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

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Outline

I. Introduction

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

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III. Heavy Quark Production J.H.K., A.Scharf, P.Uwer

Eur. Phys. J., C45, (2006) 139,
+ work in preparation

IV. Conclusions

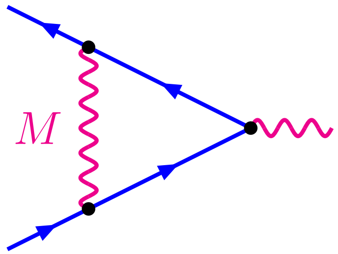
I. Introduction

"Typical" size of electroweak corrections: $\frac{\alpha_{\text{weak}}}{\pi} \approx 10^{-2}$

new aspects at LHC: $\sqrt{\hat{s}} \approx$ 1-2TeV $\gg M^2_{W,Z}$

strong enhancement of negative corrections

one-loop example: massive U(1)



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

$\frac{s}{M^2}$	$-\ln^2\frac{s}{M^2}$	$+3\ln\frac{s}{M^2}$	$-\frac{7}{2}+\frac{\pi^2}{3}$	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

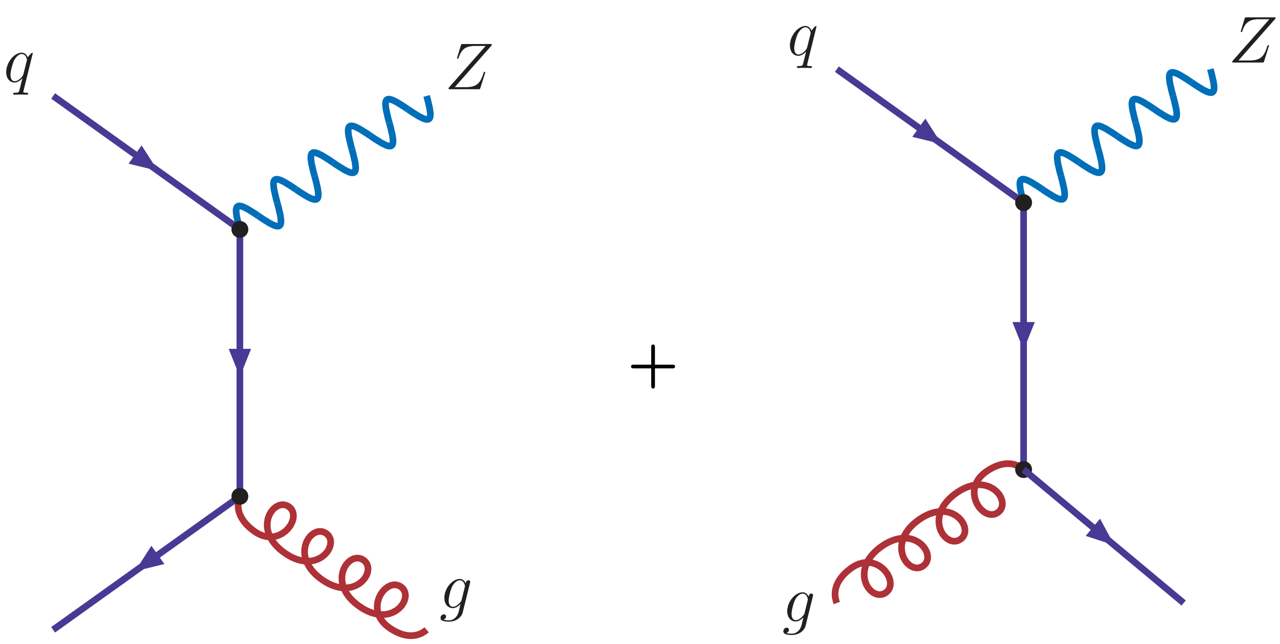
- interplay between electroweak and QCD corrections

- 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 ($\hat{s} \gg M_{W,Z}^2$)



one-loop corrections:

Result decomposed into "abelian" (A) and "non-abelian" (N) parts $H_1^{A,N}$ plus counterterms $\delta C^{A,N}$ in closed analytical form: kinematical functions of $(\hat{s}, \hat{t}, \hat{u})$ 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

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

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

(remaining subleading terms $\leq$ 2.5%)

NNLL: includes non-enhanced terms (angular dependent)

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

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

+ simple approximations for finite parts of counter terms

size of the correction:

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

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

Result consistent with general considerations

one-loop:

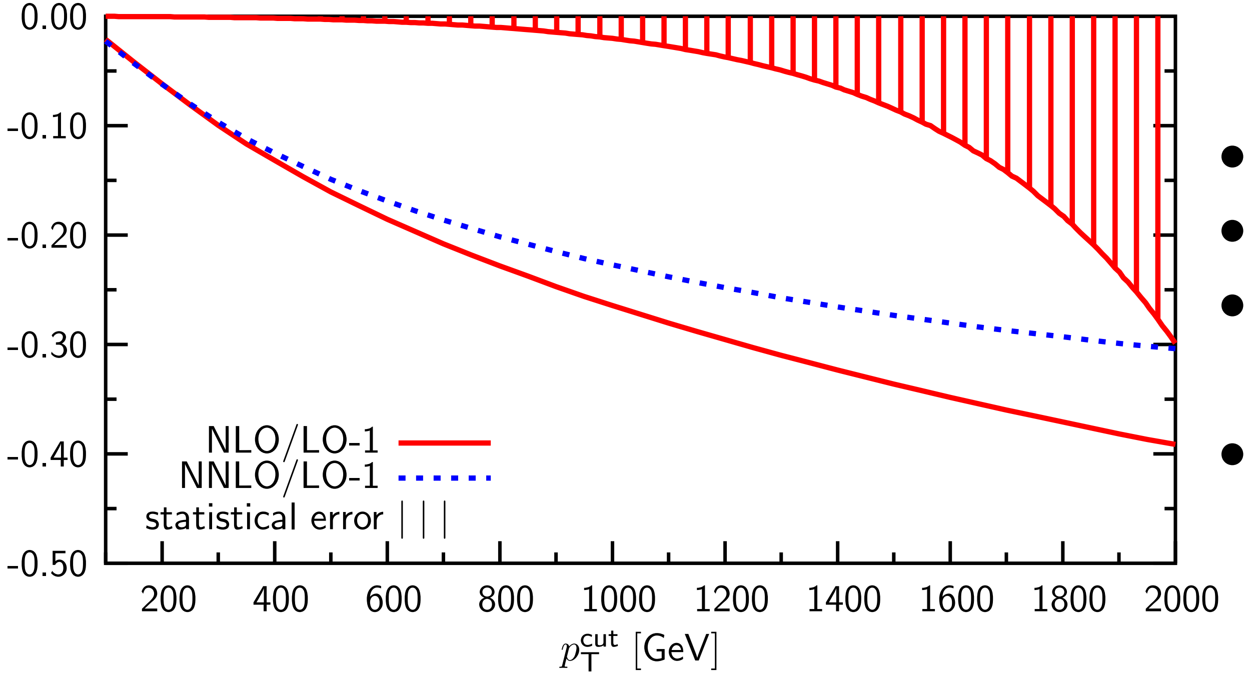
$$A^{(1)} = -\sum_{\lambda=\mathsf{L},\mathsf{R}} I^Z_{q_\lambda}\left[I^Z_{q_\lambda} C^{\mathrm{ew}}_{q_\lambda}\left(\mathsf{L}^2_{\hat{s}} - 3\mathsf{L}_{\hat{s}}\right) + \frac{c_\mathrm{W}}{s^3_\mathrm{W}} T^3_{q_\lambda}\left(\mathsf{L}^2_{\hat{t}} + \mathsf{L}^2_{\hat{u}} - \mathsf{L}^2_{\hat{s}}\right)\right]$$

