Weak Corrections to hadronic Z production at high transverse momentum

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Overview

- Introduction
  - why Z at high p_{T}?
  - why weak corrections?
  - basic set-up
- $\mathcal{O}(\alpha)$ weak corrections
  - structure and properties
  - renormalization
  - LHC predictions
- Logarithmic approximation
  - definition
  - 1-loop and 2-loop NLL results
  - comparison of 1-loop NLL with the full result

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- Z + 1 jet signal at the LHC: large cross section
- probe of the partonic content of the colliding hadrons:
  at values of $p_{\rm T}$ considered here ($p_{\rm T} \gtrsim 100$ GeV) production dominated by the gluonic contribution $\Longrightarrow$ gluon's pdfs

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. . . but not everywhere

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Logarithmic corrections

$$\mathcal{O}(\alpha^N): \qquad \alpha^N \ln^{2N}\left(\frac{\hat{s}}{M_W^2}\right) \qquad \text{leading}$$

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[*Accomando, Denner, Pozzorini'02*] [*Hollik, Meier'04*]

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Origin: soft/collinear emission of virtual *massive* gauge bosons (W, Z) off initial and final states

- 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

Introduction

$$\frac{\mathrm{d}\sigma^{h_1 h_2}}{\mathrm{d}p_\mathrm{T}} = \sum_{i,j} \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2 \; \theta(x_1 x_2 - \hat{\tau}_\mathrm{min}) f_{h_1,i}(x_1,\mu^2) f_{h_2,j}(x_2,\mu^2) \frac{\mathrm{d}\hat{\sigma}^{ij}}{\mathrm{d}p_\mathrm{T}}$$

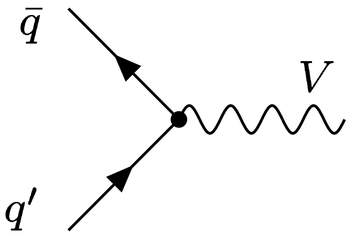
with $\hat{\tau}_\mathrm{min} = (p_\mathrm{T} + m_\mathrm{T})^2/s$ $\qquad m_\mathrm{T} = \sqrt{p_\mathrm{T}^2 + M_Z^2}$

$$\frac{d\hat{\sigma}^{ij}}{dp_\mathrm{T}} = \frac{p_\mathrm{T}}{8\pi N_{ij}\hat{s}|\hat{t}-\hat{u}|} \left[\overline{\sum} |\mathcal{M}^{ij}|^2 + (\hat{t} \leftrightarrow \hat{u}) \right]$$

Partonic subprocesses: $\bar{q}q \to Zg\,, \quad q\bar{q} \to Zg\,, \quad gq \to Zq, \quad g\bar{q} \to Z\bar{q}, \quad qg \to Zq, \quad \bar{q}g \to Z\bar{q}$

related by crossing symmetries $\Longrightarrow$ enough to consider $\bar{q}q \to Zg$

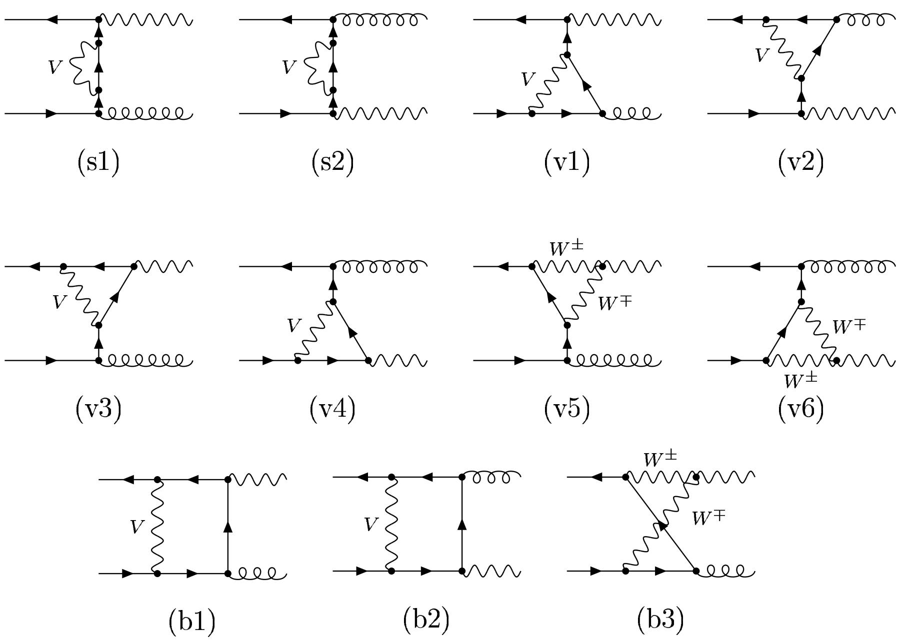
$$\mathrm{LO:} \qquad \overline{\sum} |\mathcal{M}^{\bar{q}q}|^2 = 8\pi^2 \alpha\alpha_s (N_c^2 - 1) \sum_{\lambda=\mathrm{L,R}} (I_{q_\lambda}^Z)^2 H_0 \qquad H_0 = \frac{\hat{t}^2 + \hat{u}^2 + 2\hat{s}M_Z^2}{\hat{t}\hat{u}}$$



