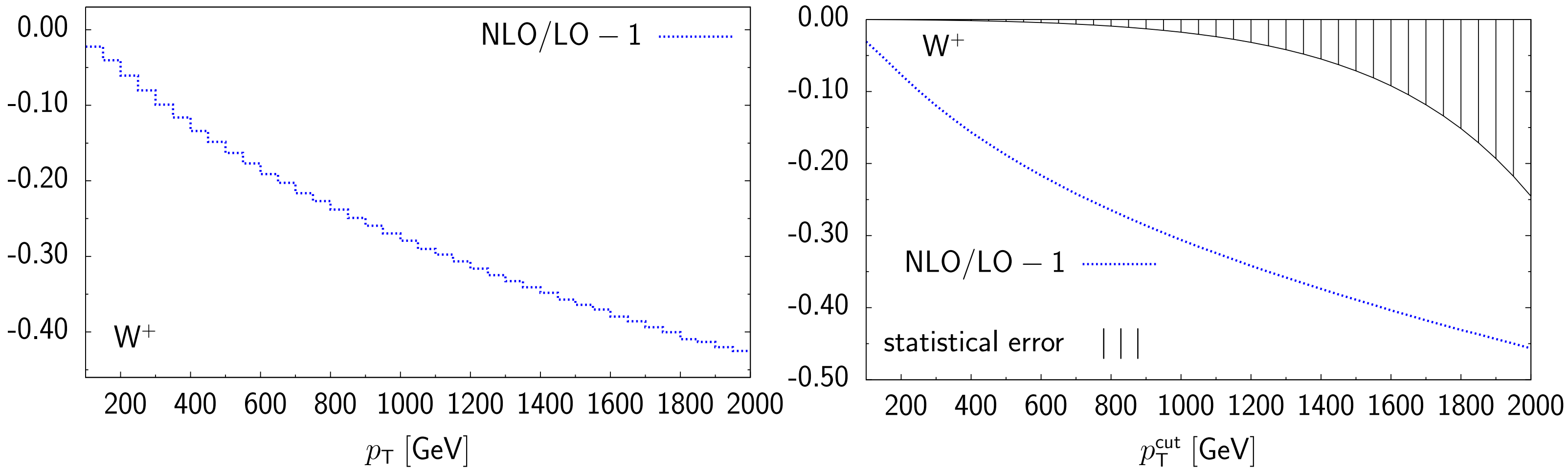
$$\begin{aligned} A^{(2)} \quad &= \quad \left\{\frac{1}{2}\left(C^{\text{ew}}_{q_L}+\frac{1}{{s_W}^2}\right)\left[\left(\mathrm{L}^4_{\hat{s}}-6\mathrm{L}^3_{\hat{s}}\right)+\frac{1}{{s_W}^2}\left(\mathrm{L}^4_{\hat{t}}+\mathrm{L}^4_{\hat{u}}-\mathrm{L}^4_{\hat{s}}\right)\right]\right. \\ &\left. +\frac{1}{6}\left[\frac{b_1}{c^2_W}\left(\frac{Y_{q_L}}{2}\right)^2+\frac{7}{8}\frac{b_2}{s^2_W}\right]\mathrm{L}^3_{\hat{s}}\right\} \end{aligned}$$

$$L_{\hat{r}} = \log\left(\frac{|\hat{r}|}{M^2_W}\right),\ \hat{r}=\hat{s},\hat{t},\hat{u}; \qquad C^{\text{ew}}_{q_L} = \frac{Y^2_{q_L}}{4{c_W}^2}+\frac{3}{4{s_W}^2}, \qquad b_1 = -\frac{41}{6c^2_W}, \qquad b_2 = \frac{19}{6s^2_W}$$