two-loop (NLL):

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

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



- one-loop $\sim 30\%$ at $p_T \sim 1$TeV
- two-loop relevant above 1 TeV
- important angular-dependent logarithmic terms
- experiment: p_T up to 2 TeV

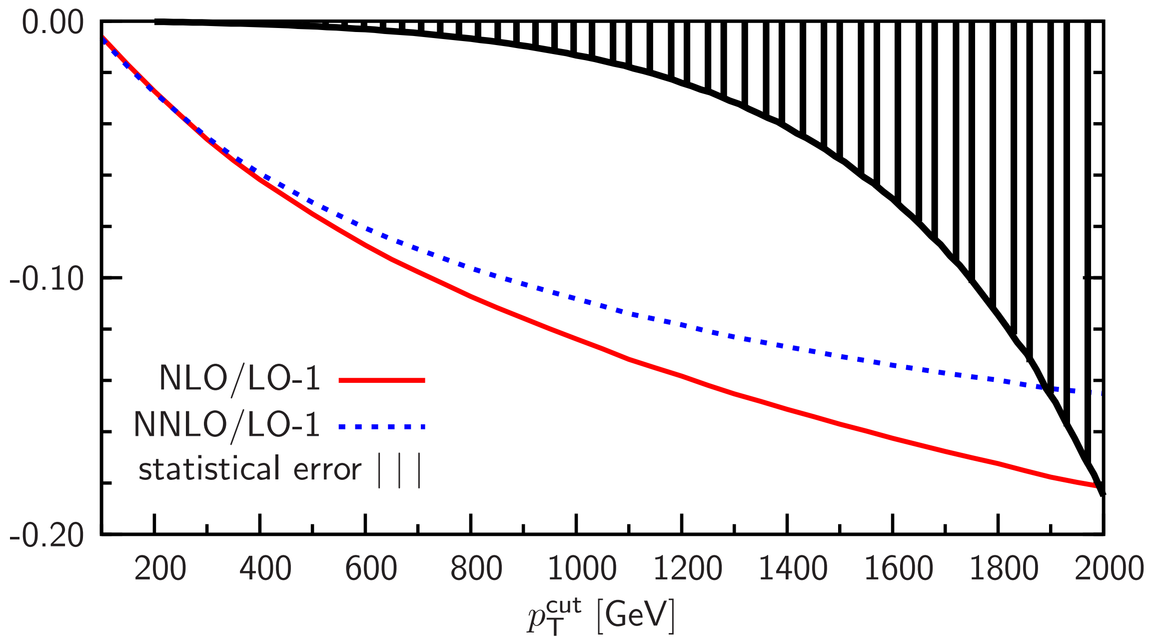
Relative **NLO** and **NNLO** corrections w.r.t. the **LO** and statistical error for the unpolarized integrated cross section for $pp \to Zj$ at $\sqrt{s} = 14$ TeV.

(related work: Maina, Moretti, Ross)