$$= ie\gamma^\mu \sum_{\lambda=\mathrm{R,L}} \omega_\lambda I^V_{q_\lambda q'_\lambda} \qquad \omega_{\mathrm{R/L}} = \frac{1}{2}(1 \pm \gamma_5)$$

Only weak corrections considered here, i.e. no electromagnetic corrections

$\mathcal{O}(\alpha)$ corrections to $\bar{q}q \to Zg$



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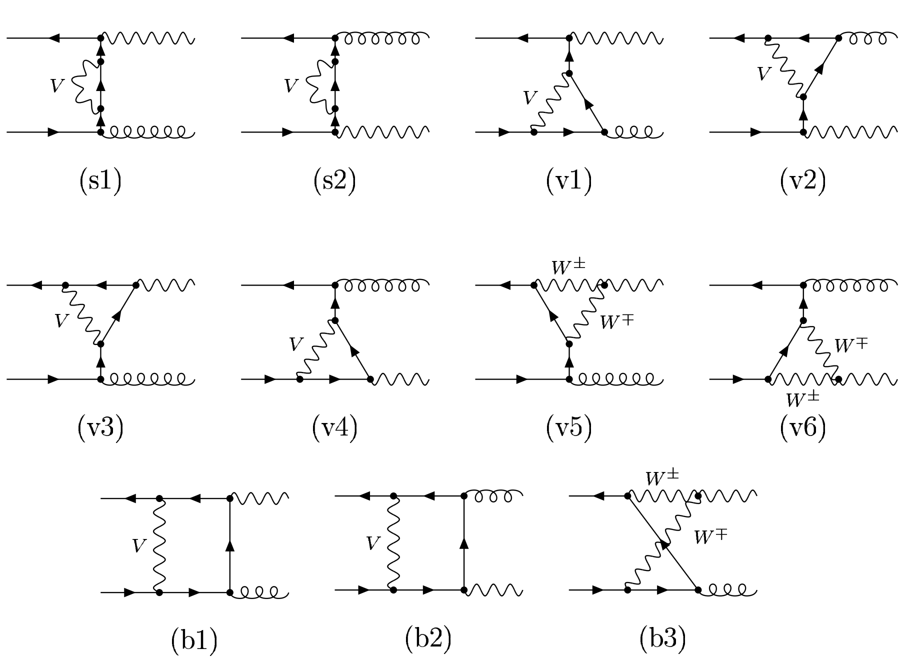


All dependence on flavour and chirality of incoming quarks organized in two coupling factors:

"abelian" $\quad I^Z I^{W^\pm} I^{W^\mp} = I^{W^\pm} I^{W^\mp} I^Z$ $\quad$ (diagrams s1, s2, v1, v2)

"non-abelian" $\quad \frac{i}{s_W} \varepsilon^{W^\pm W^\mp Z} I^{W^\pm} I^{W^\mp} = \frac{c_W}{{s_W}^3} T^3$ $\quad$ (diagrams v5, v6, b3)

mixed $\quad I^{W^\pm} I^Z I^{W^\mp} = I^Z I^{W^\pm} I^{W^\mp} - \frac{c_W}{{s_W}^3} T^3$ $\quad$ (diagrams v3, v4, b1, b2)

$\mathcal{O}(\alpha)$ corrections to $\bar{q}q\to Zg$

- Passarino-Veltman tensor reduction
- sum over gauge boson polarization states

$$\overline{\sum}|\mathcal{M}_1^{\bar{q}q}|^2 = 8\pi^2\alpha\alpha_S(N_c^2-1)\times\sum_{\lambda=\mathrm{R,L}}\Bigg\{\left(I_{q_\lambda}^Z\right)^2 H_0$$

$$+\frac{\alpha}{2\pi}\Bigg[\left(I_{q_\lambda}^Z\right)^2\sum_{V=\mathrm{Z,W^\pm}}\left(I^V I^{\bar{V}}\right)_{q_\lambda} H_1^{\mathrm{A}}(M_V^2)+\frac{c_W}{{s_W}^3}T_{q_\lambda}^3 I_{q_\lambda}^Z H_1^{\mathrm{N}}(M_W^2)\Bigg]\Bigg\}$$

