ELECTROWEAK CORRECTIONS TO GAUGE BOSON AND TOP QUARK PRODUCTION AT HADRON COLLIDERS

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I. **Introduction**

II. **Z- and Photon Production** J.H.K., A.Kulesza, S.Pozzorini, M.Schulze

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III. **Top Production** J.H.K., A.Scharf, P.Uwer

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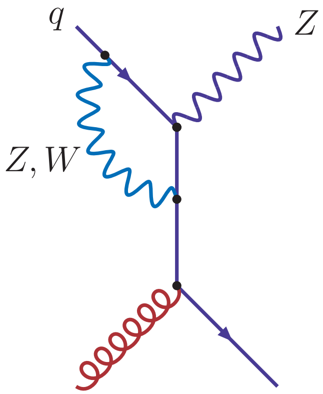
IV. **Conclusions**

I. Introduction

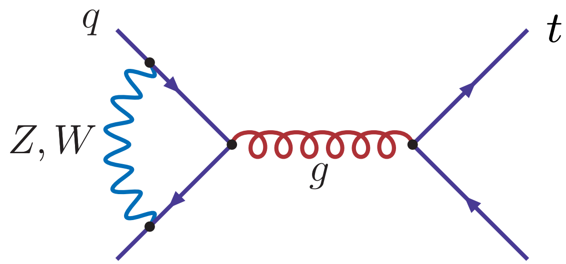
$$\frac{\alpha_{\text{weak}}}{\pi} \approx 10^{-2}$$

expectation for "typical" size of electroweak corrections
for hadronic processes

building blocks:



$qg \longrightarrow qZ$



$q\bar{q} \longrightarrow t\bar{t}$

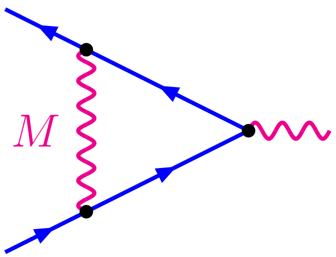
$+ \ \ldots$

new aspects at LHC: $\sqrt{\hat{s}} \approx$ 1-2TeV

$$s \gg \hat{s} \gg M^2_{W,Z}$$

strong enhancement of negative corrections

one-loop example: massive U(1)



$$\Rightarrow \ \text{Born} * \left[1 + \frac{\alpha}{4\pi}\left(-\ln^2\frac{s}{M^2} + 3\ln\frac{s}{M^2} - \frac{7}{2} + \frac{\pi^2}{3}\right)\right]$$

$\frac{s}{M^2}$	$-\ln^2\frac{s}{M^2}$	$+3\ln\frac{s}{M^2}$	$-\frac{7}{2}+\frac{\pi^2}{3}$	Σ	$* 4\,\frac{\alpha_w}{4\pi}$
$\left(\frac{1000}{80}\right)^2$	−25.52	+15.15	−0.21	−10.6	−13%
$\left(\frac{2000}{80}\right)^2$	−41.44	+19.31	−0.21	−22.3	−27%

(four-fermion cross section ⇒ factor 4)

- leading $\log^2$ multiplied by (charge)$^2 = I(I+1) = \begin{cases} 3/4 & I = 1/2 \\ 2 & I = 1 \end{cases}$

- important subleading logarithms (NLL+...)
  ($\Rightarrow$ Penin: $f\bar{f} \to f'\bar{f}'$)

- two-loop terms may be relevant

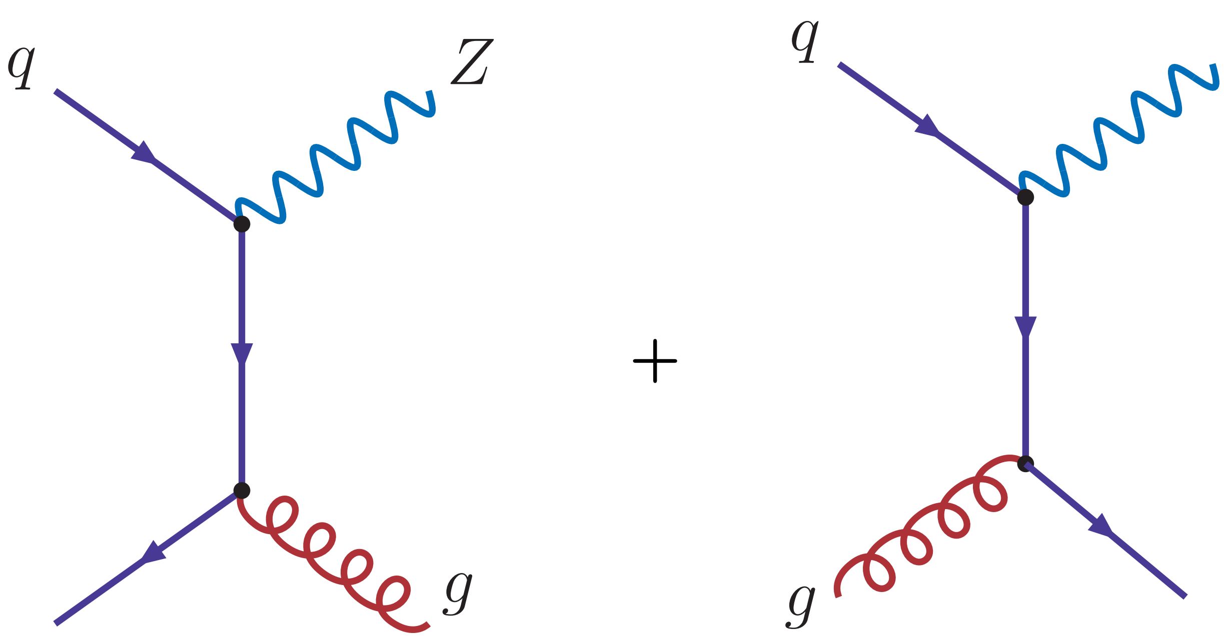
- interplay between electroweak and QCD corrections