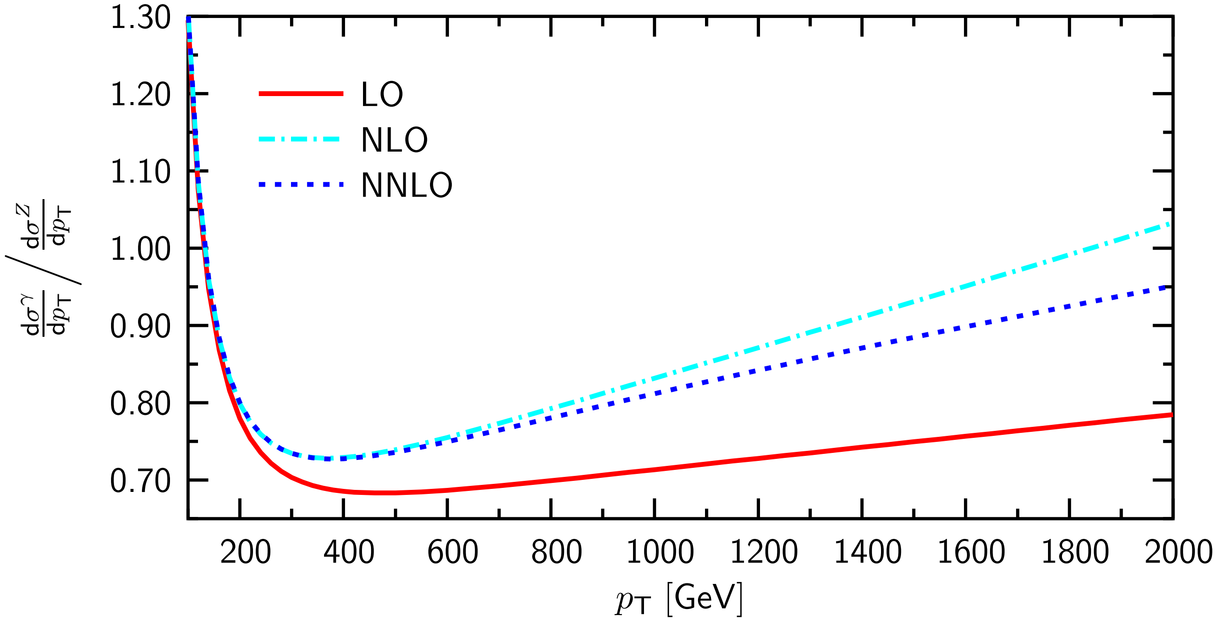
Photon production

- full **NLO** and logarithmic approximations ($\log^2 + \log + \text{const}$) available

- dominant two-loop terms ($\log^4 + \log^3$) available



Photons vs. Z at large p_T

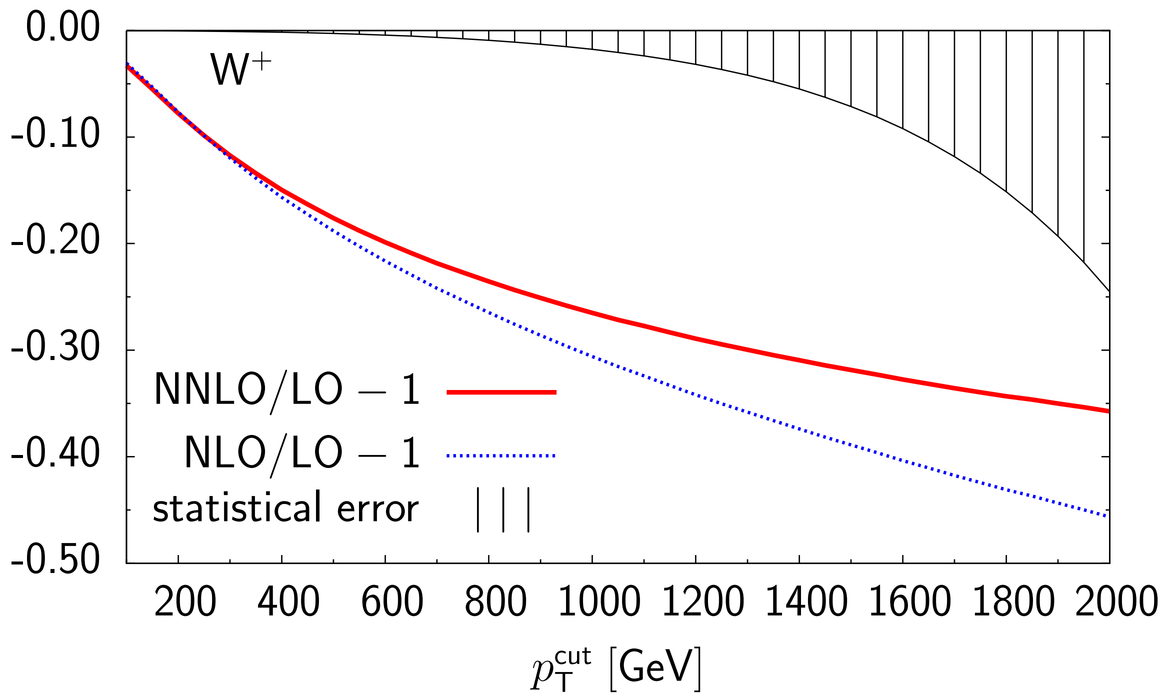


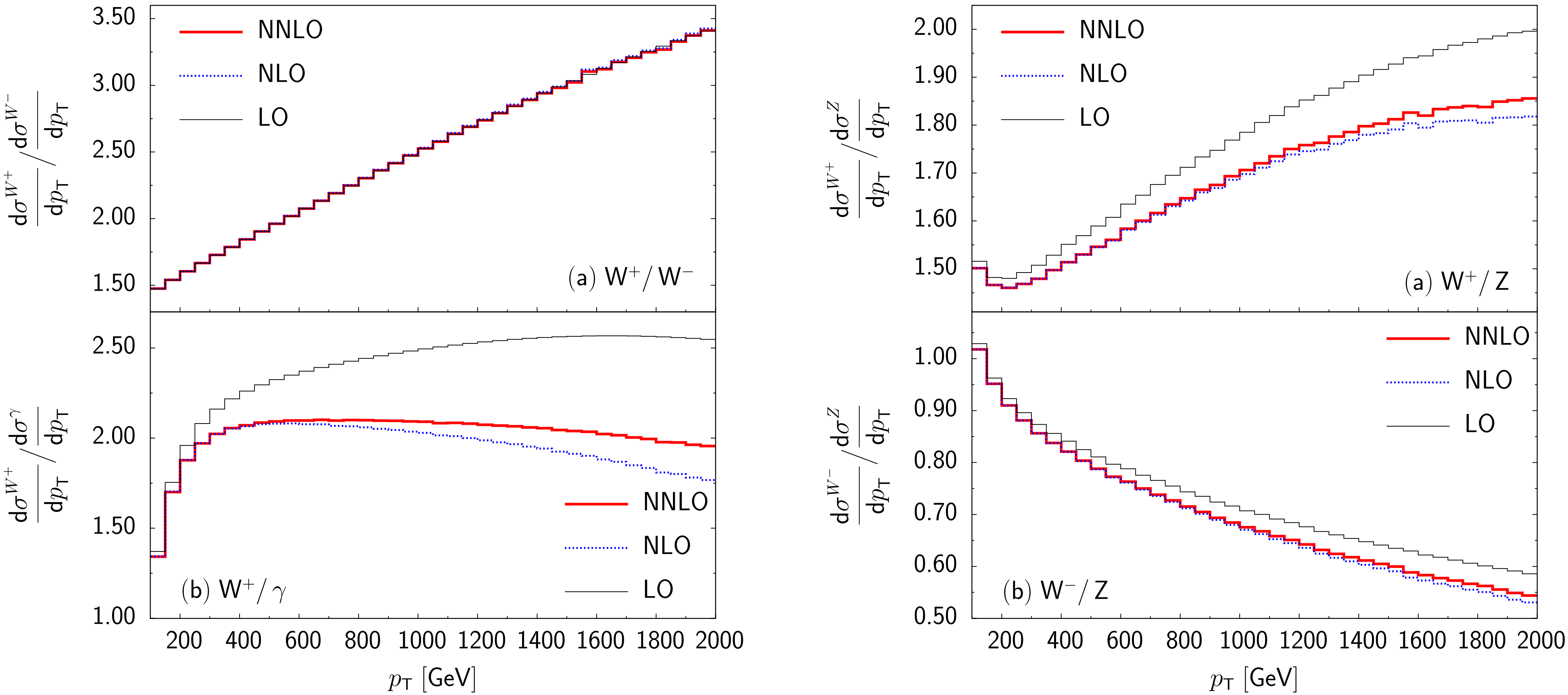
numerical results in qualitative agreement with Maina, Moretti, Ross