$$H_1^{\mathrm{A/N}}(M_V^2)=\mathrm{Re}\left[\sum_{j=0}^{14}K_j^{\mathrm{A/N}}(M_V^2)\,J_j(M_V^2)\right]\leftarrow\left(\begin{array}{l}\text{independent of}\\\text{flavour and chirality}\end{array}\right)$$

$$K_j^{\mathrm{A/N}}(M_V^2)=K_j^{\mathrm{A/N}}(\hat{s},\hat{t},\hat{u},M_V^2)$$

$J_0(M_V^2)=1$ $\quad$ $J_2(M_V^2)\ldots J_6(M_V^2)=B_0(\ldots)$ $\quad$ $J_{12}(M_V^2)\ldots J_{14}(M_V^2)=$

$J_1(M_V^2)=A_0(M_V^2)$ $\quad$ $J_7(M_V^2)\ldots J_{11}(M_V^2)=C_0(\ldots)$ $\quad$ box integrals

$\mathcal{O}(\alpha)$ corrections to $\bar{q}q \to Zg$

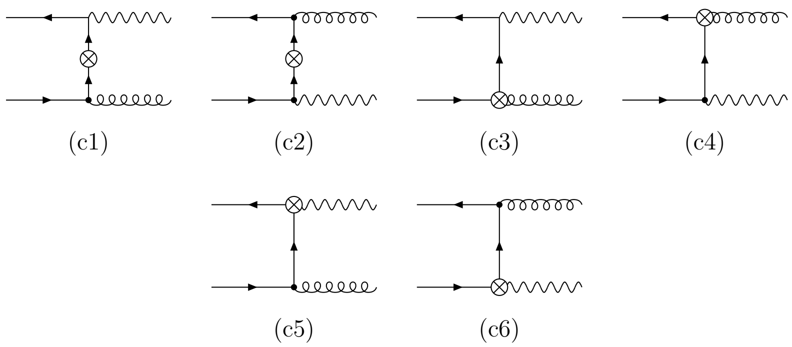
Compact analytical expressions for $K_j^{\mathrm{A/N}}(M_V^2)$, of an average size of (for example):

$$
\begin{aligned}
K_8^{\mathrm{A}}(M_V^2) \quad = \quad & -\Big[(M_Z^2-\hat{s}-\hat{t})\hat{t}(\hat{s}+\hat{t})^3\Big]^{-1} \\
& \Big[2(\hat{s}^4+4\hat{t}\hat{s}^3+6\hat{t}^2\hat{s}^2-2\hat{t}(M_Z^4+\hat{t}M_Z^2-2\hat{t}^2)\hat{s}+(M_Z^2-\hat{t})^2\hat{t}^2)M_V^4+ \\
& 2(\hat{s}+\hat{t})(-2\hat{s}\hat{t}M_Z^4+2\hat{s}^4+\hat{t}^4+5\hat{s}\hat{t}^3+9\hat{s}^2\hat{t}^2+7\hat{s}^3\hat{t})M_V^2+ \\
& (\hat{s}+\hat{t})^4(2\hat{s}^2+2\hat{t}\hat{s}+\hat{t}^2)\Big](M_Z^4+\hat{t}M_Z^2-2\hat{t}^2)\hat{s}+(M_Z^2-\hat{t})^2\hat{t}^2)M_V^4+ \\
& 2(\hat{s}+\hat{t})(-2\hat{s}\hat{t}M_Z^4+2\hat{s}^4+\hat{t}^4+5\hat{s}\hat{t}^3+9\hat{s}^2\hat{t}^2+7\hat{s}^3\hat{t})M_V^2+ \\
& (\hat{s}+\hat{t})^4(2\hat{s}^2+2\hat{t}\hat{s}+\hat{t}^2)\Big] \\
K_{14}^{\mathrm{N}}(M_W^2) \quad = \quad & \Big[(M_Z^2-\hat{s}-\hat{t})\hat{t}\Big]^{-1} \\
& ((M_Z^2-\hat{s})M_W^2+\hat{t}(-M_Z^2+\hat{s}+\hat{t})) \\
& \Big[(2M_W^4+2(M_Z^2+\hat{s})M_W^2+\hat{s}^2+2\hat{t}^2+2\hat{s}\hat{t}-M_Z^2(\hat{s}+2\hat{t}))\Big]
\end{aligned}
$$

$\mathcal{O}(\alpha)$ corrections to $\bar{q}q \to Zg$

• A_0 , B_0 integrals UV-divergent $\to$ renormalization

Counterterm diagrams:



Contribution from c1 + c2 + c3 + c4 = 0

$$\overline{\sum}|\mathcal{M}_1^{\bar{q}q}|^2 \to \overline{\sum}|\mathcal{M}_1^{\bar{q}q}|^2 + 8\pi^2\alpha\alpha_S(N_c^2-1)\sum_{\lambda=\mathrm{R,L}}\left\{2\left(I^Z_{q_\lambda}\right)^2 H_0\delta C^A_{q_\lambda} + 2\frac{c_W}{s_W}T^3_{q_\lambda}I^Z_{q_\lambda}H_0C^N_{q_\lambda}\right\}$$

$$\delta C^{\mathrm{A}}_{q_\lambda} = \delta Z_{q_\lambda} + \frac{1}{2}\left(\delta Z_{ZZ} + \frac{c_W}{s_W}\delta Z_{AZ} + \frac{\delta e^2}{e^2} - \frac{1}{{s_W}^2}\frac{\delta {c_W}^2}{{c_W}^2}\right)$$

$$\delta C^{\mathrm{N}}_{q_\lambda} = -\frac{1}{2s_W c_W}\delta Z_{AZ} + \frac{1}{{s_W}^2}\frac{\delta {c_W}^2}{{c_W}^2}.$$

$\Longrightarrow$ cancellation of UV-poles in $\overline{\sum}|\mathcal{M}_1^{\bar{q}q}|^2$

$\mathcal{O}(\alpha)$ corrections to $\bar{q}q \to Zg$

- "Fake" IR singularities in box diagrams:

massless quark lines $\Longrightarrow$ after tensor reduction IR-divergent box and vertex integrals

Cancellations between D_0 and C_0 integrals in the IR limit $\Longrightarrow$ fi nite result

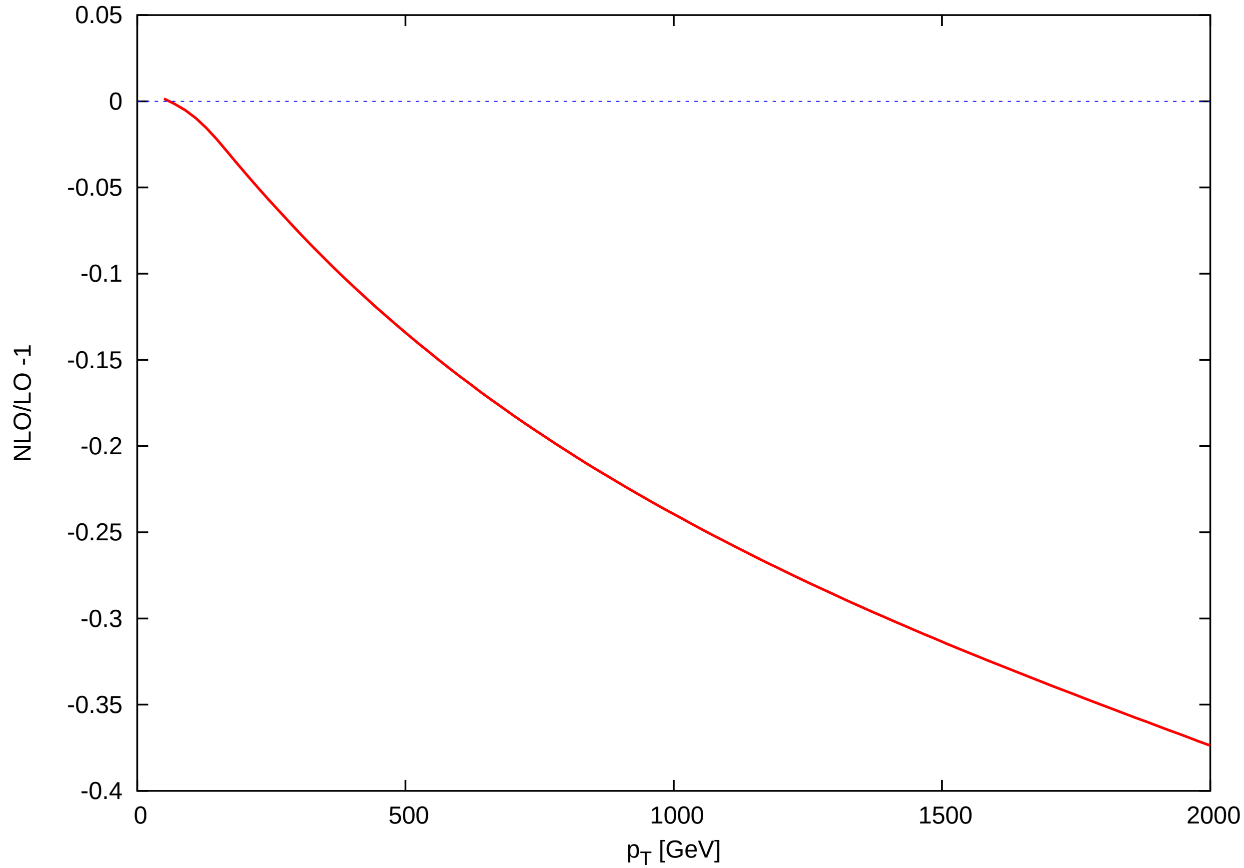
[*Dittmaier'03*]