- important differences between fermions and electroweak gauge bosons

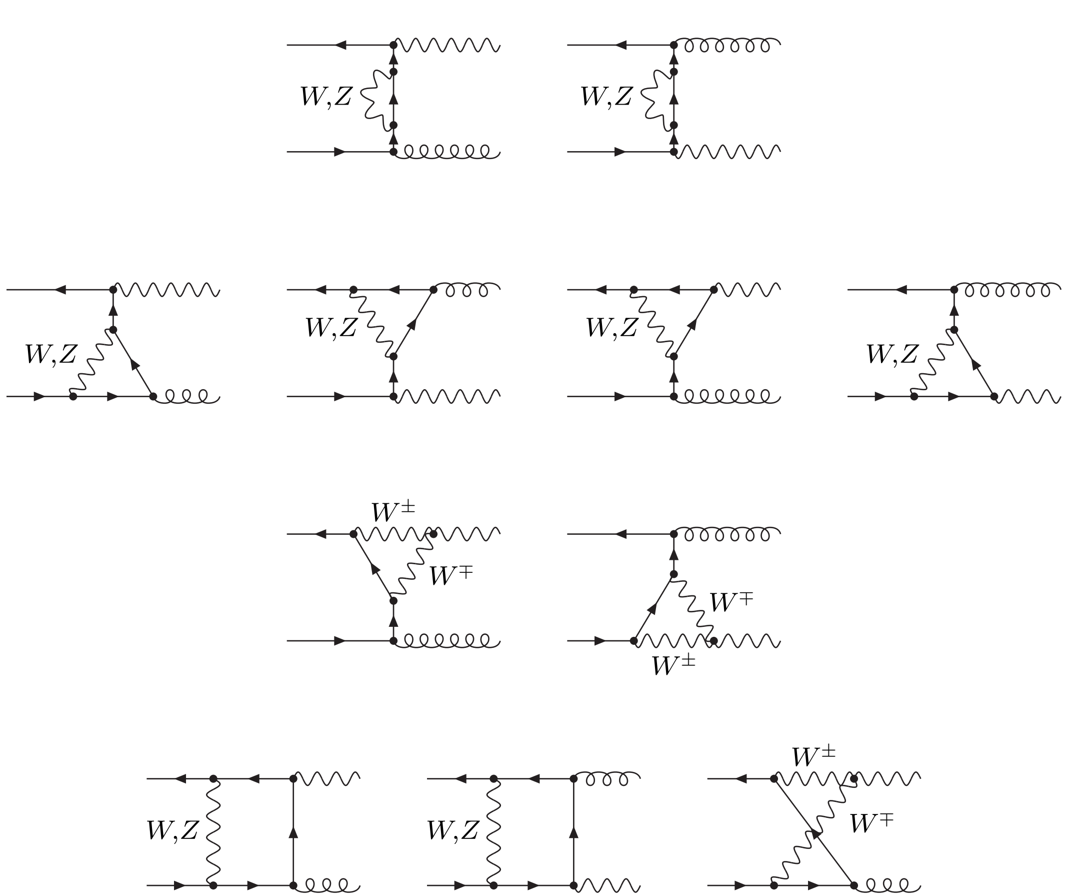
II. Z and Photon Production

J.H.K., Kulesza, Pozzorini, Schulze

Large rate for Z-boson and photon production at LHC at large p_T (1-2 TeV)
Large electroweak corrections ($\hat{s} \gg M^2_{W,Z}$)



one-loop corrections



plus counter terms

Result decomposed into "abelian" (A) and "non-abelian" (N) parts

$$\overline{\sum}|\mathcal{M}_1|^2 = 8\pi^2\alpha\alpha_s(N_c^2-1)$$
$$\times \sum_{\lambda=R,L}\Bigg\{\left(I^Z_{q_\lambda}\right)^2\left[H_0\left(1+2\delta C^A_{q_\lambda}\right)+\frac{\alpha}{2\pi}\sum_{V=Z,W^\pm}\left(I^V I^{\bar{V}}\right)_{q_\lambda} H_1^A(M_V^2)\right]$$
$$+\frac{c_W}{s_W}T^3_{q_\lambda}I^Z_{q_\lambda}\left[2H_0\delta C^N_{q_\lambda}+\frac{\alpha}{2\pi}\frac{1}{s_W^2}H_1^N(M_W^2)\right]\Bigg\}$$

with $H_0 = \frac{\hat{t}^2+\hat{u}^2+2\hat{s}M_Z^2}{\hat{t}\hat{u}}$; I^V, T^3 couplings

$H_1^{A,N}$, $\delta C^{A,N}$ given in closed analytical form
consisting of kinematical functions $(\hat{s},\hat{t},\hat{u})$ and 14 combinations of
$1\times A_0,\ 5\times B_0,\ 5\times C_0,\ 3\times D_0$

High energy limit

consider $q\bar{q} \to Zg$

NLL $\widehat{=}$ double + single logarithmic terms

$$H_1^{\mathrm{A}}(M_V^2) \stackrel{\mathrm{NLL}}{=} -\left[\log^2\left(\frac{|\hat{s}|}{M_W^2}\right) - 3\log\left(\frac{|\hat{s}|}{M_W^2}\right)\right] H_0,$$
$$H_1^{\mathrm{N}}(M_W^2) \stackrel{\mathrm{NLL}}{=} -\left[\log^2\left(\frac{|\hat{t}|}{M_W^2}\right) + \log^2\left(\frac{|\hat{u}|}{M_W^2}\right) - \log^2\left(\frac{|\hat{s}|}{M_W^2}\right)\right] H_0$$

$$\delta C_{q_\lambda}^{\mathrm{A}} \stackrel{\mathrm{NLL}}{=} \delta C_{q_\lambda}^{\mathrm{N}} \stackrel{\mathrm{NLL}}{=} 0$$

(remaining subleading terms $\leq 2.5\%$)

NNLL: includes non-enhanced terms (angular dependent)

$$H_1^{A/N}(M_V^2) \overset{\text{NNLL}}{=} \text{Re}\left[g_0^{A/N}(M_V^2)\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}} + g_1^{A/N}(M_V^2)\frac{\hat{t}^2-\hat{u}^2}{\hat{t}\hat{u}} + g_2^{A/N}(M_V^2)\right]$$

$$\begin{aligned}
g_0^N(M_W^2) &= 2\bar{\Delta}_{UV} + \log^2\left(\frac{-\hat{s}}{M_W^2}\right) - \log^2\left(\frac{-\hat{t}}{M_W^2}\right) - \log^2\left(\frac{-\hat{u}}{M_W^2}\right) + \log^2\left(\frac{\hat{t}}{\hat{u}}\right) \\
&\quad - \frac{3}{2}\left[\log^2\left(\frac{\hat{t}}{\hat{s}}\right) + \log^2\left(\frac{\hat{u}}{\hat{s}}\right)\right] - \frac{20\pi^2}{9} - \frac{2\pi}{\sqrt{3}} + 4, \\
g_1^N(M_W^2) &= \frac{1}{2}\left[\log^2\left(\frac{\hat{u}}{\hat{s}}\right) - \log^2\left(\frac{\hat{t}}{\hat{s}}\right)\right], \\
g_2^N(M_W^2) &= -2\left[\log^2\left(\frac{\hat{t}}{\hat{s}}\right) + \log^2\left(\frac{\hat{u}}{\hat{s}}\right) + \log\left(\frac{\hat{t}}{\hat{s}}\right) + \log\left(\frac{\hat{u}}{\hat{s}}\right)\right] - 4\pi^2 \\
g_0^A(M_V^2) &= -\log^2\left(\frac{-\hat{s}}{M_V^2}\right) + 3\log\left(\frac{-\hat{s}}{M_V^2}\right) + \frac{3}{2}\left[\log^2\left(\frac{\hat{t}}{\hat{s}}\right) + \log^2\left(\frac{\hat{u}}{\hat{s}}\right)\right. \\
&\quad \left. + \log\left(\frac{\hat{t}}{\hat{s}}\right) + \log\left(\frac{\hat{u}}{\hat{s}}\right)\right] + \frac{7\pi^2}{3} - \frac{5}{2}, \\
g_1^A(M_V^2) &= -g_1^N(M_W^2) + \frac{3}{2}\left[\log\left(\frac{\hat{u}}{\hat{s}}\right) - \log\left(\frac{\hat{t}}{\hat{s}}\right)\right], \\
g_2^A(M_V^2) &= -g_2^N(M_W^2)
\end{aligned}$$