W production

additional complications:

- photon radiation as necessary part of virtual corrections (gauge invariance)
- IR singularities must be compensated by real radiation
- $p_{\mathrm{T}}(W) = p_{\mathrm{T}}(\text{jet}) + p_{\mathrm{T}}(\gamma)$





ratios are less sensitive to QCD corrections

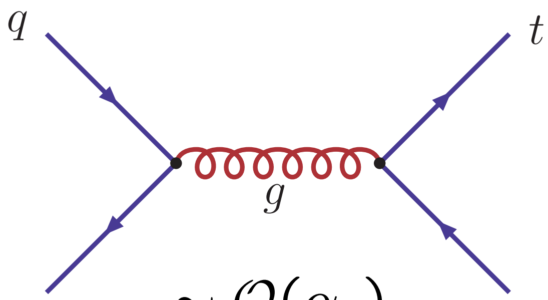
(related work on W's: Hollik, Kniehl, Kasparcik)

III. Heavy Quark Production:

J.H.K., Scharf, Uwer

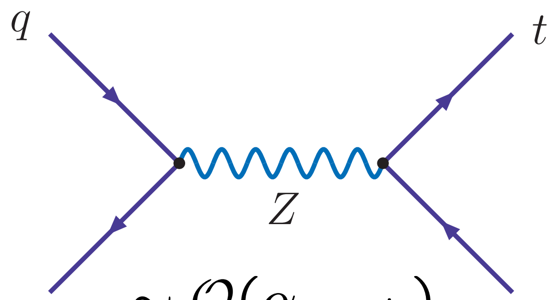
Top Quarks

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



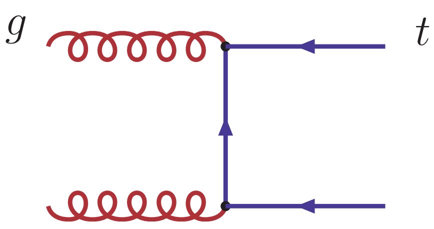
$\sim \mathcal{O}(\alpha_{\mathrm{s}})$

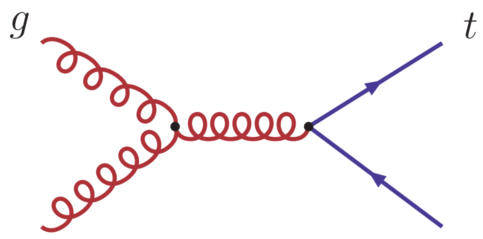
no interference with



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

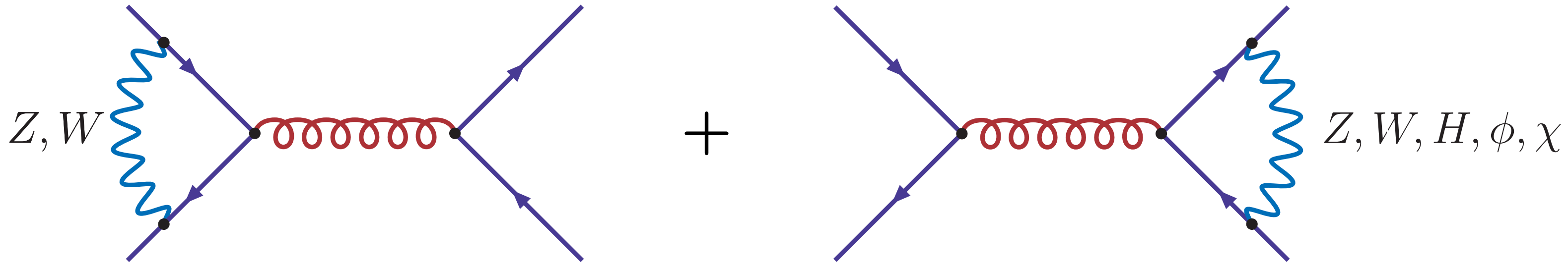
$g\,g \longrightarrow t\,\bar{t}$:





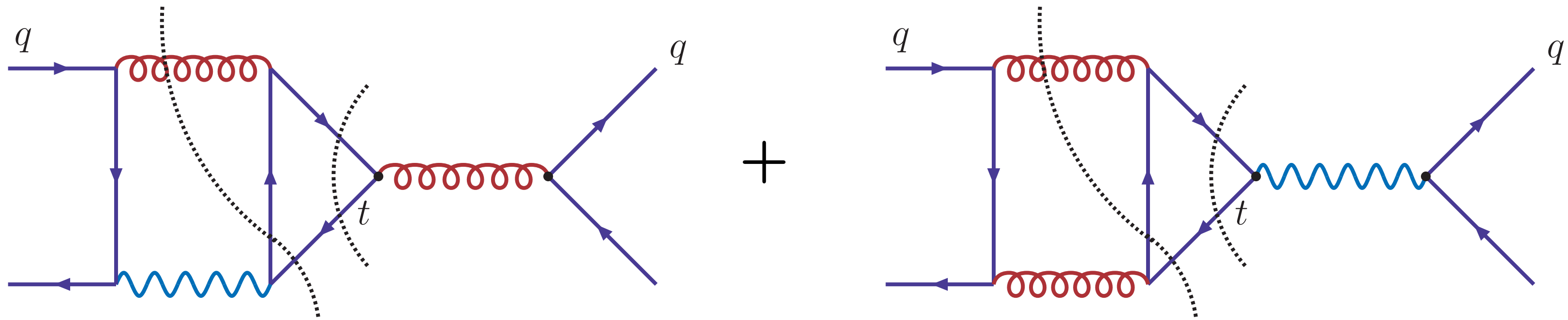
$\sim \mathcal{O}(\alpha_{\mathrm{s}})$

$\mathcal{O}(\alpha_s^2 \alpha_{\text{weak}})$ weak corrections ($q\,\bar{q} \to t\,\bar{t}$)