$J_{12}(M_V^2) \ldots J_{14}(M_V^2)$ given in terms of fi nite combinations of D_0 and C_0 functions, e.g.

$$\begin{aligned} J_{12}(M_V^2) &= D_0(0,0,M_Z^2,0,\hat{t},\hat{s};M_V^2,0,0,0) - D_0^{\rm sing} \\ &= D_0(0,0,M_Z^2,0,\hat{t},\hat{s};M_V^2,0,\lambda^2,0) \\ &\quad - \frac{\hat{t}C_0(\hat{t},0,0;M_V^2,\lambda^2,0) + (\hat{s}-M_Z^2)C_0(\hat{s},M_Z^2,0;0,0,\lambda^2)}{\hat{s}\hat{t} + (\hat{t}+\hat{u})M_V^2} \end{aligned}$$

λ - small numerical regulator, $\frac{\lambda}{M_Z} \gg 1$

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



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

Logarithmic approximation

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- High energy region: $|\hat{r}| \gg M_W^2 \sim M_Z^2$ for $\hat{s},\ \hat{t},\ \hat{u}$
- Corrections due to $Z - W$ ratio not considered
- Corrections of $\mathcal{O}\left(\frac{M_W^2}{|\hat{r}|}\right)$ not considered
- Only transverse polarization of Z

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

1- loop

proof that soft/collinear singularities from virtual weak boson emission factorize and are universal [*Denner, Pozzorini'01*]

2- loop

general (process-independent) result obtained with eikonal approximation (LL) and from resummation (NLL) [*Denner, Melles, Pozzorini'03*], [*Melles'02,'03*]

Logarithmic approximation: 1-loop and 2-loop NLL

$$\overline{\sum}|\mathcal{M}^{\bar{q}q}|^2 = 8\pi^2\alpha\alpha_s(N_c^2-1)H_0\left[A^{(0)} + \left(\frac{\alpha}{2\pi}\right)A^{(1)} + \left(\frac{\alpha}{2\pi}\right)^2 A^{(2)}\right]$$