+ simple approximations for finite parts of counter terms

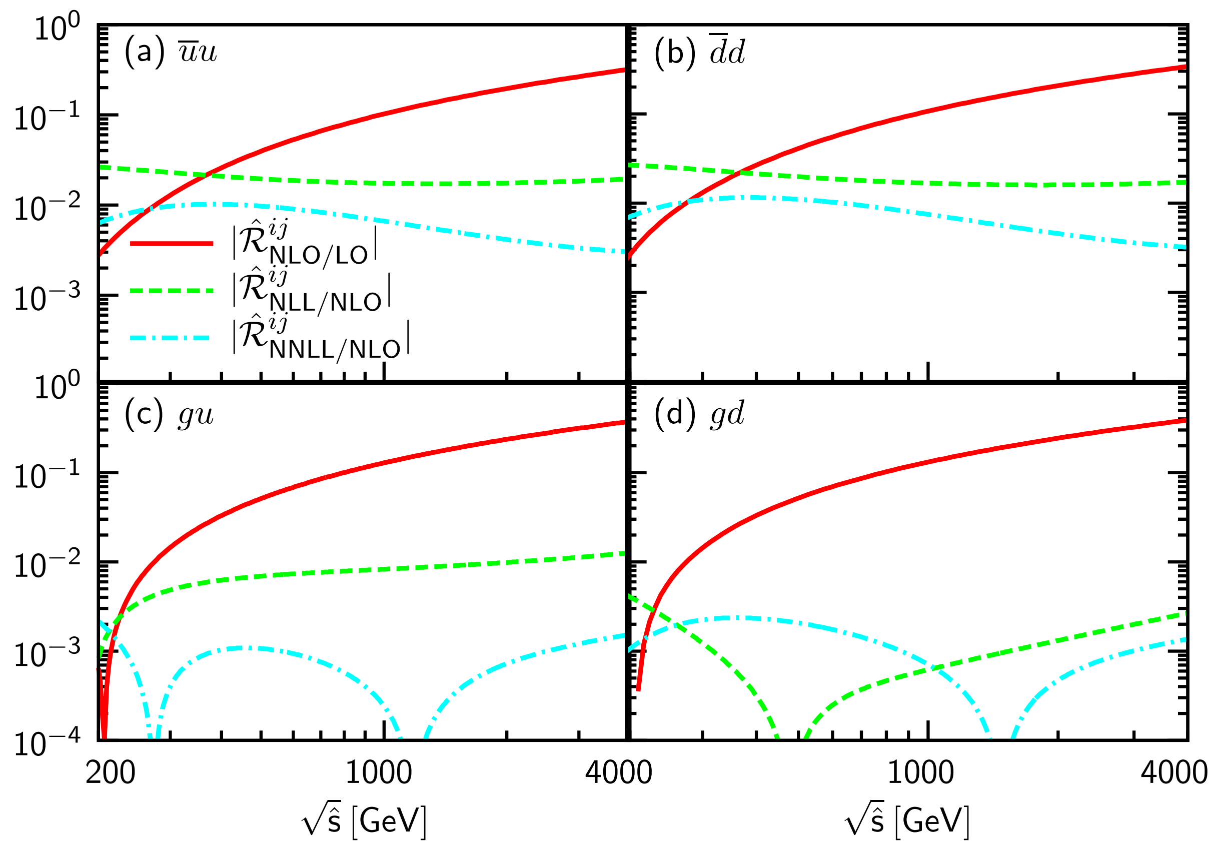
size of the correction:

$$\sqrt{\hat{s}} \;=\; 200\ \text{GeV}: \qquad \frac{\delta\sigma}{\sigma} \leq 0.3\%$$

$$\sqrt{\hat{s}} \;=\; 4000\text{GeV}: \qquad \frac{\delta\sigma}{\sigma} \approx 20 - 30\%$$

quality of the approximation:

$$\mathcal{R}\left(\text{NLL}\big/\text{NLO}\right) \leq 2.5\%$$
$$\mathcal{R}\left(\text{NNLL}\big/\text{NLO}\right) \leq 1\%$$



Relative one-loop corrections to the partonic differential cross sections $\mathrm{d}\hat{\sigma}^{ij}/\mathrm{d}\cos\theta$ at $\cos\theta = 0$ for (a) $\bar{u}u$ channel, (b) $\bar{d}d$ channel, (c) gu channel, (d) gd channel. The solid, dashed and dashed-dotted lines denote the modulus of the $\hat{\mathcal{R}}$ ratios for the full NLO cross section, the NLL approximation and the NNLL approximation of the one-loop cross section, respectively.

Result consistent with general considerations

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one-loop:

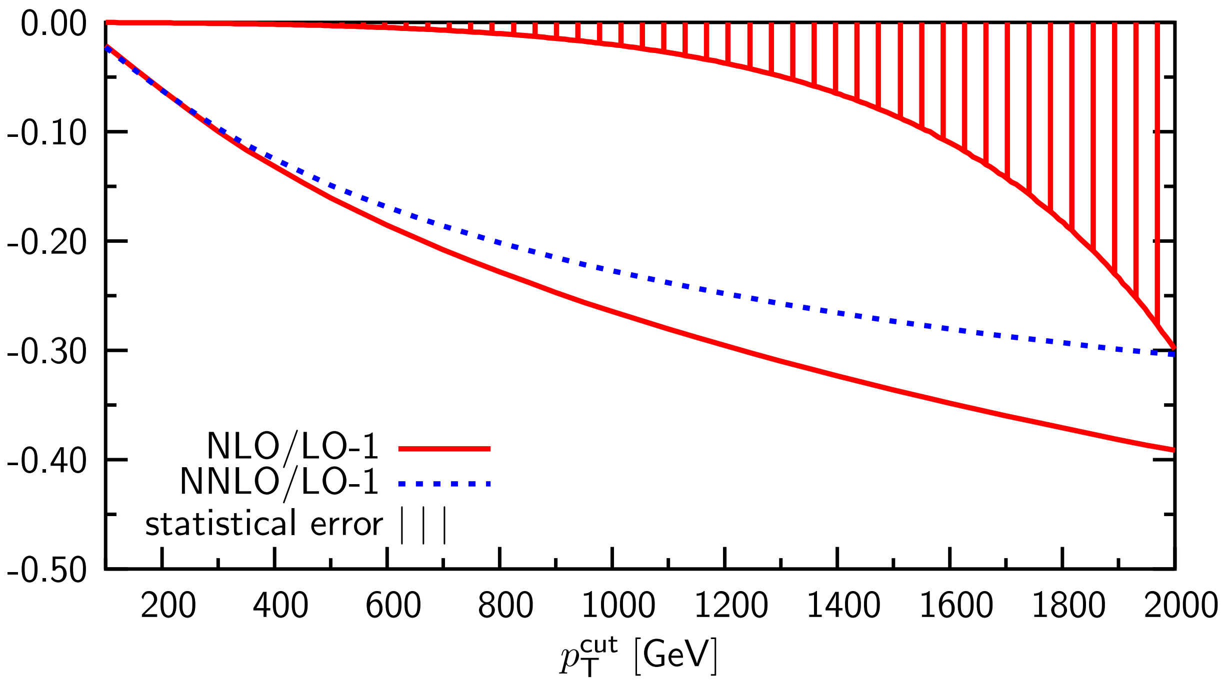
$$A^{(1)} = - \sum_{\lambda=\mathrm{L,R}} I^Z_{q_\lambda} \left[I^Z_{q_\lambda} C^{\mathrm{ew}}_{q_\lambda} \left(\mathsf{L}^2_{\hat{s}} - 3\mathsf{L}_{\hat{s}} \right) + \frac{c_\mathrm{W}}{s^3_\mathrm{W}} T^3_{q_\lambda} \left(\mathsf{L}^2_{\hat{t}} + \mathsf{L}^2_{\hat{u}} - \mathsf{L}^2_{\hat{s}} \right) \right]$$

