KET-Workshop
QCD and Electroweak Physics @ LHC

Gauge Bosons at High Transverse Momenta

Electroweak Loop Corrections to Hadronic Production
of Photons, Z- and W-Bosons with Single Jet Radiation

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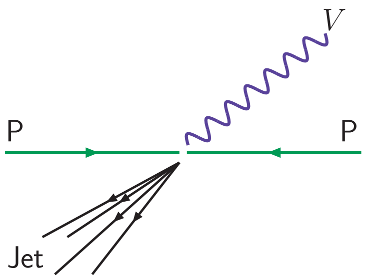
LHC & Tevatron

$$p + \overset{(-)}{p} \rightarrow Z/\gamma/W + \text{jet}$$

Outline

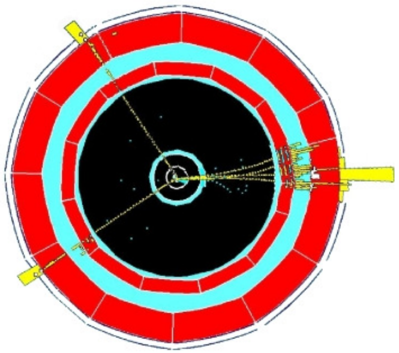
- Motivation
- Leading Order and Status of Loop Calculations
- Quantum Corrections for Z- & Photon-Production
- First Glance at W-Production
- Summary

Motivation

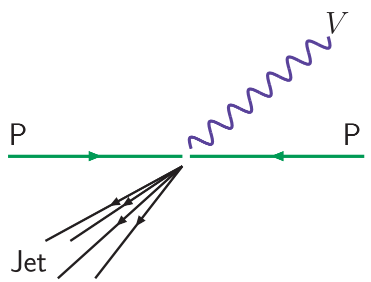


- relatively large cross sections
  $\sigma(p_{\mathrm{T}} > 1\mathrm{TeV}) \sim 10\,\mathrm{fb} \rightarrow 10^3$ evts/year

- clean experimental signature



Motivation



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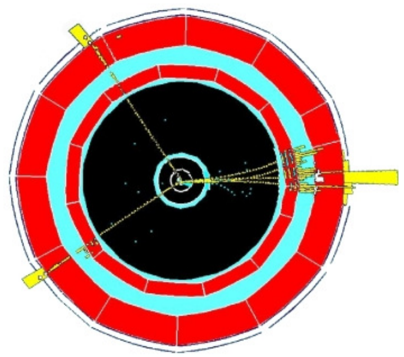
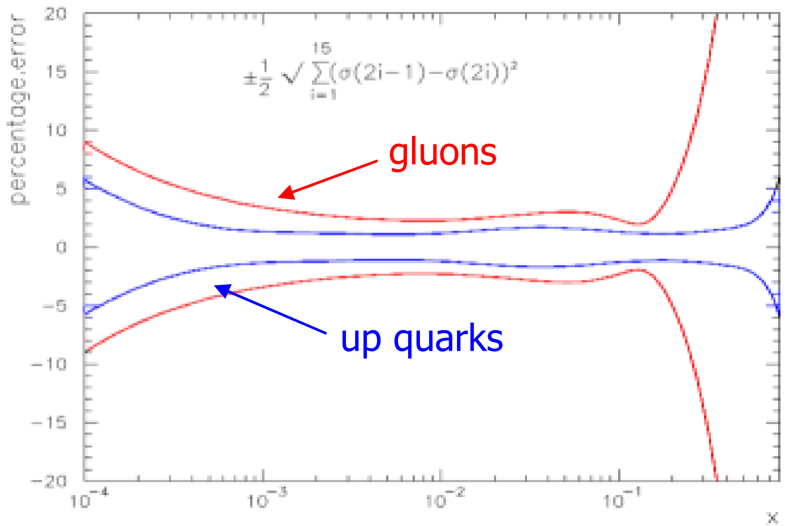


- test of the standard model
- background process for new physics
- luminosity measurement
- gauge gluon pdf`s



Leading Order (LO) Processes

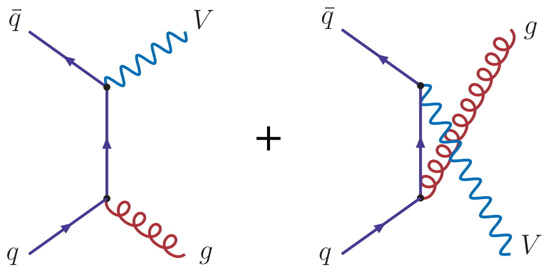
6 channels:

$$\bar{q}q \to Vg, \quad gq \to Vq, \quad g\bar{q} \to V\bar{q}, \qquad V = \mathrm{Z}/\gamma/\mathrm{W}$$

$$q\bar{q} \to Vg, \quad qg \to Vq, \quad \bar{q}g \to V\bar{q}$$

related by crossing symmetries $\Rightarrow$ focus on $\bar{q}q \to Vg$

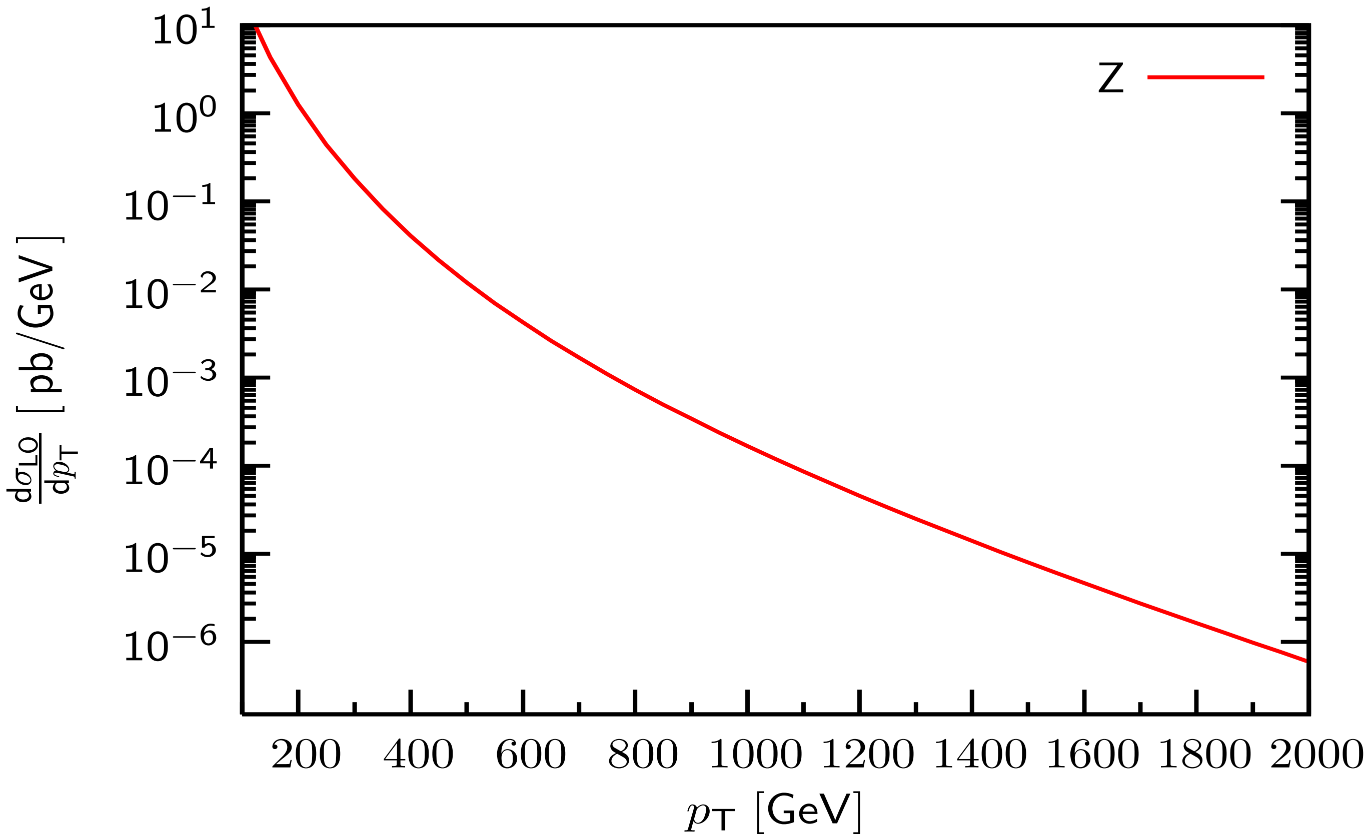
$$\mathcal{M}_{\mathrm{LO}}^{\bar{q}q\to Vg} =$$