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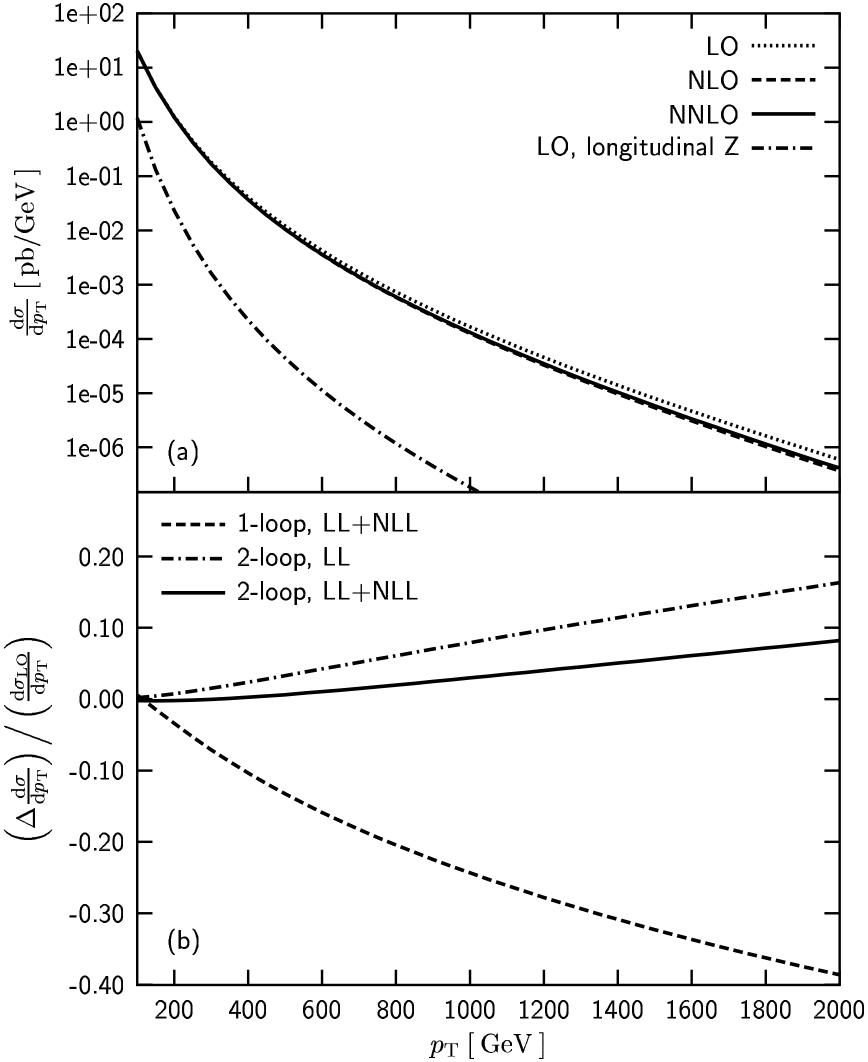
$$\begin{aligned} A^{(2)} &= \sum_{\lambda=\mathrm{L,R}}\Bigg\{\frac{1}{2}\left(I^Z_{q_\lambda}C^{\mathrm{ew}}_{q_\lambda} + \frac{c_W}{{s_W}^3}T^3_{q_\lambda}\right)\Bigg[I^Z_{q_\lambda}C^{\mathrm{ew}}_{q_\lambda}\left(L^4_{\hat{s}} - 6L^3_{\hat{s}}\right) \\ &+ \frac{c_W}{{s_W}^3}T^3_{q_\lambda}\left(L^4_{\hat{t}} + L^4_{\hat{u}} - L^4_{\hat{s}}\right)\Bigg] - \frac{T^3_{q_\lambda}Y_{q_\lambda}}{8{s_W}^4}\left(L^4_{\hat{t}} + L^4_{\hat{u}} - L^4_{\hat{s}}\right) \\ &+ \frac{1}{6}I^Z_{q_\lambda}\left[I^Z_{q_\lambda}\left(\frac{b_1}{{c_W}^2}\left(\frac{Y_{q_\lambda}}{2}\right)^2 + \frac{b_2}{{s_W}^2}C_{q_\lambda}\right) + \frac{c_W}{{s_W}^3}T^3_{q_\lambda}b_2\right]L^3_{\hat{s}}\Bigg\} \end{aligned}$$

$$C^{\mathrm{ew}}_{q_\lambda} = Y^2_{q_\lambda}/(4{c_W}^2) + C_{q_\lambda}/{s_W}^2 \qquad b_1 = -41/(6{c_W}^2) \qquad b_2 = 19/(6{s_W}^2)$$

Logarithmic approximation: 1-loop and 2-loop NLL



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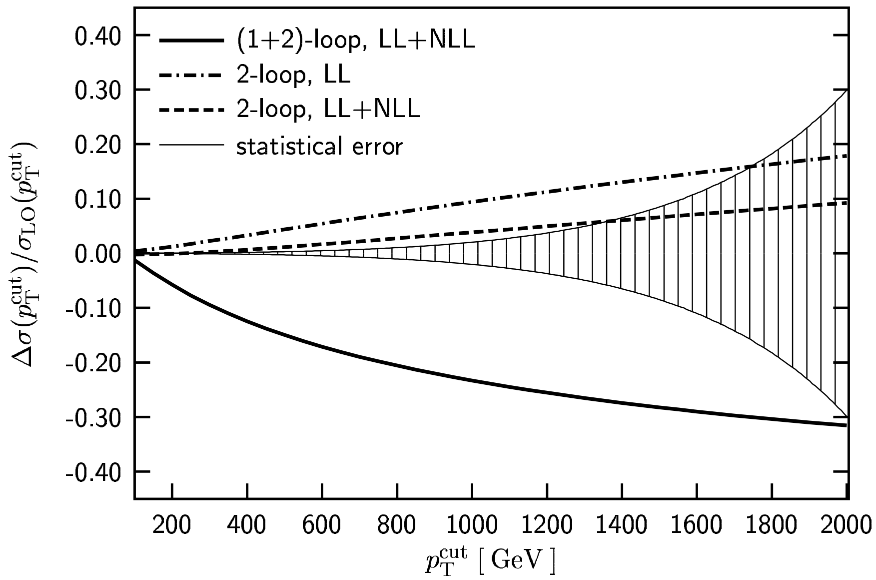

Integrated cross section $\Delta\sigma(p_T^{cut})$ vs.