two-loop (NLL, based on Denner, Melles, Pozzorini):

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

with $L^n_{\hat{r}} = \log^n \left(\frac{|\hat{r}|}{M^2_W} \right)$, $b_1 = -41/(6c^2_\mathrm{W})$ and $b_2 = 19/(6s^2_\mathrm{W})$

Complete one loop calculation
NLL approximation at two loops (="NNLO")

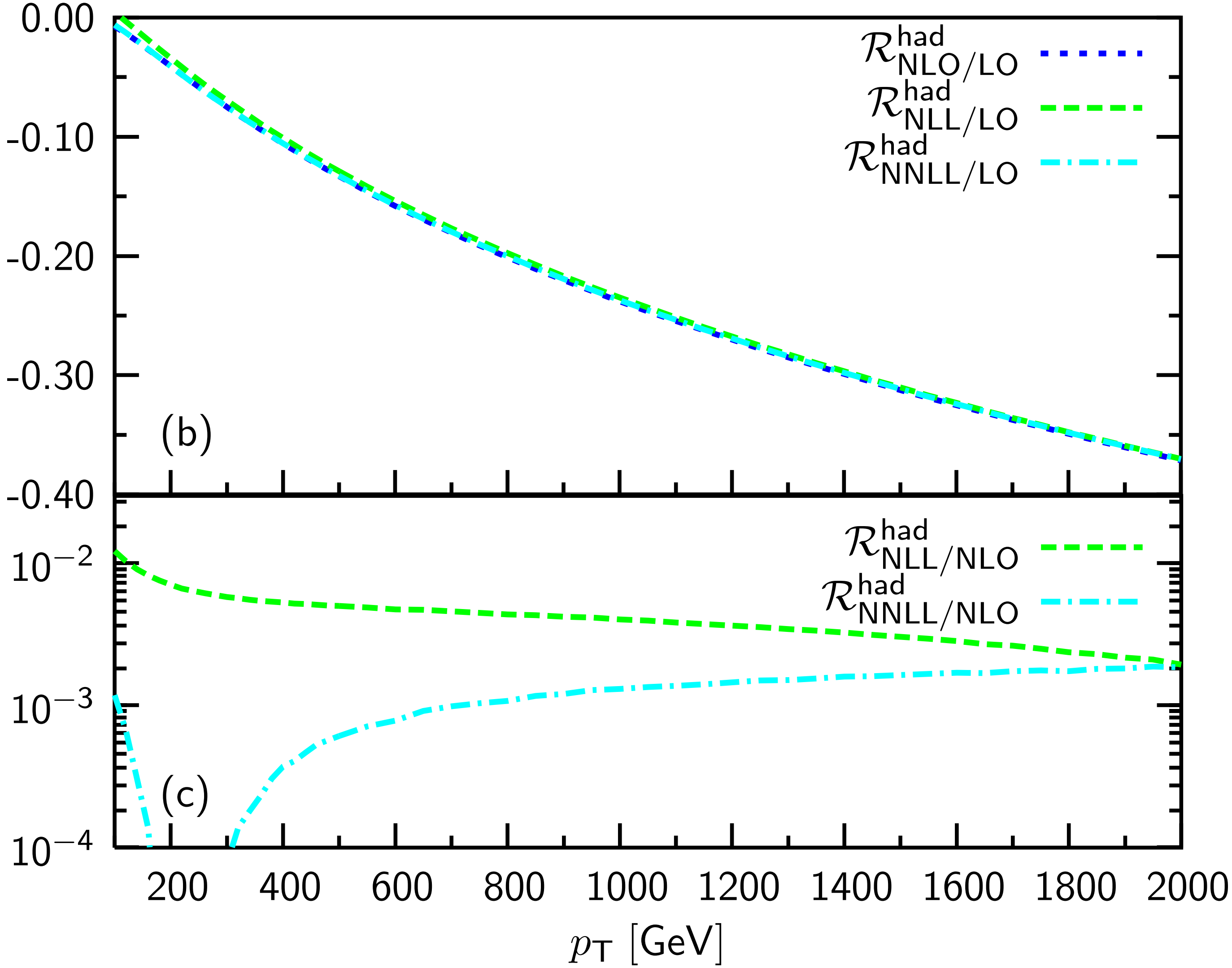


Relative **NLO** and **NNLO** corrections w.r.t. the **LO** and statistical error for the unpolarized integrated cross section for $pp \to Zj$ at $\sqrt{s} = 14$ TeV.

- one-loop effects are large ($\sim 30\%$ at $p_T \sim 1$Tev)
- two-loop effects (based on Denner, Melles, Pozzorini; Melles)
- become relevant above 1 TeV
- important angular-dependent logarithmic terms
- experiment will explore p_T up to 2 TeV

Compact analytical formulae for one-loop results

in **NNLL** approximation ($\ln^2 + \ln + \text{const.}$) provide an excellent description (better than 2×10^{-3}) of complete result