$$|\mathcal{M}_{\mathrm{LO}}^{\bar{q}q\to Vg}|^2 \sim \sum_{\lambda=\mathrm{L,R}} \left(I_{q_\lambda}^V\right)^2 \frac{\hat{t}^2 + \hat{u}^2 + 2M_V^2\hat{s}}{\hat{t}\hat{u}}$$

$$I_{q_\lambda}^V = \begin{cases} -Q_q & V = \gamma \\ \frac{c_\mathrm{w}}{s_\mathrm{w}} T_{q_\lambda}^3 - \frac{s_\mathrm{w}}{2c_\mathrm{w}} Y_{q_\lambda} & V = Z \\ \frac{\delta_{\lambda L}}{\sqrt{2}s_\mathrm{w}} & V = W \end{cases}$$

LO p_T-Distributions



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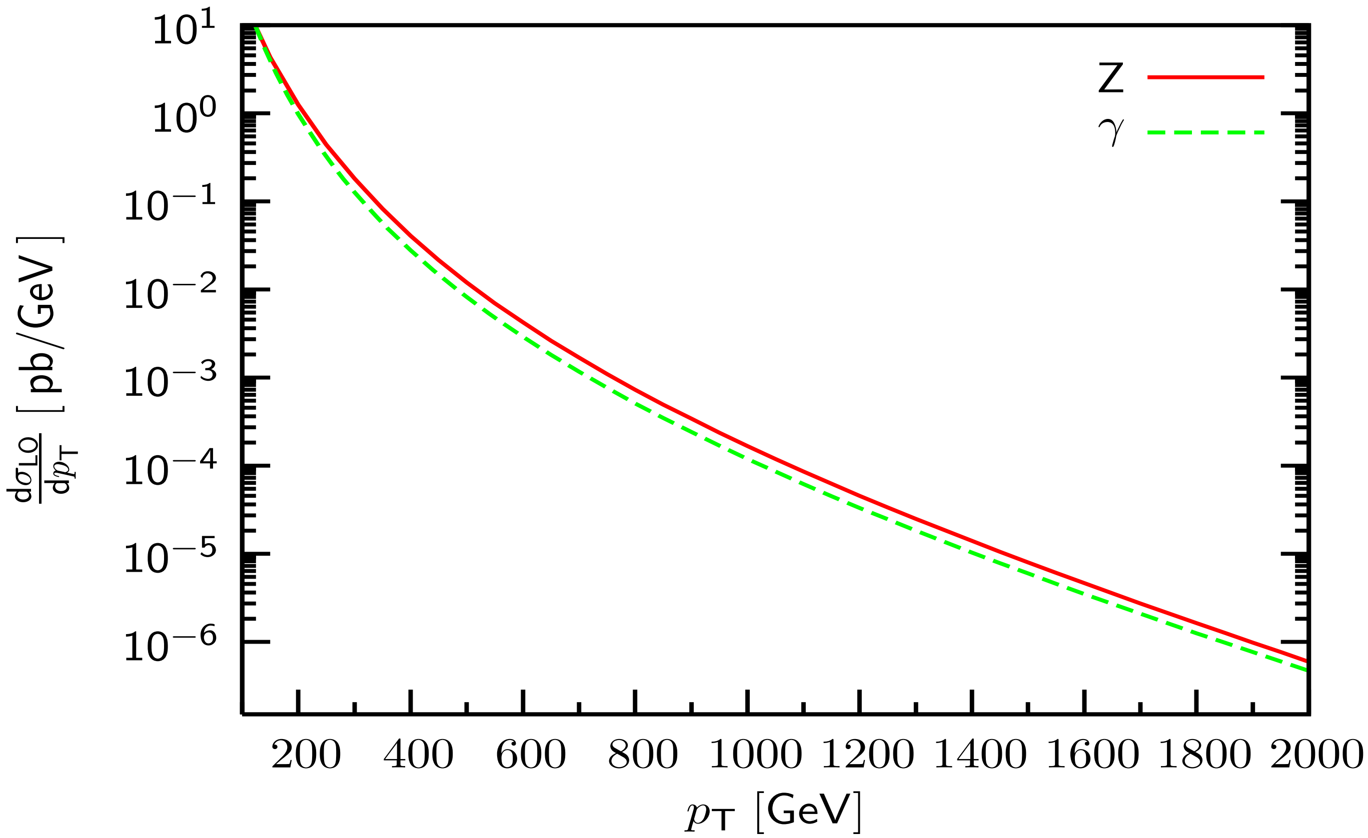