$\longrightarrow$ similar analytic results for neutral gauge boson production

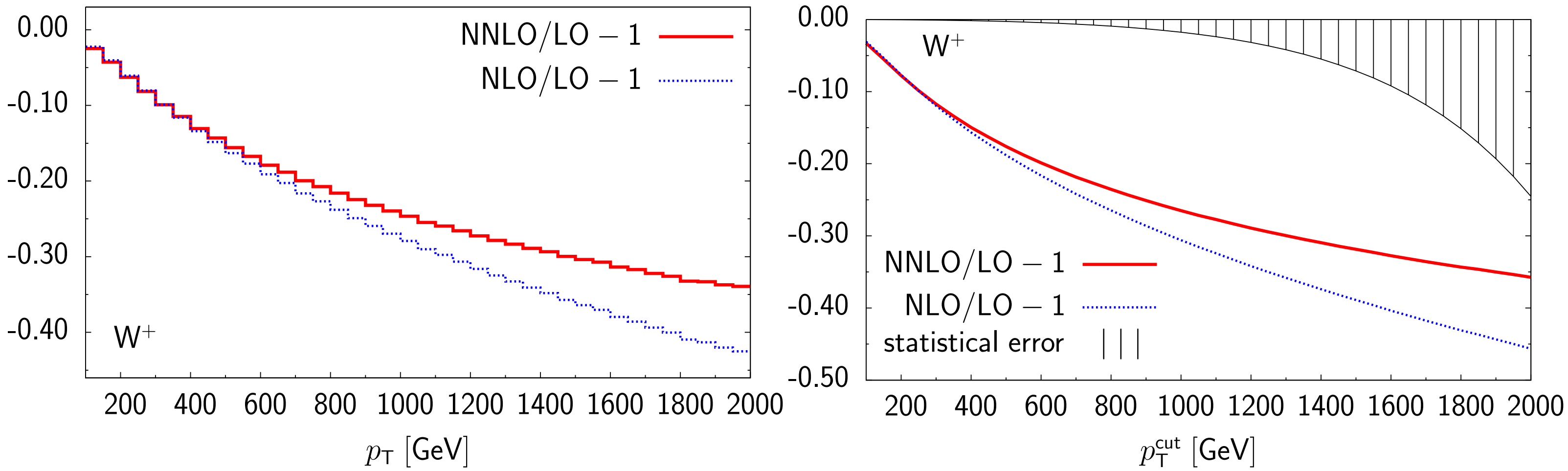
NLL approximation: 2-loop results

Large p_T W^+-boson production at the LHC



NLL approximation: 2-loop results

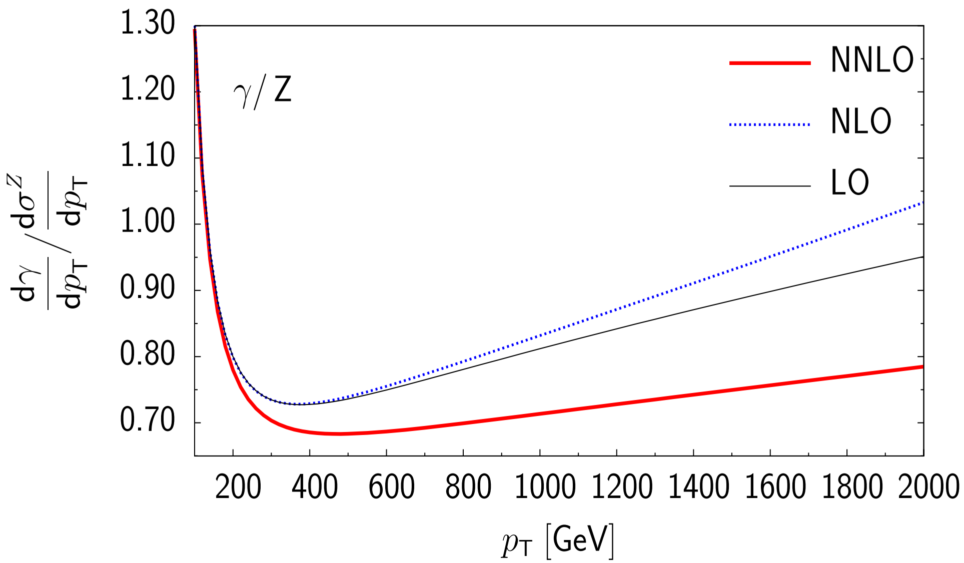
Large p_T W^+-boson production at the LHC