statistical error $\frac{\Delta\sigma_{stat}}{\sigma} = \frac{1}{\sqrt{N}}$

$N = \mathcal{L} \times \mathrm{BR}(Z \to l,\ \nu_l) \times \sigma_{LO}$

$\mathrm{BR}(Z \to l,\ \nu_l) = 30.6\%$

$\mathcal{L} = 300$ fb^{-1}

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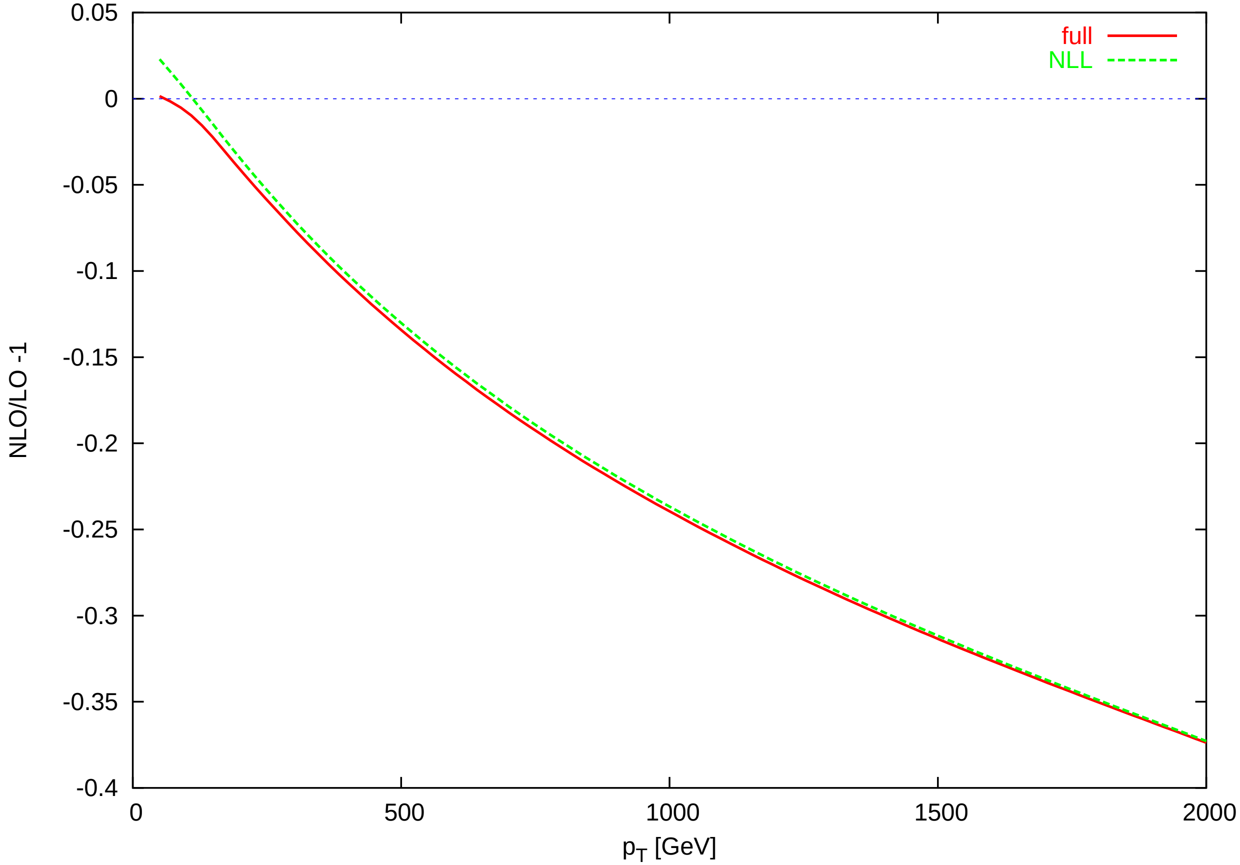
Logarithmic approximation: 1-loop full vs. NLL result