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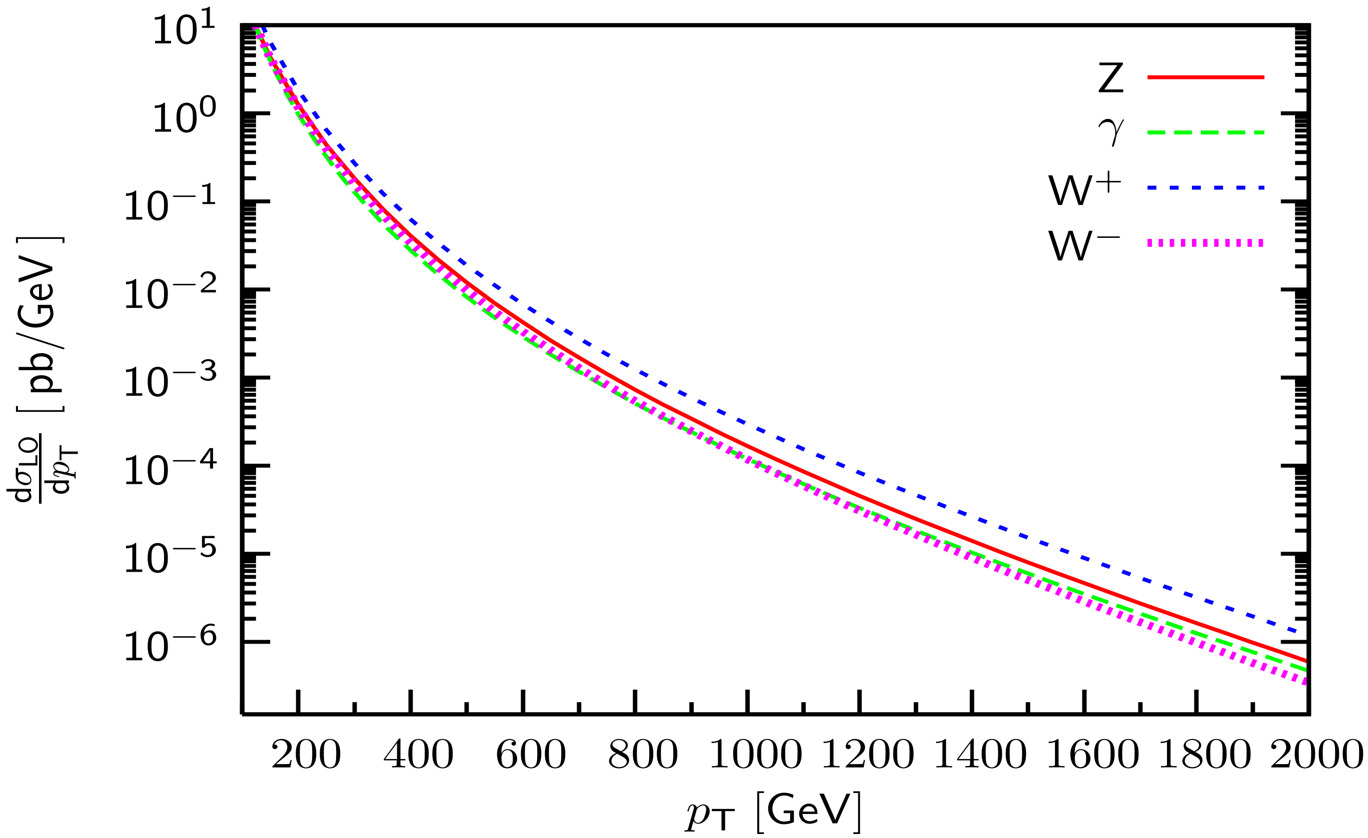

Status of Loop Calculations for LHC

QCD:
$\mathcal{O}(\alpha_s)$

numerical NLO results for $Z/W + 0, 1, 2$ jets at LHC & TEV: using MCFM	[Campbell, Ellis, Rainwater, 2002/03]
various analytic NLO results for $Z/W/ + 0, 1$ jet:	[Giele, Glover, Kosower, 1993]
	[Gonsalves, Pawlowski, Wai, 1989]
	[Arnold, Reno, 1989]
	[Ellis, Martinelli, Petronzio, 1983]
NLO results for direct photon production $\gamma + 1$ jet:	[Aurenche *et al.*, 1984, 1993]
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$\mathcal{O}(\alpha)$

weak:

numerical NLO results for $Z/\gamma + 1$ jet:	[Maina, Moretti, Ross, 2004. +Erratum]
analytic NLO results+dominant NNLO contributions for $Z + 1$ jet:	[Kühn, Kulesza, Pozzorini, Schulze, 2004]
analytic NLO results+dominant NNLO contributions for $\gamma + 1$ jet:	[Kühn, Kulesza, Pozzorini, Schulze, 2005]

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$\alpha_s \approx 10\,\alpha$?

but: $\alpha\ \log^2\left(\frac{\hat{s}}{M_W^2}\right)$

weak: $\mathcal{O}(\alpha)$

numerical NLO results for $Z/\gamma + 1$ jet: [Maina, Moretti, Ross, 2004. +Erratum]

analytic NLO results+dominant NNLO contributions for $Z + 1$ jet: [Kühn, Kulesza, Pozzorini, Schulze, 2004]

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Photon- & Z-Production

some technical details:

1-loop: **(NLO)**

- omitted QED corrections
- massless quarks
- P-V-reduction of tensor integrals
- renormalization of the coupling in the $\overline{\text{MS}}$ scheme
- compact analytical results
- derived NNLL approximation $(\leq 0.2\%$ accuracy, fast, very compact$)$

1-Loop: Analytical Results

$$|\mathcal{M}_{\mathrm{NLO}}|^2 \sim \sum_{V=Z,W^\pm} \left(I_q^V\right)^2 K_i^{\mathrm{Ab}} J_i \ldots + \frac{c_{\mathrm{w}}}{s_{\mathrm{w}}} K_i^{\mathrm{nAb}} J_i \ldots \qquad (i = 0 \ldots 14)$$

$$J_i : \; A_0, B_0, C_0, D_0$$

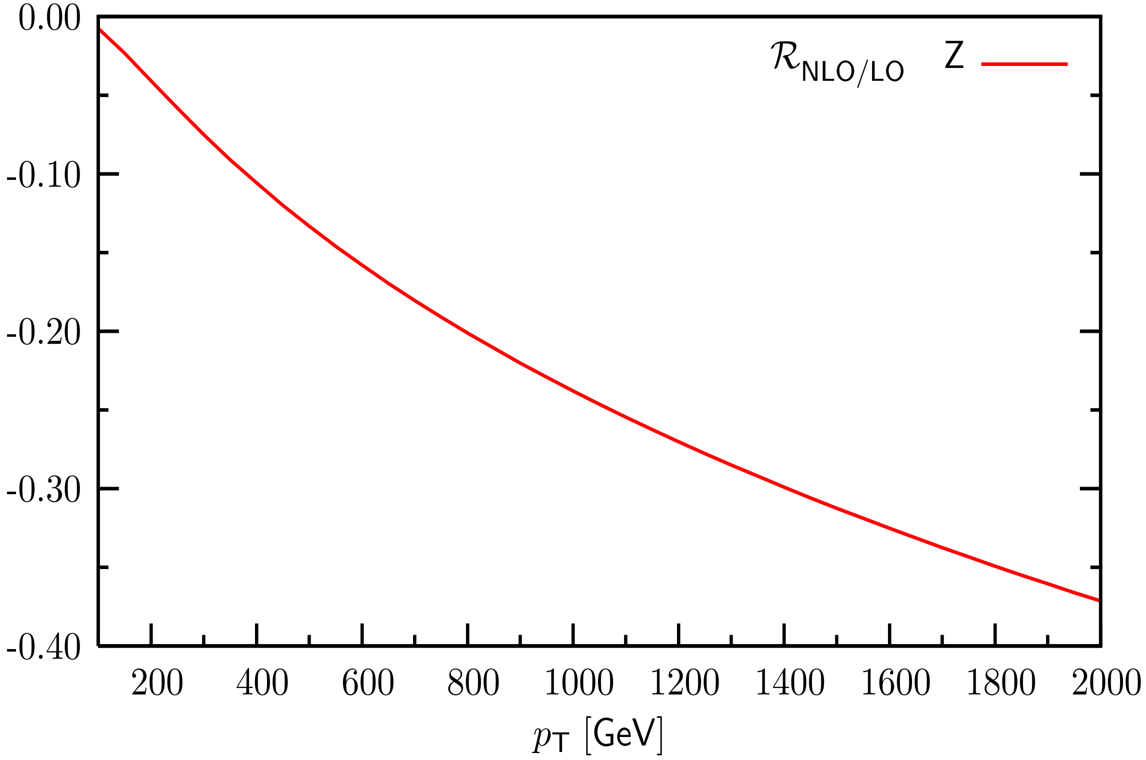
the most complicated term for Z production:

$$K_3^{\mathrm{nAb}}(M_W^2) = -\frac{1}{\hat{t}\hat{u}}\left(\frac{1}{(\hat{s}+\hat{t})^2} + \frac{1}{(\hat{s}+\hat{u})^2}\right) + 2M_W^2\left(\frac{3\hat{s}\hat{t}}{(\hat{s}+\hat{u})^3} + \frac{3\hat{s}\hat{u}}{(\hat{s}+\hat{t})^3}\right) \cdot$$
$$\left(\hat{s}^4 + \hat{s}^2\left(\hat{t}+\hat{u}\right)\left(2\hat{s}+\hat{t}+\hat{u}\right) - 2\hat{t}^2\hat{u}^2 + 2M_W^2\left(\hat{s}^2(\hat{s}+\hat{t}+\hat{u}) - \hat{t}\hat{u}(2\hat{s}-\hat{t}-\hat{u})\right)\right)$$

$$J_3 = B_0(M_V^2; M_W^2, M_W^2)$$

1-Loop: Numerical Results @ LHC

relative corrections for the p_T-distribution



p_T: transverse momentum

$$\mathcal{R}_{NLO/LO} = \left(\frac{d\sigma_{NLO}}{dp_T} \Big/ \frac{d\sigma_{LO}}{dp_T} \right) - 1$$

large negative corrections
($\approx -25\%$ at p_T=1 TeV)

1-Loop: Numerical Results @ LHC

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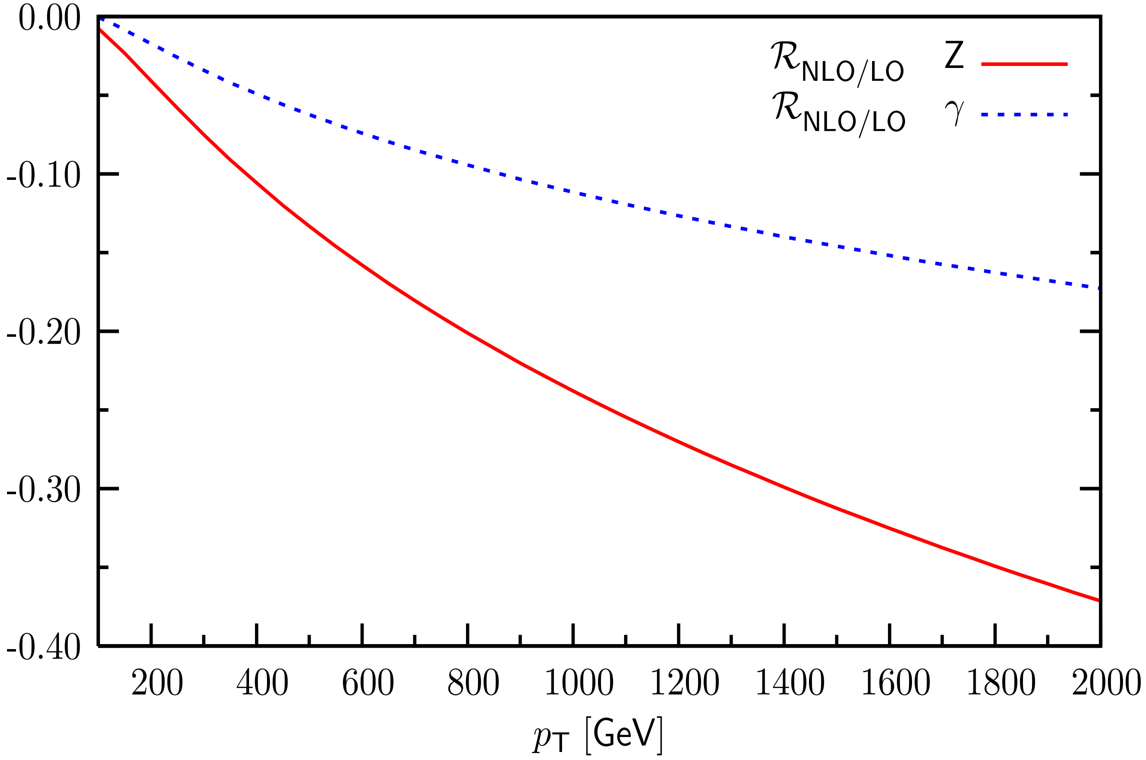

p_T: transverse momentum

$$\mathcal{R}_{\mathrm{NLO/LO}} = \left(\frac{d\sigma_{\mathrm{NLO}}}{dp_T} \Big/ \frac{d\sigma_{\mathrm{LO}}}{dp_T} \right) - 1$$

sizable negative corrections ($\approx -10\%$ at p_T=1 TeV)

large negative corrections ($\approx -25\%$ at p_T=1 TeV)

2-Loop: Analytical Results

high energy approximation: $|r| \gg M_Z^2 \approx M_W^2$ $\quad r = s, t, u$

consider dominant contributions: $\log^4\left(\frac{|r|}{M_\mathrm{W}^2}\right)$, $\log^3\left(\frac{s}{M_\mathrm{W}^2}\right)$

based on [Denner,Melles,Pozzorini]

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consider dominant contributions: $\log^4\left(\frac{|r|}{M_\mathrm{W}^2}\right)$, $\log^3\left(\frac{s}{M_\mathrm{W}^2}\right)$

result for Z production: based on [Denner,Melles,Pozzorini]