- NLL 2-loop terms positive, up to 10% contribution (at 2 TeV)
- 1-loop + 2-loop NLL amount to up to -33% correction (at 2 TeV)
- For large range of p_T values 2-loop effects comparable with statistical error!
- very similar numbers for W^-, qualitatively similar behaviour for Z and γ

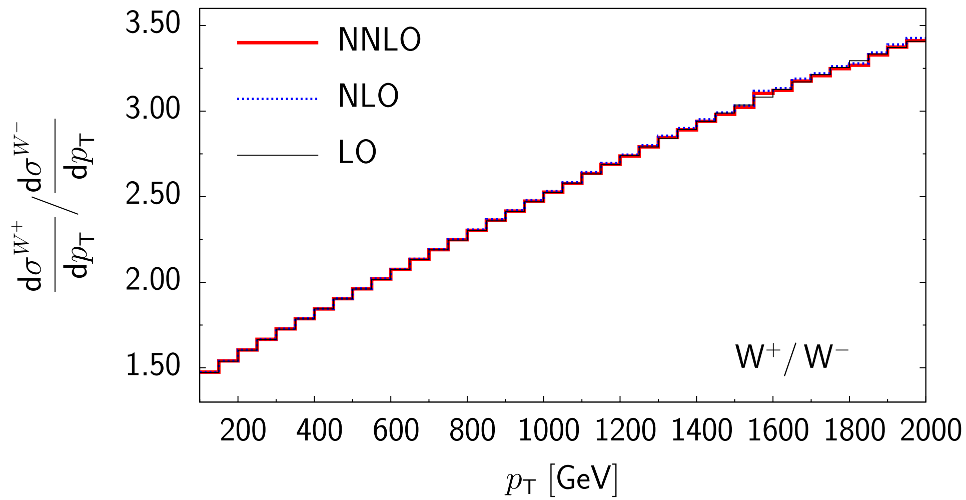
Ratio of the p_T distributions: γ to Z

- Cancellation of theoretical uncertainties (PDFs, α_S)
- Stability wrt. QCD corrections