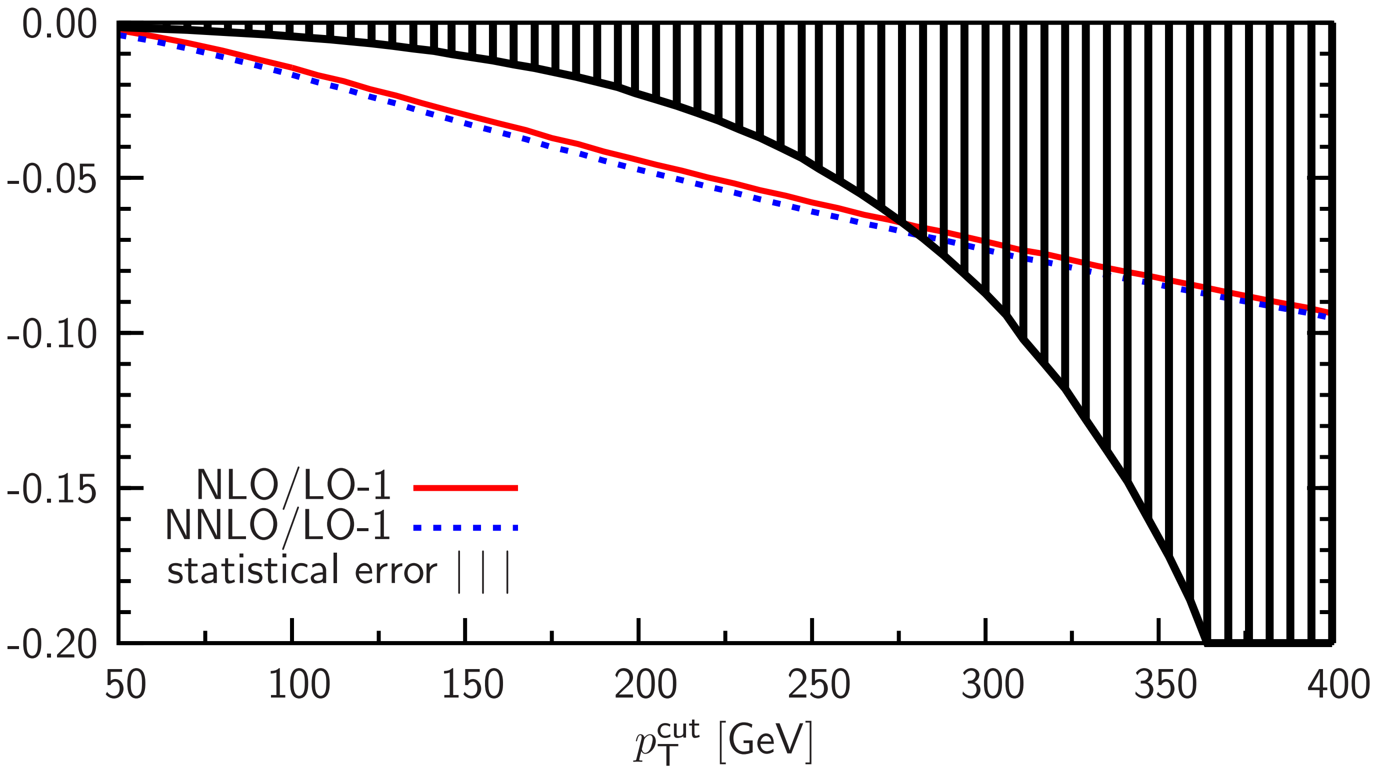
p_T distribution for $pp \to Zj$ at $\sqrt{s} = 14$ TeV:

(b) Relative **NLO, NLL** and **NNLL** weak correction w.r.t. the **LO** distribution.

(c) **NLL** and **NNLL** approximations compared to the full **NLO** result

Corrections at the Tevatron ($\sqrt{s}$=2 TeV)

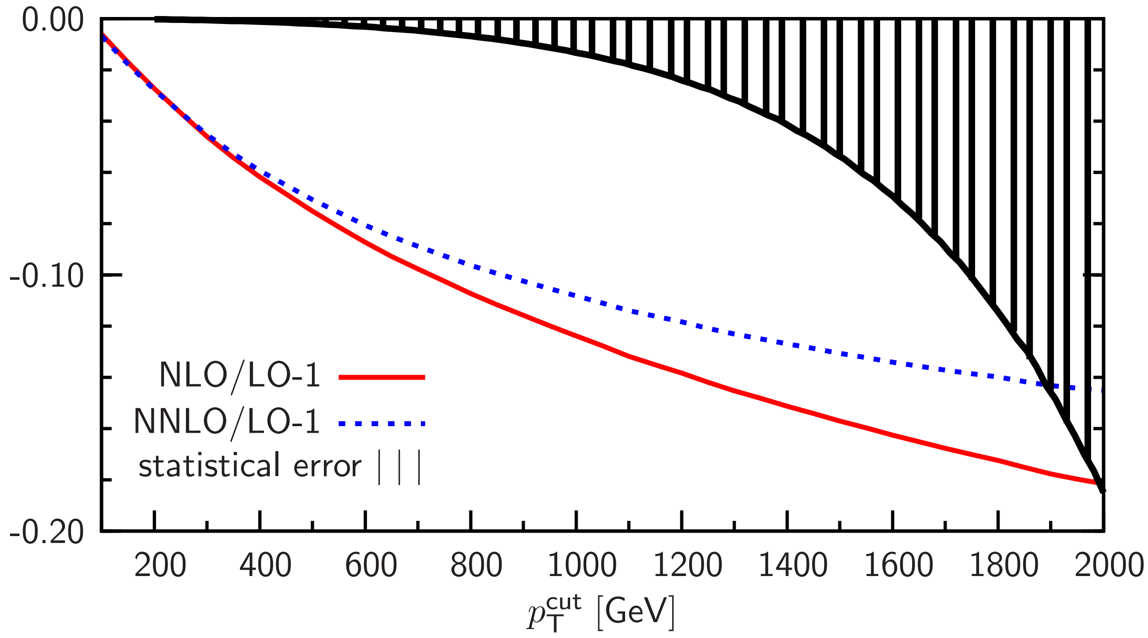
amount up to 5%



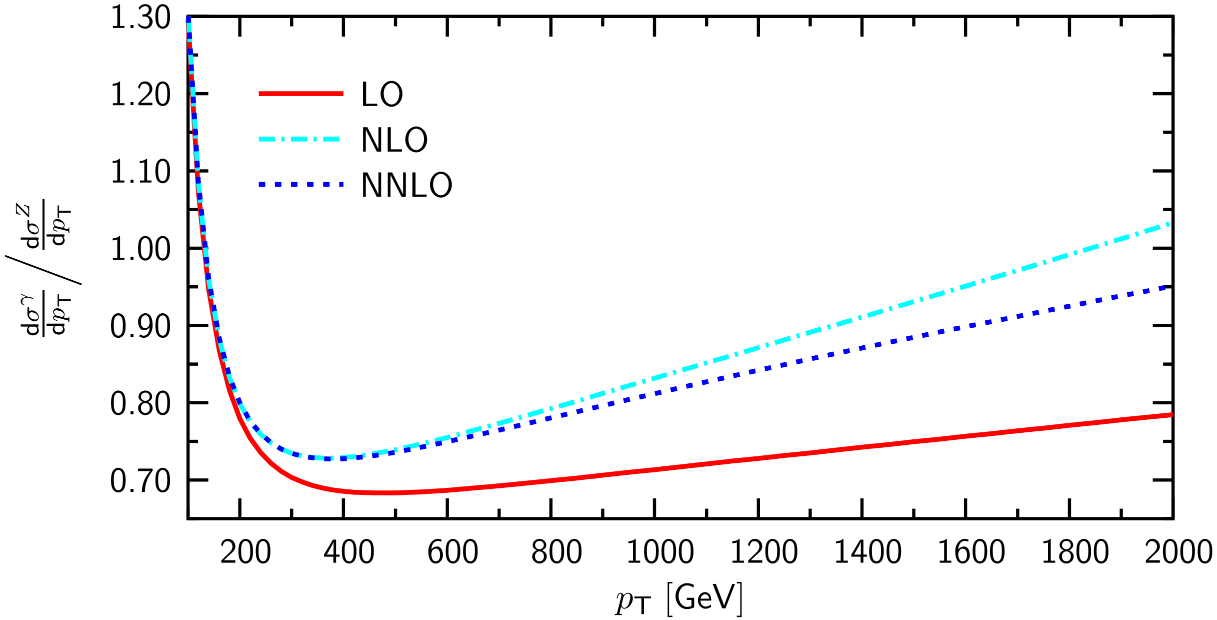
Relative **NLO** and **NNLO** corrections w.r.t. the **LO** and statistical error (shaded area) for the unpolarized integrated cross section for $p\bar{p} \to Zj$ at $\sqrt{s}$=2 TeV as a function of p_T^{cut}.