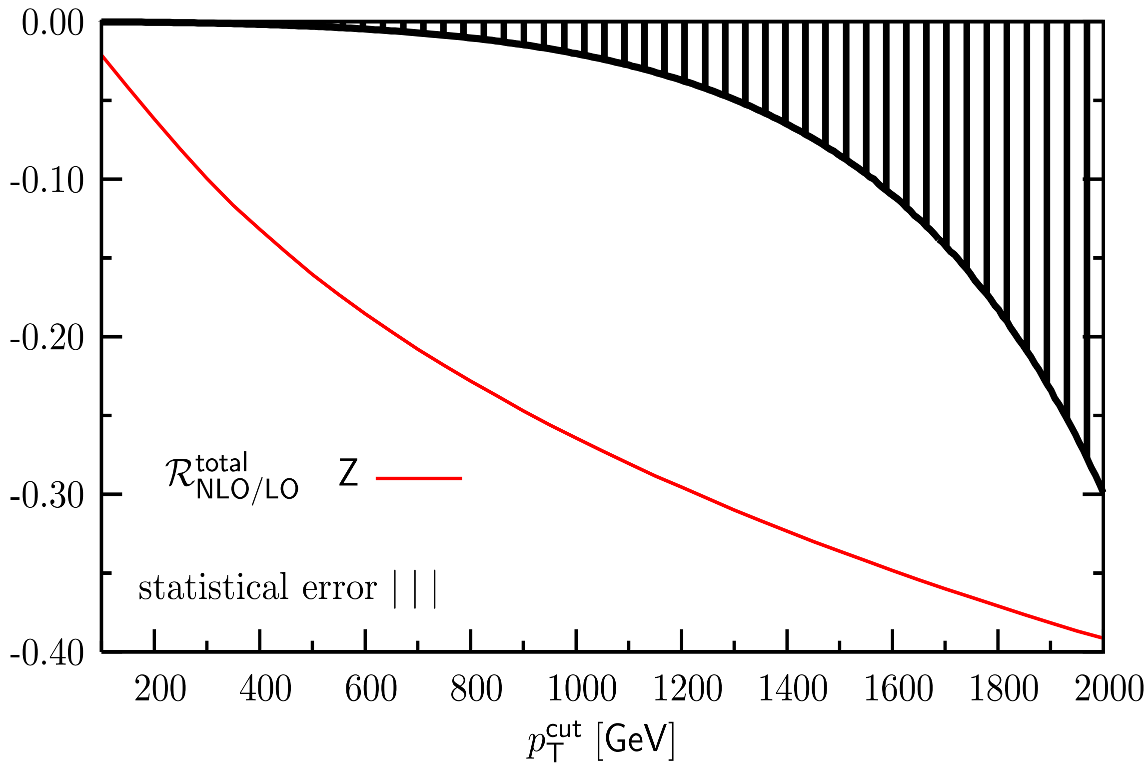
$$|\mathcal{M}_\mathrm{NNLO}|^2 \sim \left(\frac{\alpha}{2\pi}\right)^2 |\mathcal{M}_\mathrm{LO}|^2 \sum_{\lambda=\mathrm{L,R}} \left\{ \frac{1}{2}\left(I^Z_{q_\lambda} C^\mathrm{ew}_{q_\lambda} + \frac{c_\mathrm{W}}{s_\mathrm{W}{}^3} T^3_{q_\lambda}\right)\left(I^Z_{q_\lambda} C^\mathrm{ew}_{q_\lambda} X_1 + \frac{c_\mathrm{W}}{s_\mathrm{W}{}^3} T^3_{q_\lambda} X_2\right) - \frac{T^3_{q_\lambda} Y_{q_\lambda}}{8 s_\mathrm{W}{}^4} X_2 \right.$$
$$\left. + \frac{1}{6} I^Z_{q_\lambda}\left[I^Z_{q_\lambda}\left(\frac{b_1}{c_\mathrm{W}{}^2}\left(\frac{Y_{q_\lambda}}{2}\right)^2 + \frac{b_2}{s_\mathrm{W}{}^2} C_{q_\lambda}\right) + \frac{c_\mathrm{W}}{s_\mathrm{W}{}^3} T^3_{q_\lambda} b_2 \right] X_3 \right\}$$

with

$$X_1 = \ln^4\left(\frac{\hat{s}}{M_W^2}\right) - 6\ln^3\left(\frac{\hat{s}}{M_W^2}\right), \quad X_2 = \ln^4\left(\frac{\hat{t}}{M_W^2}\right) + \ln^4\left(\frac{\hat{u}}{M_W^2}\right) - \ln^4\left(\frac{\hat{s}}{M_W^2}\right),$$
$$X_3 = \ln^3\left(\frac{\hat{s}}{M_W^2}\right)$$

2-Loop: Numerical Results @ LHC

total cross section & statistical error



$$\mathcal{R}^{total}_{NLO/LO} = \left(\frac{\sigma_{NLO}(p_T^{cut})}{\sigma_{LO}(p_T^{cut})}\right) - 1$$

$$\sigma(p_T^{cut}) = \int_{p_T^{cut}}^{\infty} dp_T \, \frac{d\sigma}{dp_T}$$

$$\delta_{stat} = \frac{1}{\sqrt{N}}$$

$$N = \mathcal{B}_r \, \mathcal{L} \, \sigma$$

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

$\mathcal{B}_r(Z \to \text{leptons}) = 30.6\%$

2-Loop: Numerical Results @ LHC

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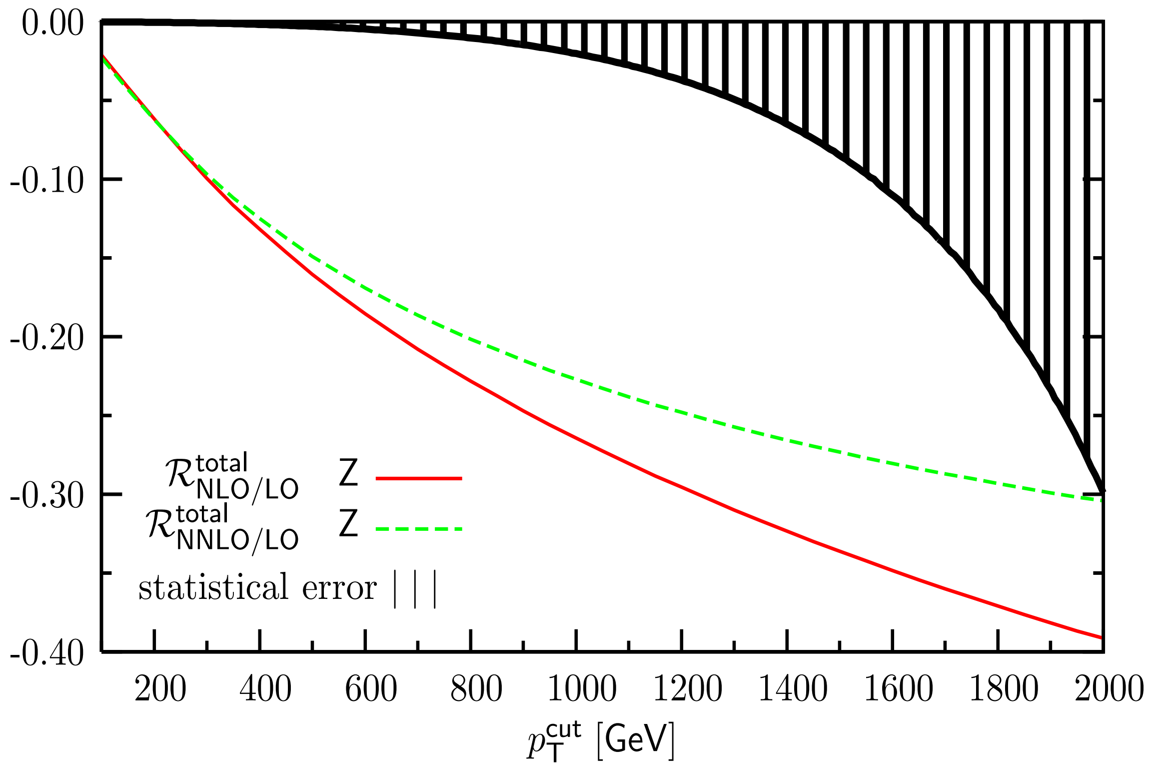