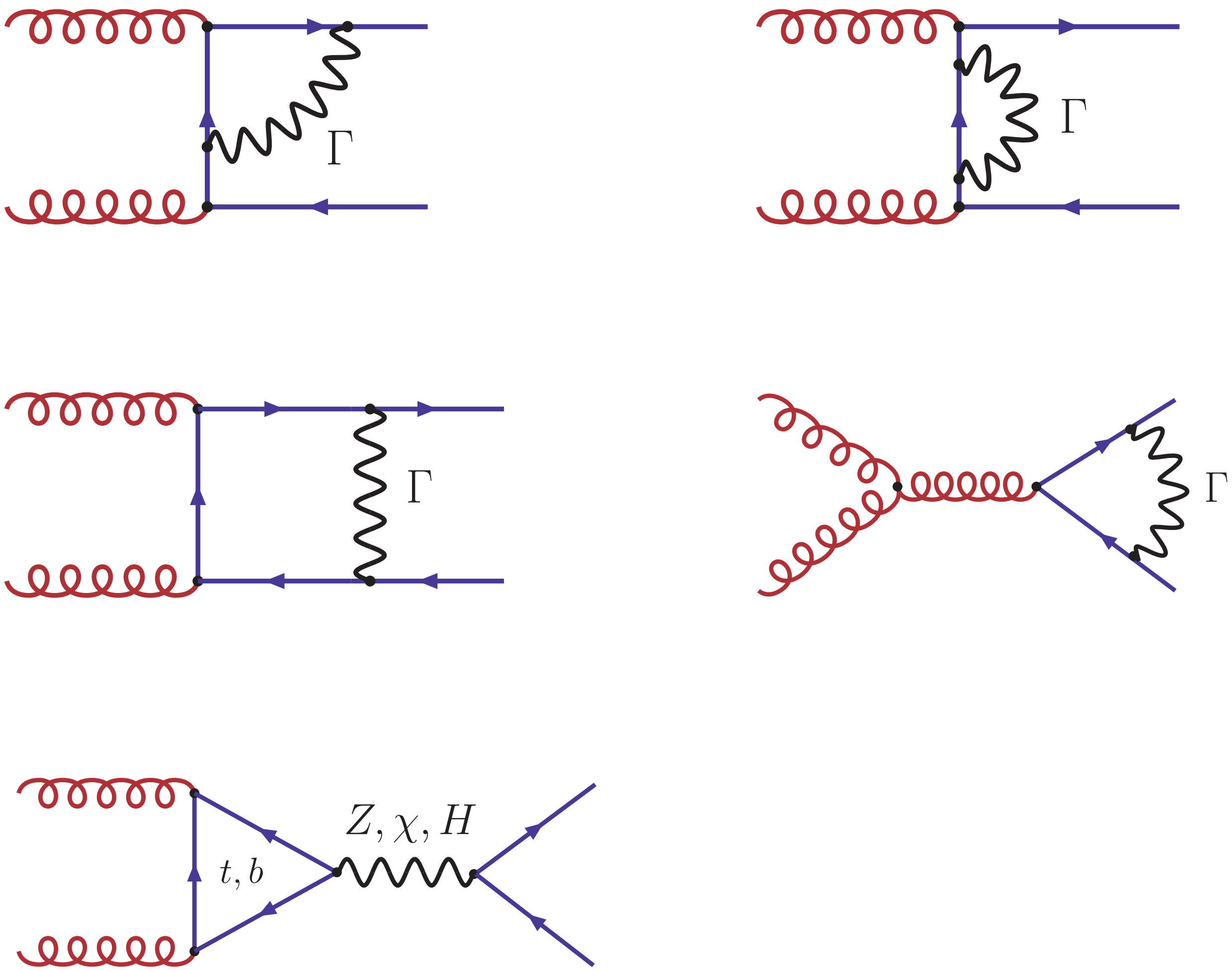
also Beenakker et. al

Kao & Wackeroth



cuts of second group individually IR-divergent

$\mathcal{O}(\alpha_s^2 \alpha_{\text{weak}})$ weak corrections ($g\,g \to t\,\bar{t}$)



- analytical & numerical results available
  (independent evaluation of Bernreuther & Fücker, many independent checks)