Photon production

- also large corrections
- **NLO** and approximations (**NLL, NNLL**)
- dominant two-loop terms available ("**NNLO**")



Photons vs. Z at large p_T

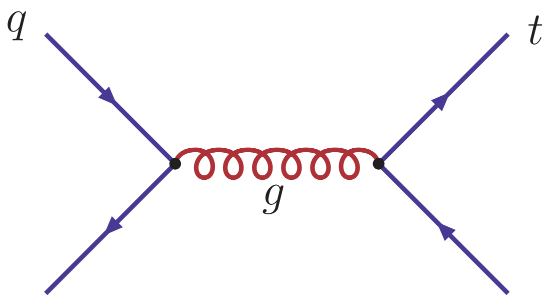


numerical results in qualitative agreement with Maina, Moretti, Ross

III. Top Production $(q\bar{q} \to t\bar{t})$

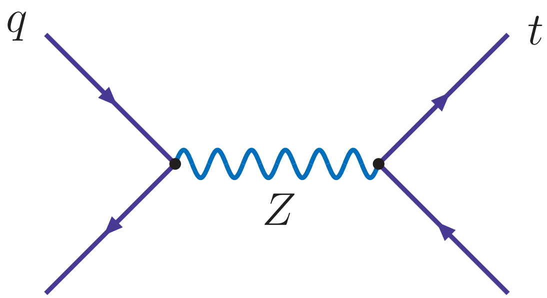
J.H.K., Scharf, Uwer

work on $gg \to t\bar{t}$ in progress



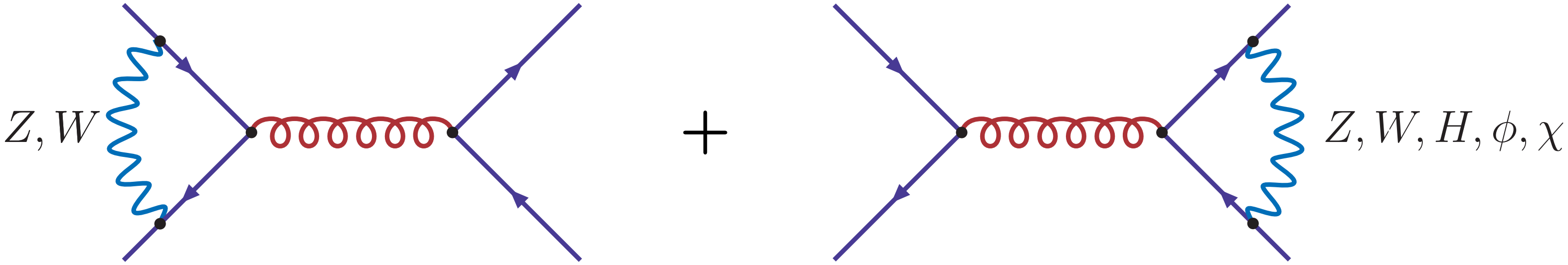
$\sim \mathcal{O}(\alpha_{\mathrm{s}})$

no interference with

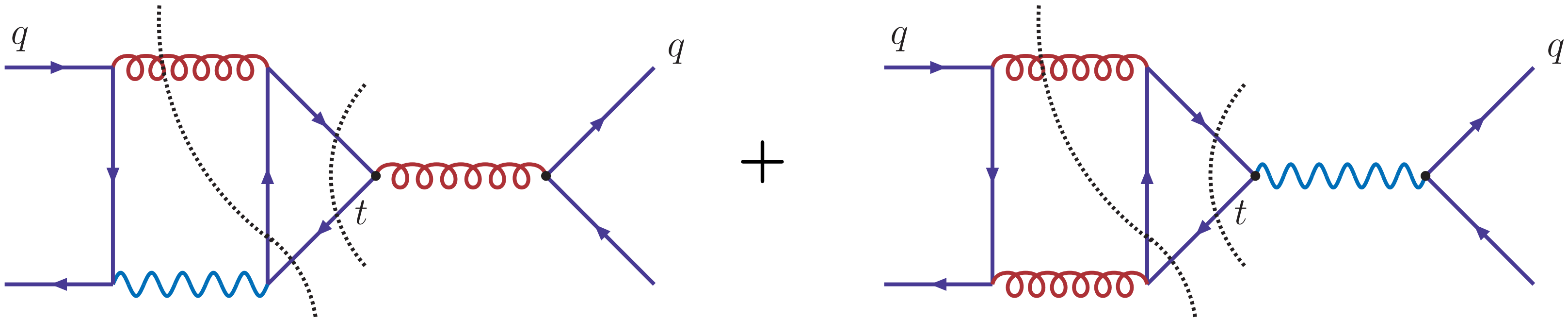


$\sim \mathcal{O}(\alpha_{\mathrm{weak}})$

$\mathcal{O}(\alpha_s^2 \alpha_{weak})$ weak corrections from



also Beenakker et. al



cuts of second group individually IR-divergent

- analytical & numerical results available: $q\bar{q} \to t\bar{t}$
  (independent evaluation of Bernreuther & Fücker, many independent checks)
  $gg \to t\bar{t}$ in progress