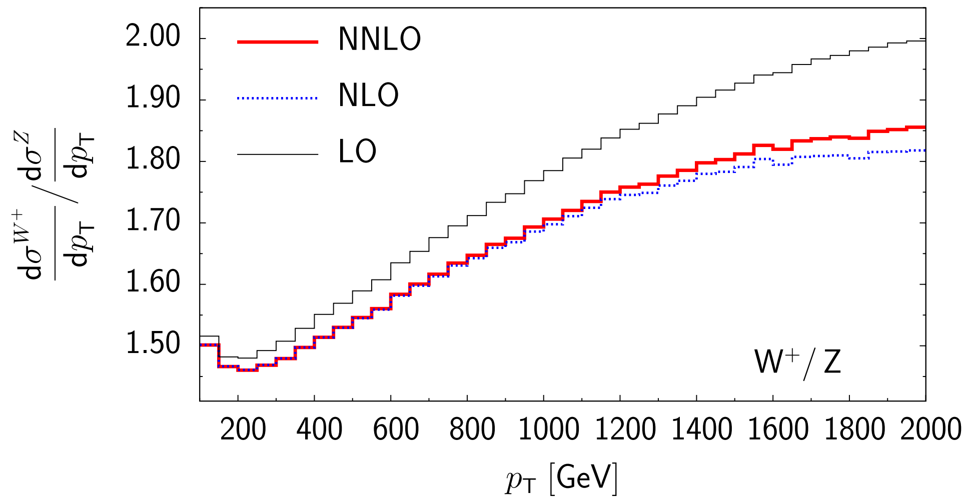


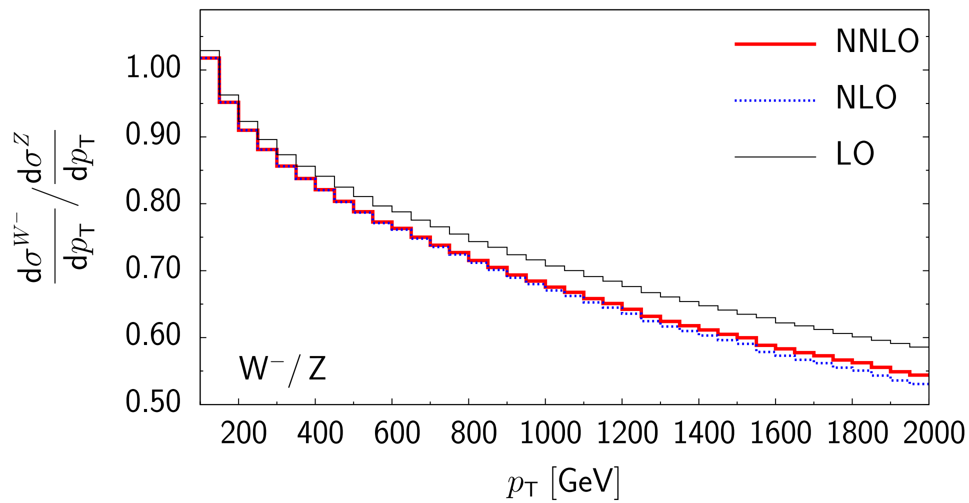
- Ratio of the LO distributions: $\frac{d\sigma^\gamma}{dp_T} / \frac{d\sigma^Z}{dp_T} \sim 0.7 - 0.8$
- EW corrections modify the ratio; strongest effect at large p_T
  NLO: $\frac{d\sigma^\gamma}{dp_T} / \frac{d\sigma^Z}{dp_T} \sim 0.75 - 1$, NNLO: $\frac{d\sigma^\gamma}{dp_T} / \frac{d\sigma^Z}{dp_T} \sim 0.75 - 0.95$