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

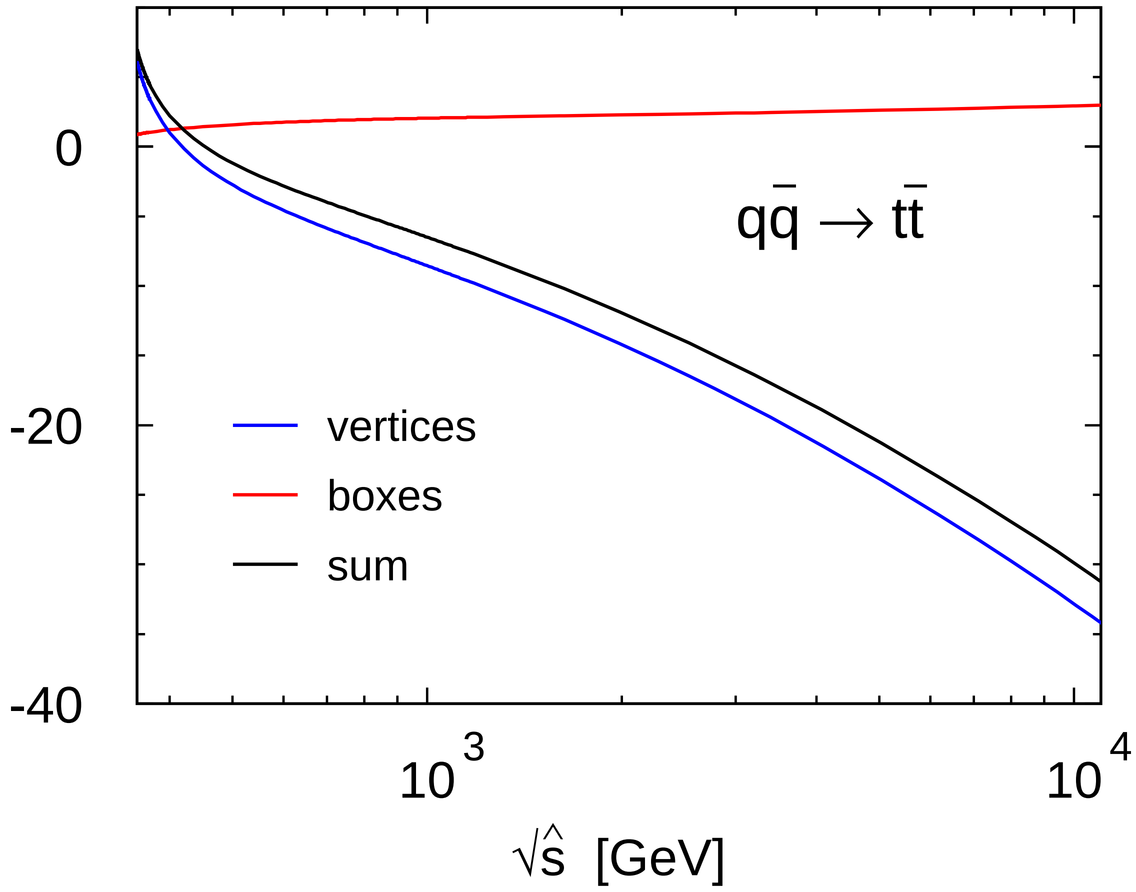
- box contribution moderately $\hat{s}$-dependent

- strong increase with $\hat{s}$

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

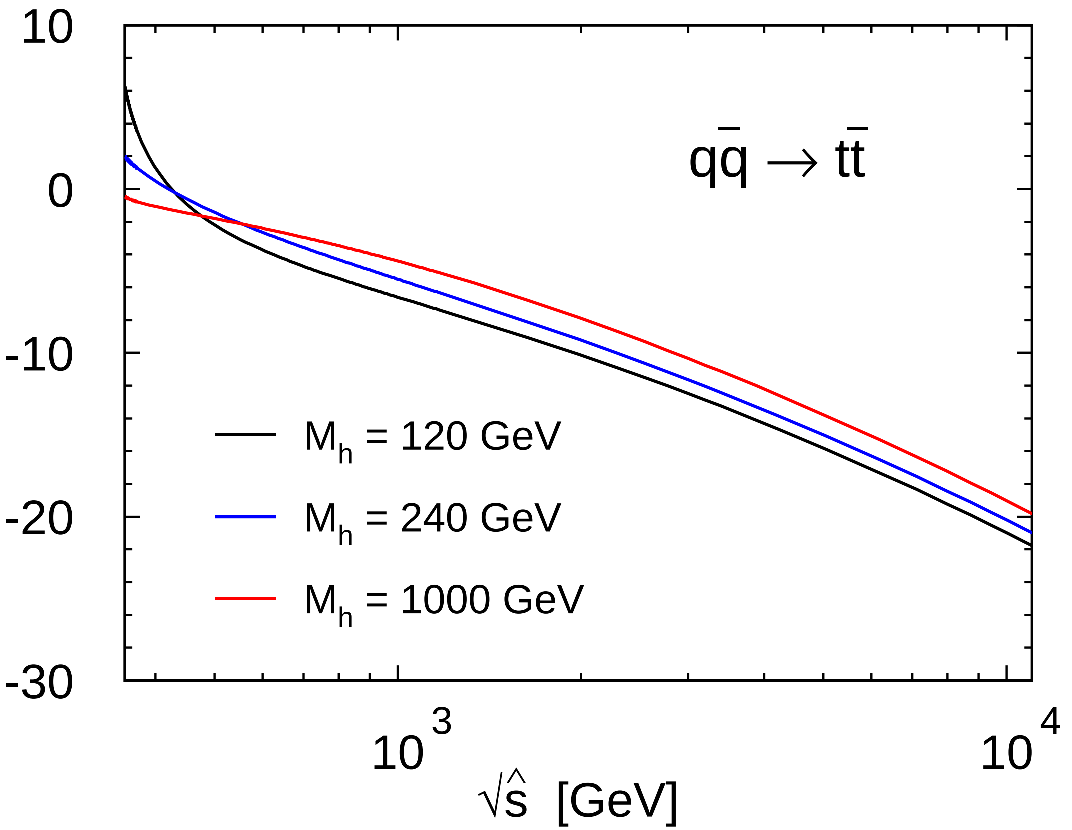
large corrections for large $\sqrt{\hat{s}}$