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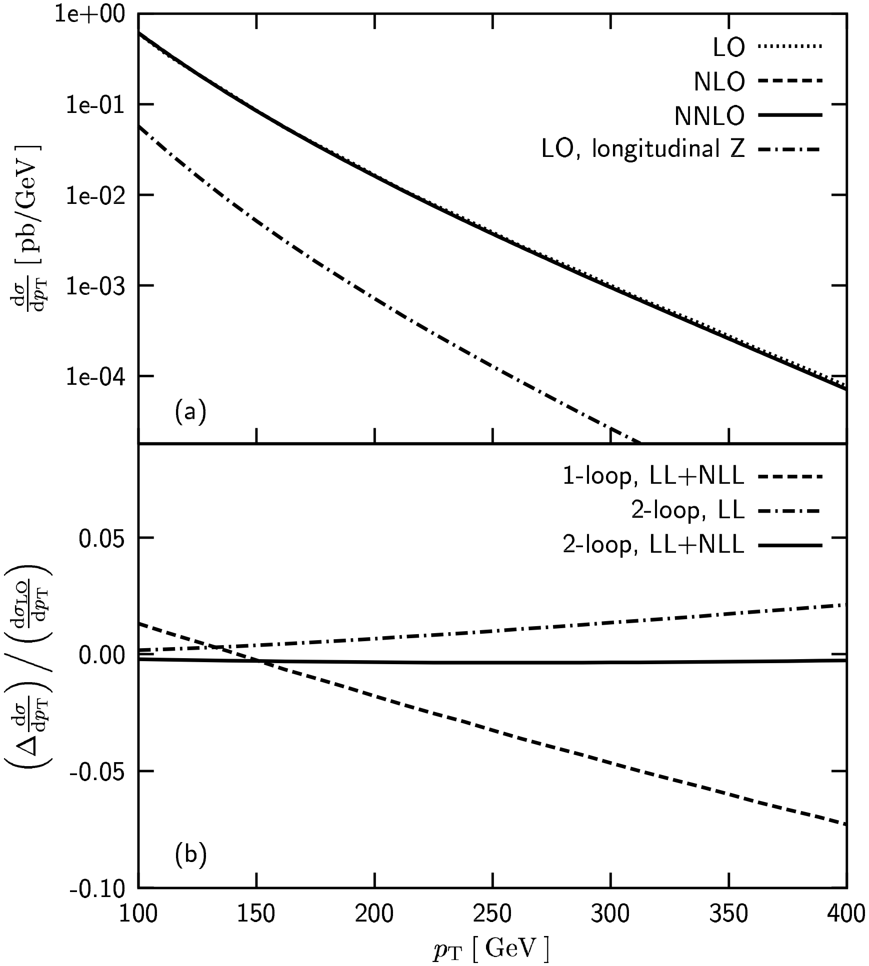
Conclusions

- Analytic result for the full 1-loop $\mathcal{O}(\alpha)$ weak correction (literature: only numerical) [*Maina, Moretti, Ross'04*]
- NLL approximation: 1-loop and 2-loop corrections
- Results explicitly applicable for the case of polarized quarks
- Negative 1-loop correction of the order of tens of percent at high p_{T}, $p_{\mathrm{T}} \geq 300$ GeV
- Positive 2-loop NLL correction of the order of several percent at high p_{T}
- Full 1-loop result approximated very well by the NLL
- Same study for the Tevatron: corrections not significant numerically

Extras: Logarithmic approximation: 1-loop and 2-loop NLL, Tevatron



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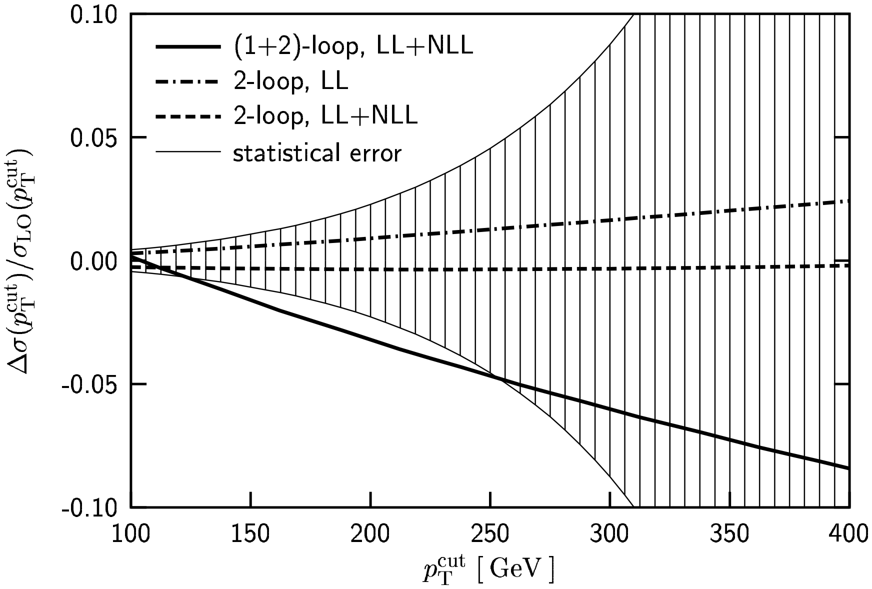

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$\mathcal{L} = 11$ fb^{-1}

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Extras: $\mathcal{O}(\alpha_S)$ QCD corrections to p_{T} of Z at the LHC

[Campbell, Ellis, Rainwater'03]