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2-loop effects are important for precision measurements

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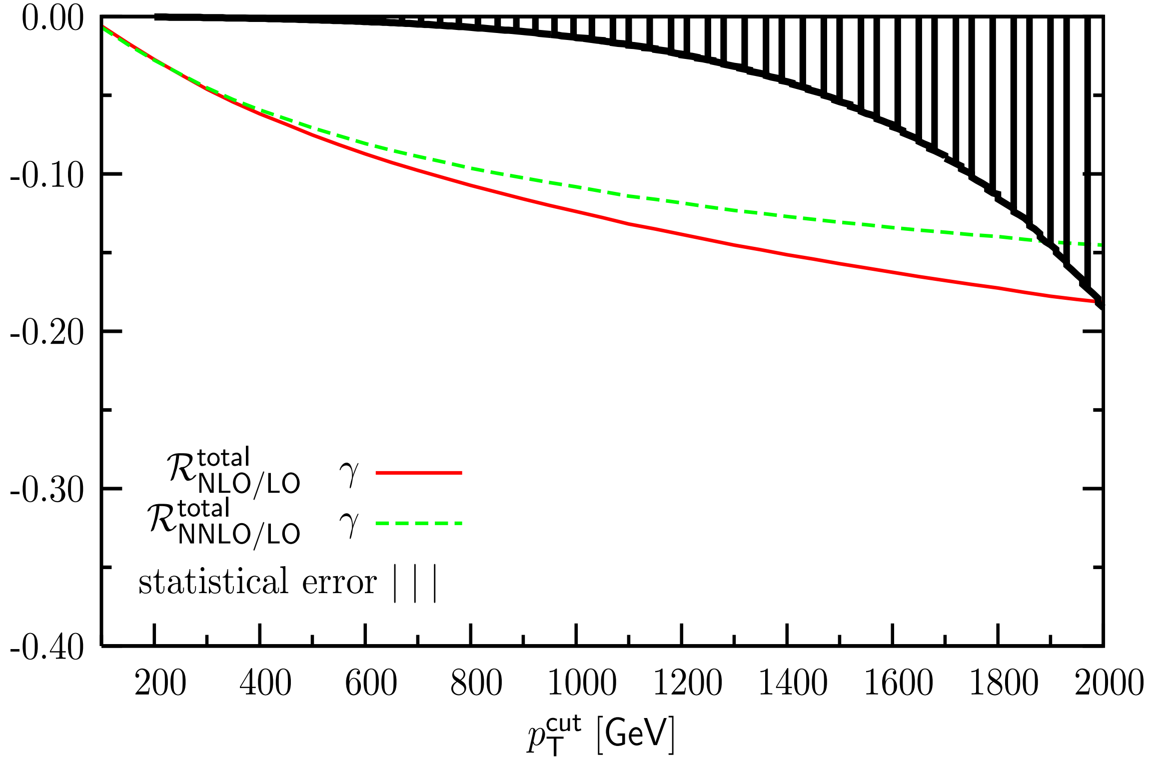

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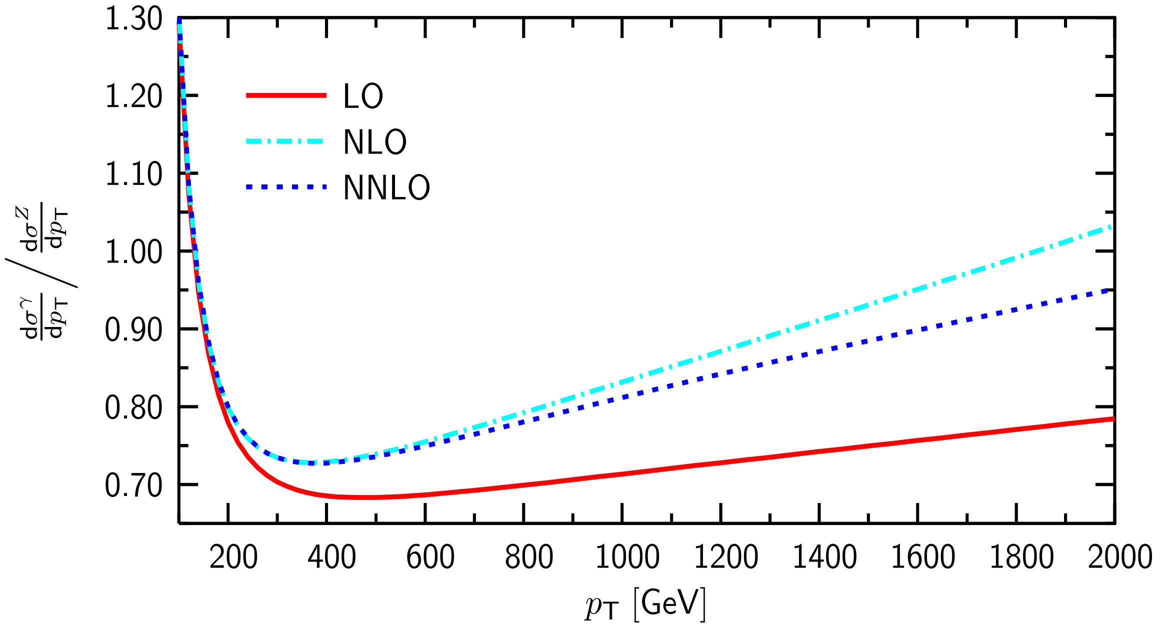
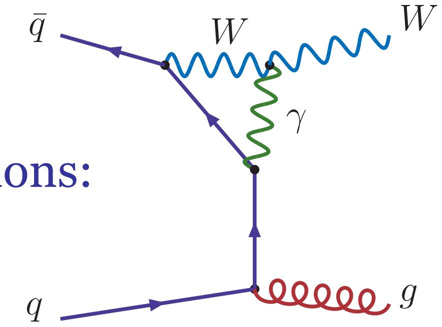
Ratio of Photon- & Z- Cross Section