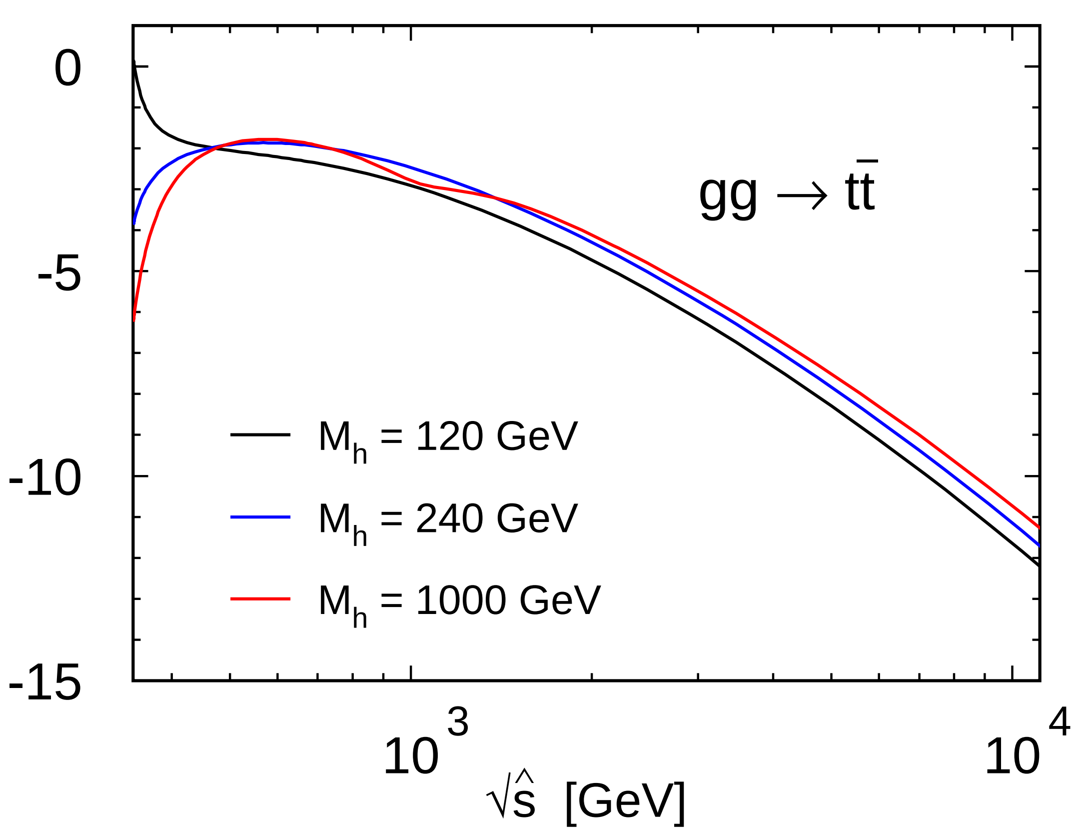
(relative weak corrections [%])