Ratio of the p_T distributions: W^+ to W^-, W^+ to Z

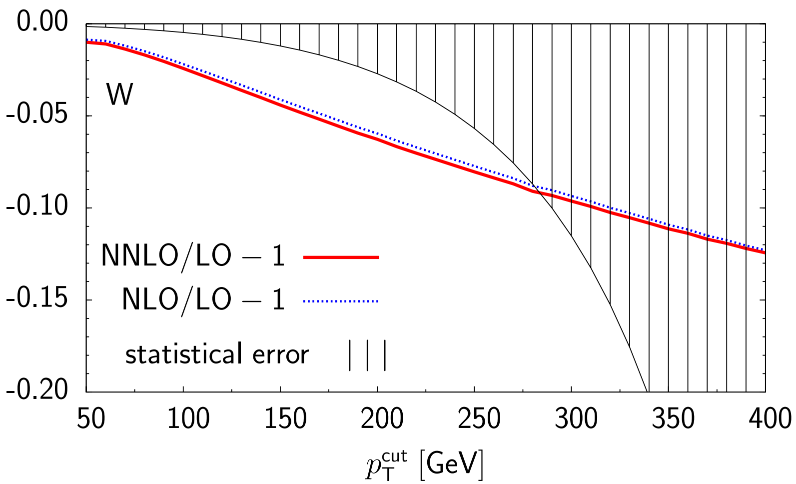


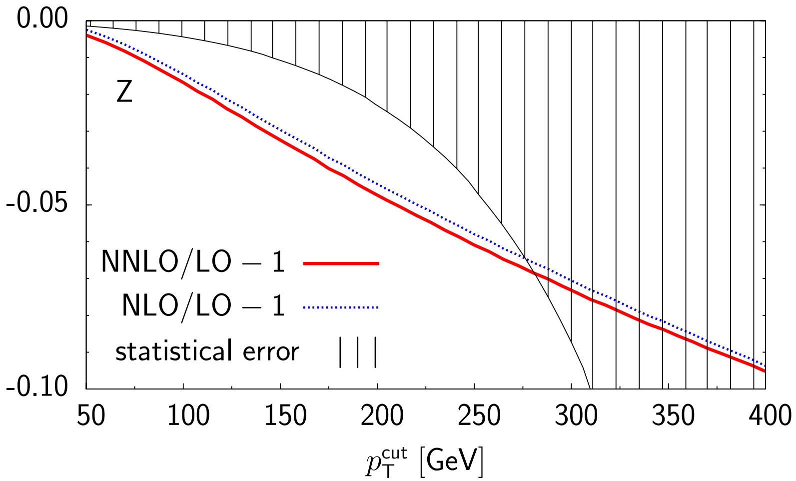
- $\frac{d\sigma^{W^+}}{dp_T} / \frac{d\sigma^{W^-}}{dp_T}$ not affected by EW corrections
- Above 1 TeV, EW corrections to $\frac{d\sigma^{W^+\ (W^-)}}{dp_T} / \frac{d\sigma^{Z}}{dp_T}$ are of the $5-7\%$ size



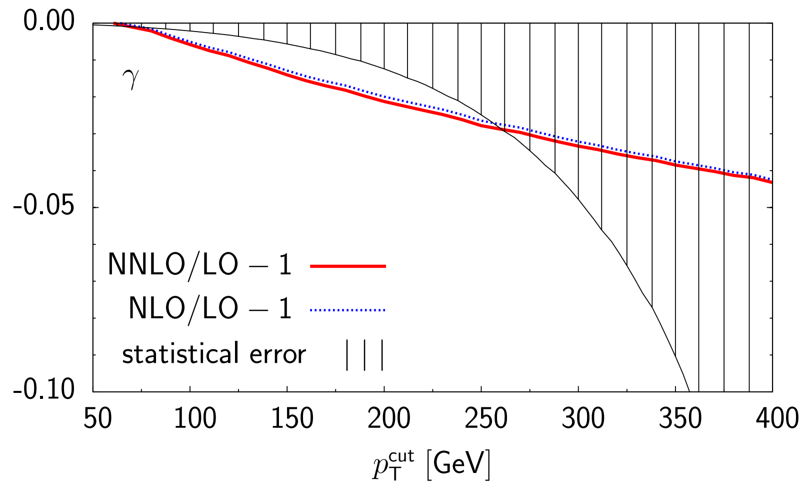


Gauge boson production at the Tevatron





- $\mathcal{L} = 11\text{fb}^{-1}$
- NLO corrections bigger than stat. error
- NLL 2-loop corrections small