- stable against QCD corrections
- cancellation of uncertainties in pdf`s



W-Production (First Glance)



No gauge invariant splitting of QED corrections:

$\Rightarrow$ virtual photonic corrections needed

$\Rightarrow$ real photon radiation needed

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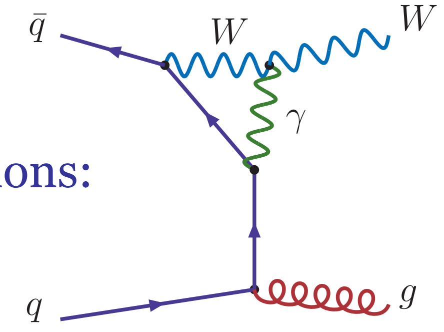


No gauge invariant splitting of QED corrections:

$\Rightarrow$ virtual photonic corrections needed

$\Rightarrow$ real photon radiation needed

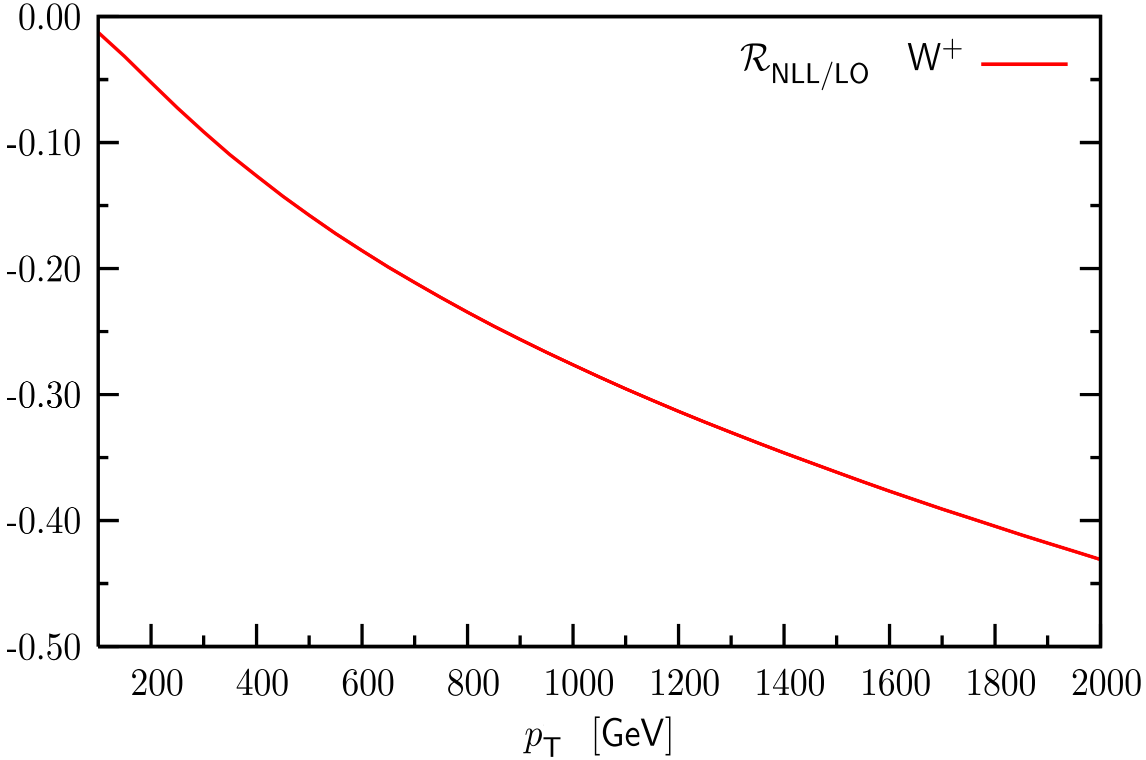
First approximation of the virtual corrections:

- **1-loop** logarithmic approximation

LL, NLL: $\log^2\left(\frac{|r|}{M_W^2}\right)$, $\log\left(\frac{|r|}{M_W^2}\right)$

1-Loop Logarithmic Correction @ LHC

relative corrections for the p_T-distribution



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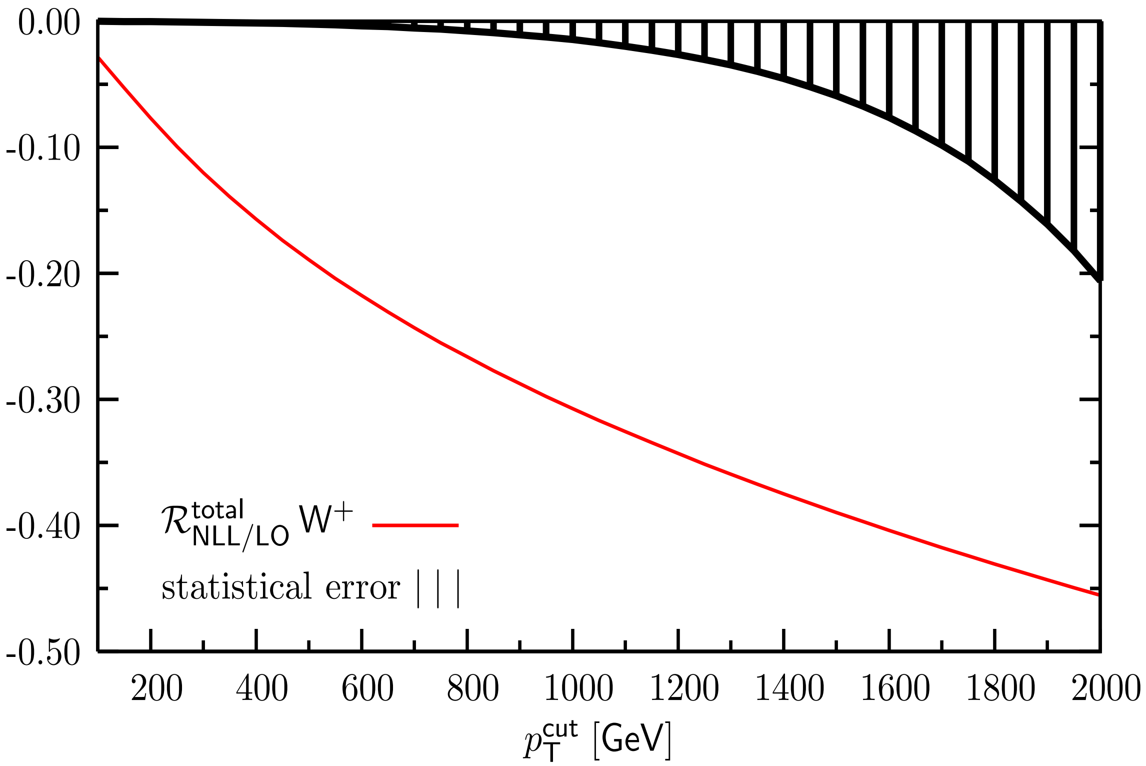
($\approx -30\%$ at p_T=1 TeV)