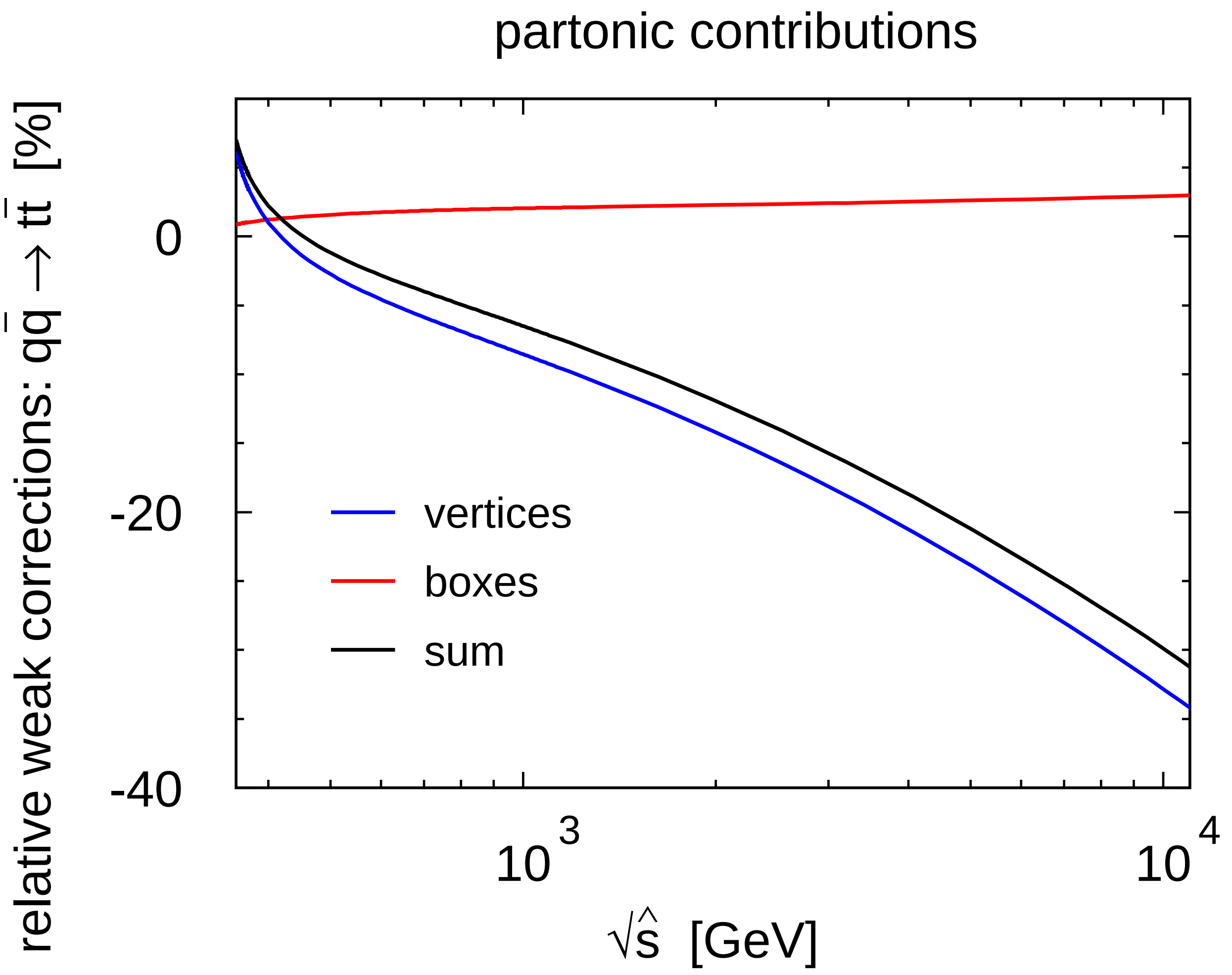
- (box contribution)$_{\text{up-quark}} = -$(box contribution)$_{\text{down-quark}}$
  $\Rightarrow$ suppression