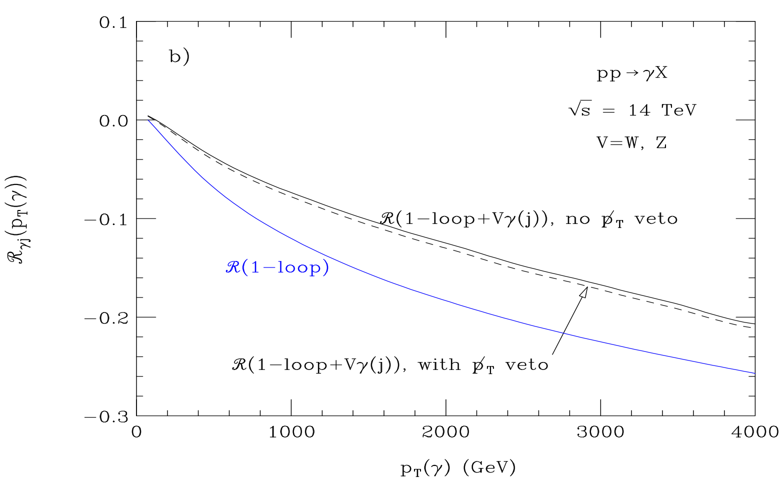


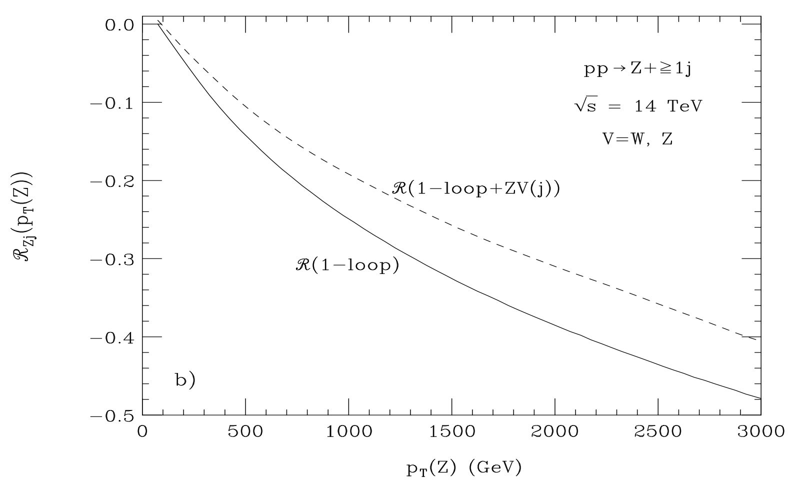
Effects of real emission

[*Baur'06*]

- No real corrections for exclusive processes
- Effects from *real* weak boson emission for inclusive processes
- Violation of Bloch-Nordsieck theorem for non-abelian gauge theories $\Longrightarrow$ logarithmic terms survive