1-Loop Logarithmic Correction @ LHC

total cross section & statistical error



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$$\delta_{\text{stat}} = \frac{1}{\sqrt{N}}$$

$$N = \mathcal{B}_r \, \mathcal{L} \, \sigma$$

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

$\mathcal{B}_r(W \to \text{leptons}) = 32.5\%$

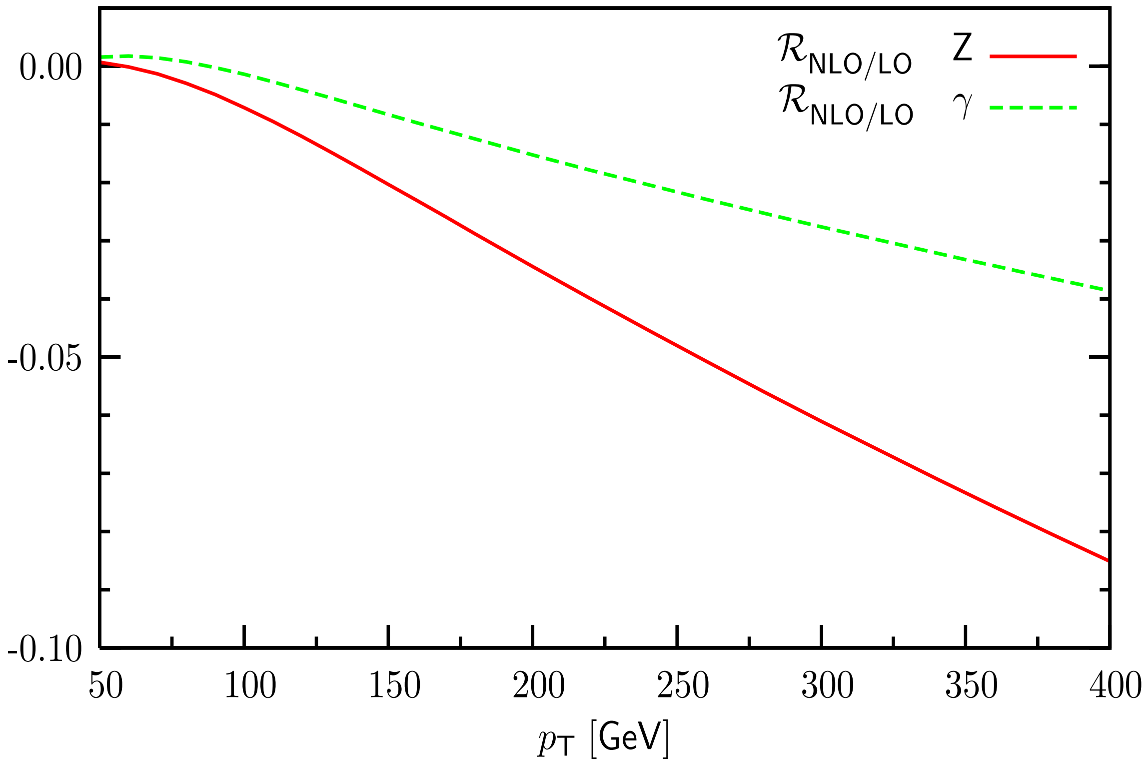
Summary

$$p + p \rightarrow Z/\gamma/W + \text{jet}$$

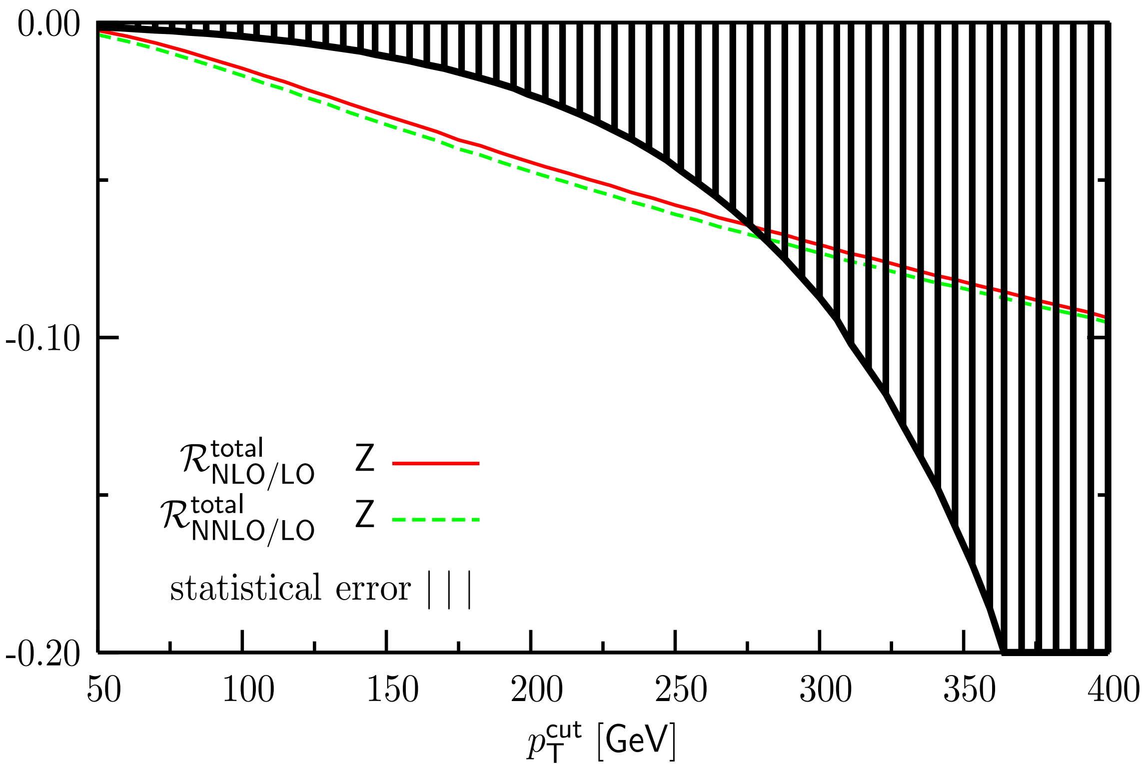
Electroweak Loop Corrections to Hadronic Production of Photons, Z- and W-Bosons with Single Jet Radiation

- important processes at LHC
- large corrections at 1-loop
- 2-loop effects are sizable
- compact analytical results

1-Loop Corrections @ Tevatron



2-Loop Corrections @ Tevatron



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$$\delta_{stat} = \frac{1}{\sqrt{N}}$$

$$N = \mathcal{B}_r \, \mathcal{L} \, \sigma$$

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

$$\mathcal{B}_r(Z \to \text{leptons}) = 30.6\%$$

1-Loop NNLL Corrections @ LHC