- box contribution moderately $\hat{s}$-dependent

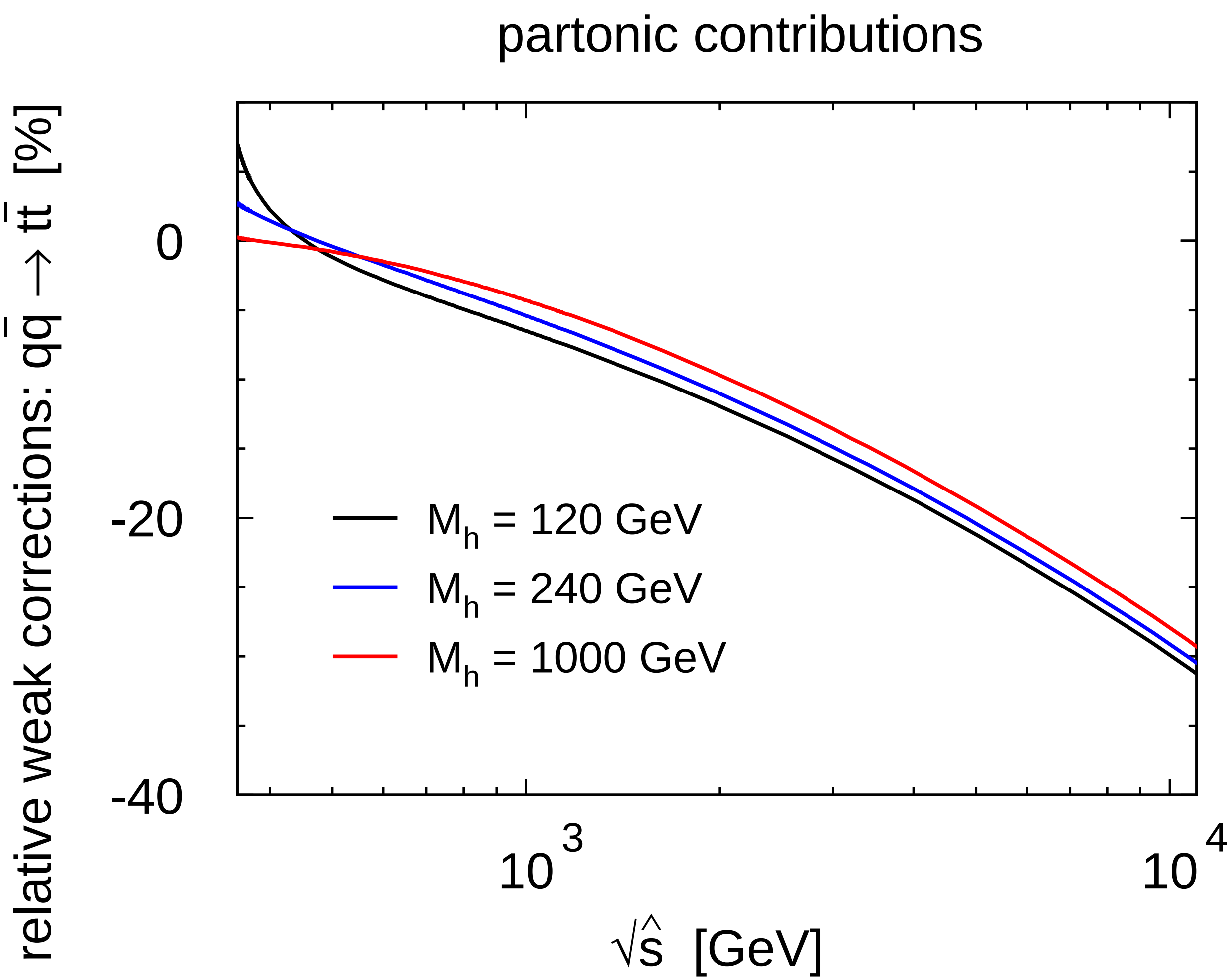
- strong increase with $\hat{s}$

- sizable M_{h}-dependence, large effect close to threshold

large corrections for large $\sqrt{\hat{s}}$

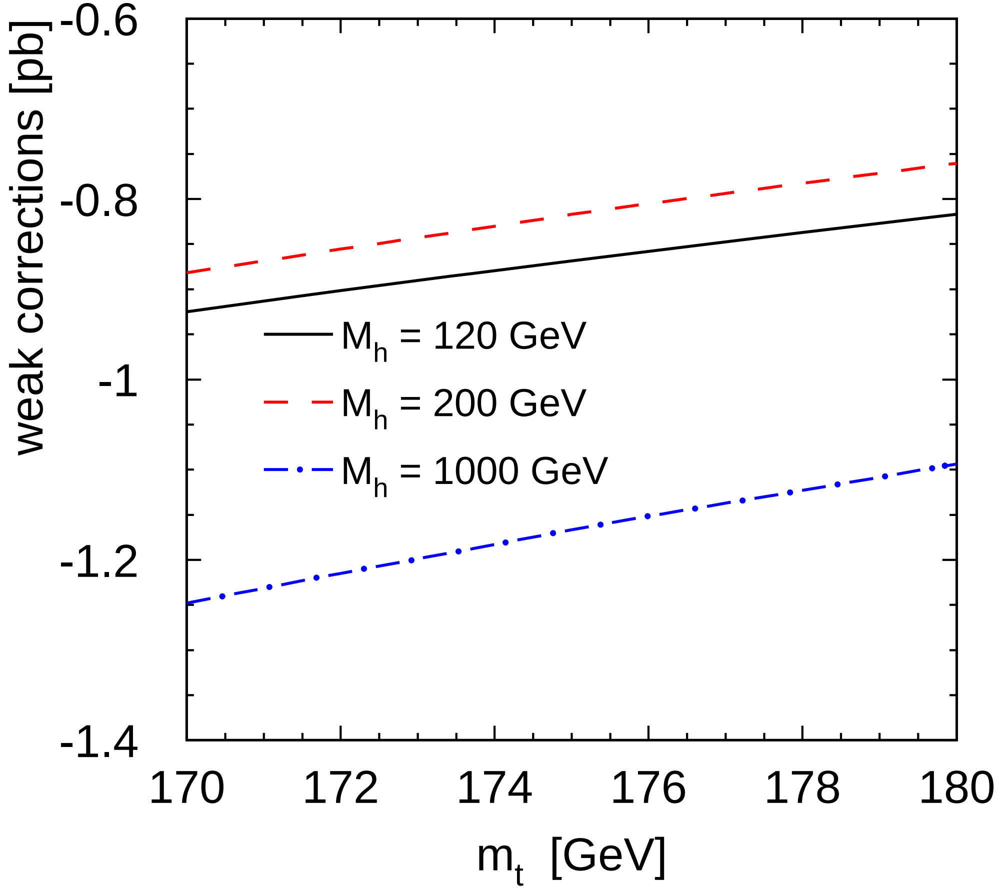


sizable M_h-dependence



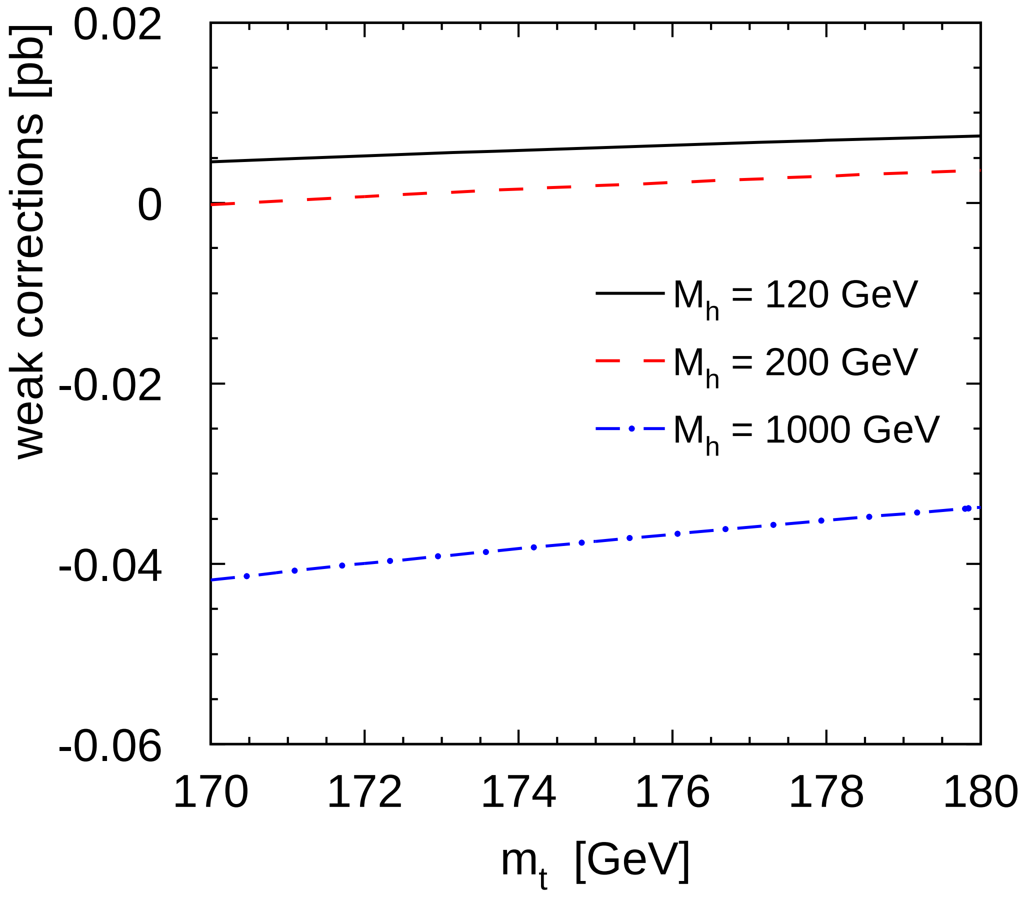
effect on the total cross section at LHC

($\sigma_{\rm tot}$=833pb)



effect on the total cross section at Tevatron

(σ_{tot}=5.75pb)



IV. Conclusions

- LHC will explore the TeV-region: $\hat{s} \Big/ M_W^2 \gg 1$
- electroweak corrections amount to $\mathcal{O}(10\% - 20\%)$ in the interesting kinematic region
- p_{T}-distributions of Z, γ and their ratio will be strongly affected
- higher orders might become relevant
- top-quark distributions at large $\hat{s}$ are strongly modified
- sizable m_H-dependence
- interplay between electroweak and QCD effects