  [*Catani, M.Ciafaloni, P. Ciafaloni, Comelli*]
- Moderate effects at the LHC



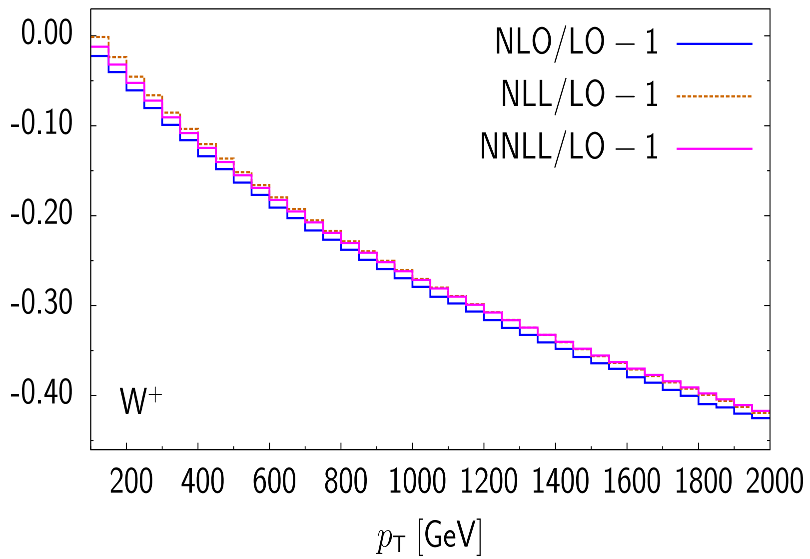


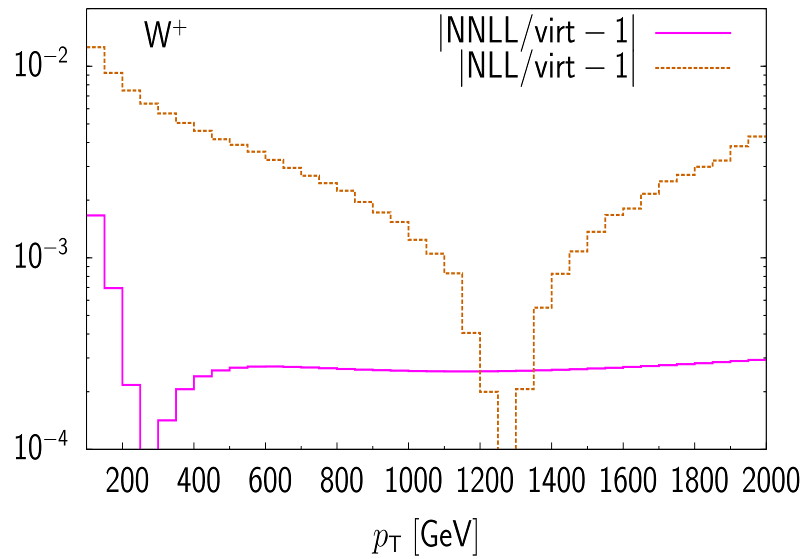
Summary

- Analytic results for the full $\mathcal{O}(\alpha)$ correction to the p_T distribution of W-bosons, Z-bosons and direct photons
- NNLL aproximation of the NLO: compact expression, excellent approximation
- NLL approximation: 1-loop and 2-loop corrections
- Conclusion: EW corrections important for the precise knowledge of the production cross sections at large p_T (large logs at TeV scales!)
  - Negative 1-loop corrections of the order of tens of percent at high p_{T} at the LHC
  - Positive 2-loop NLL corrections of the order of several percent at high p_{T} at the LHC $\Rightarrow$ relevant for the analysis!
  - Ratio $\frac{d\sigma^{\gamma}}{dp_T}/\frac{d\sigma^{Z}}{dp_T}$ and $\frac{d\sigma^{W^{\pm}}}{dp_T}/\frac{d\sigma^{Z}}{dp_T}$: significant effects due to EW corrections at large p_T
  - Same study for the Tevatron: corrections less significant numerically

Backup: High-energy approximation of the one-loop

W^+ production at the LHC





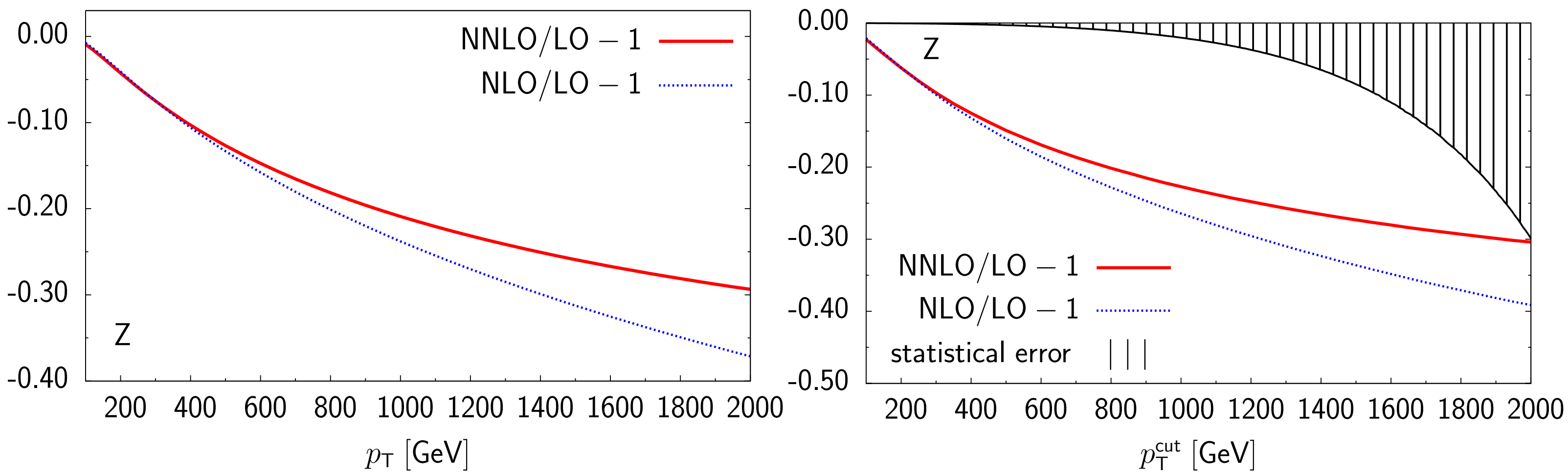
- NLL approximation: percent (or better) level

  $\sim$ 1% deviation from NLO at low p_T

  $\sim$ 0.2% deviation from NLO at $p_T = 2$ TeV
- NNLL approximation: permille level
- Similar behaviour for W^- production

Backup: NLL approximation: 2-loop results

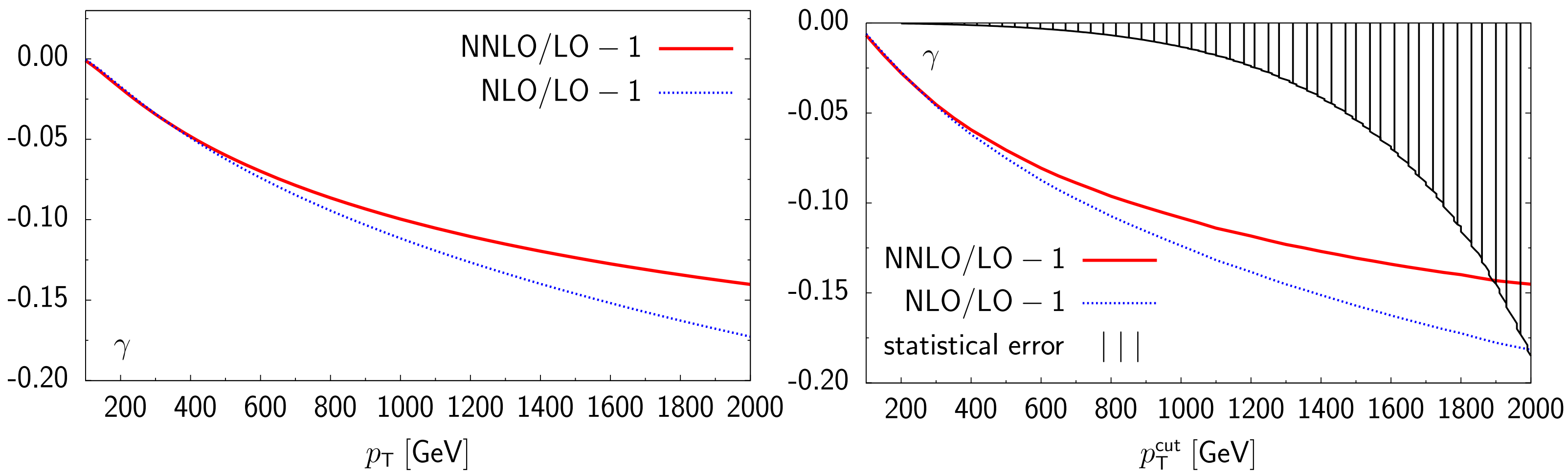
Large p_T Z-boson production at the LHC



- NLL 2-loop terms positive, up to 8% contribution (at 2 TeV)
- 1-loop + 2-loop NLL amount to up to -30% correction (at 2 TeV)
- For large range of p_T values 2-loop effects comparable with statistical error!

Backup: NLL approximation: 2-loop results

Large p_T photon production at the LHC



- NLL 2-loop terms positive, up to 3% contribution (at 2 TeV)
- 1-loop + 2-loop NLL amount to up to -14% correction (at 2 TeV)
- For large range of p_T values 2-loop effects comparable with statistical error!