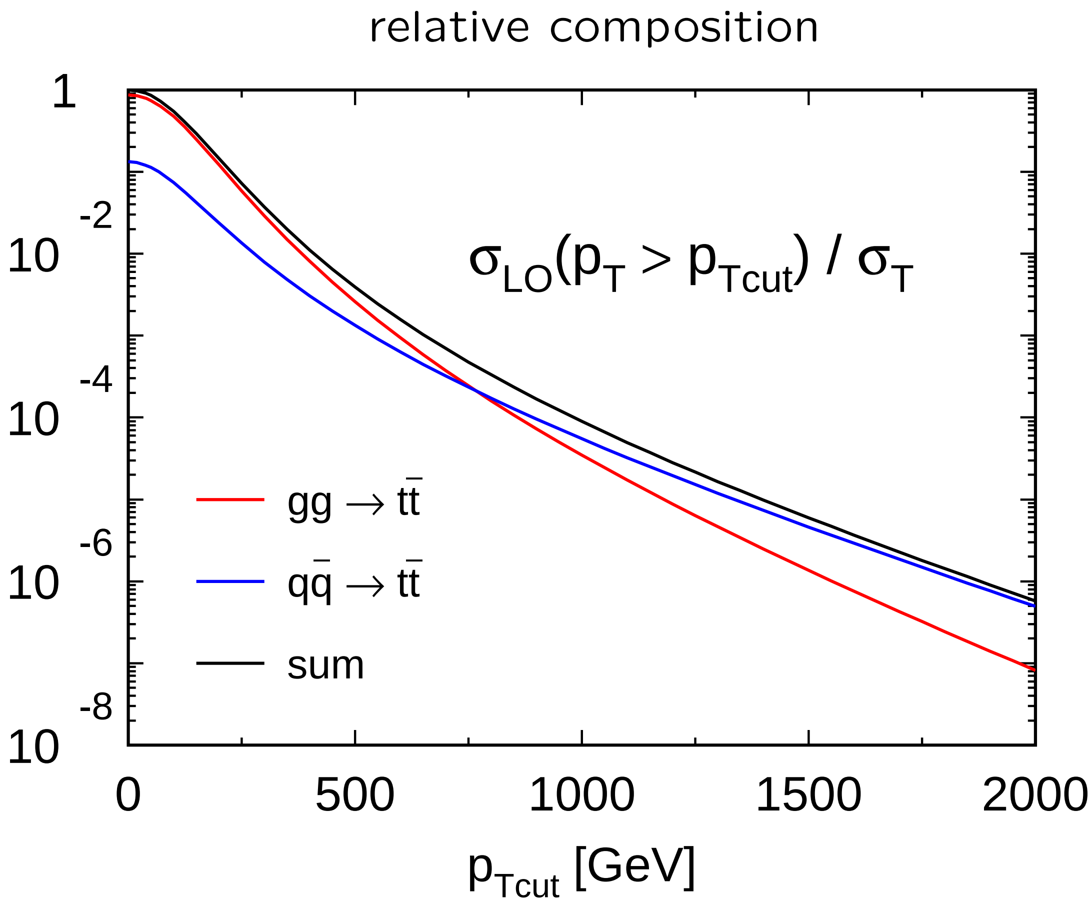
sizable M_h-dependence

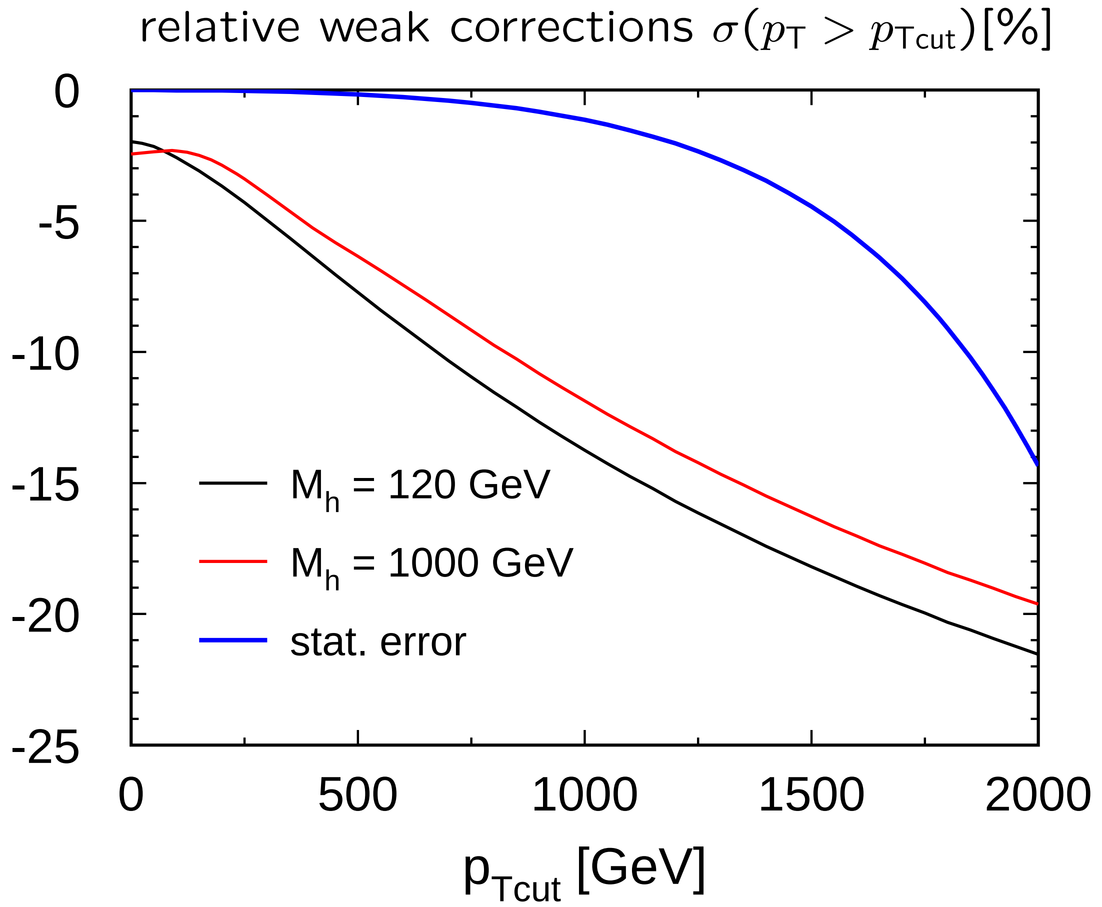
(relative weak corrections [%])



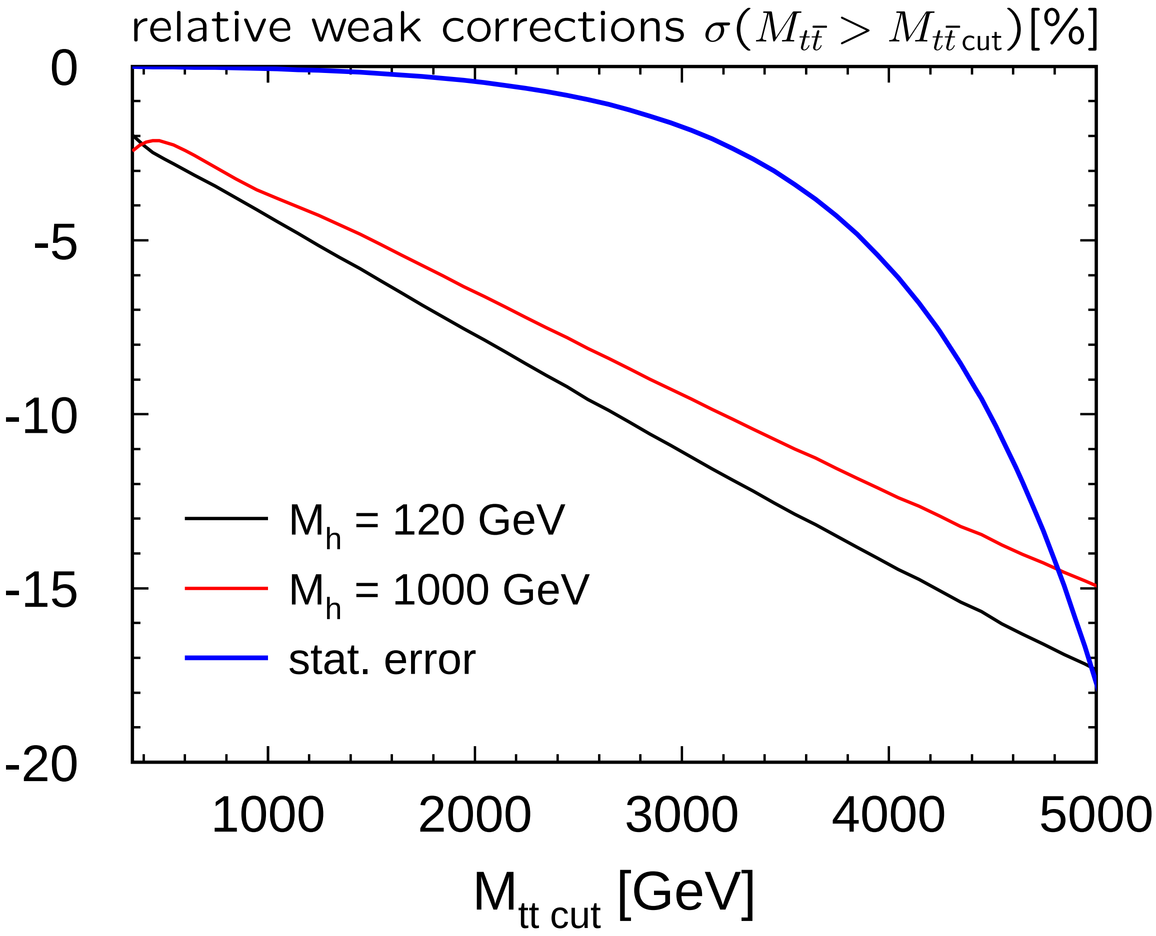


Transverse momentum dependence





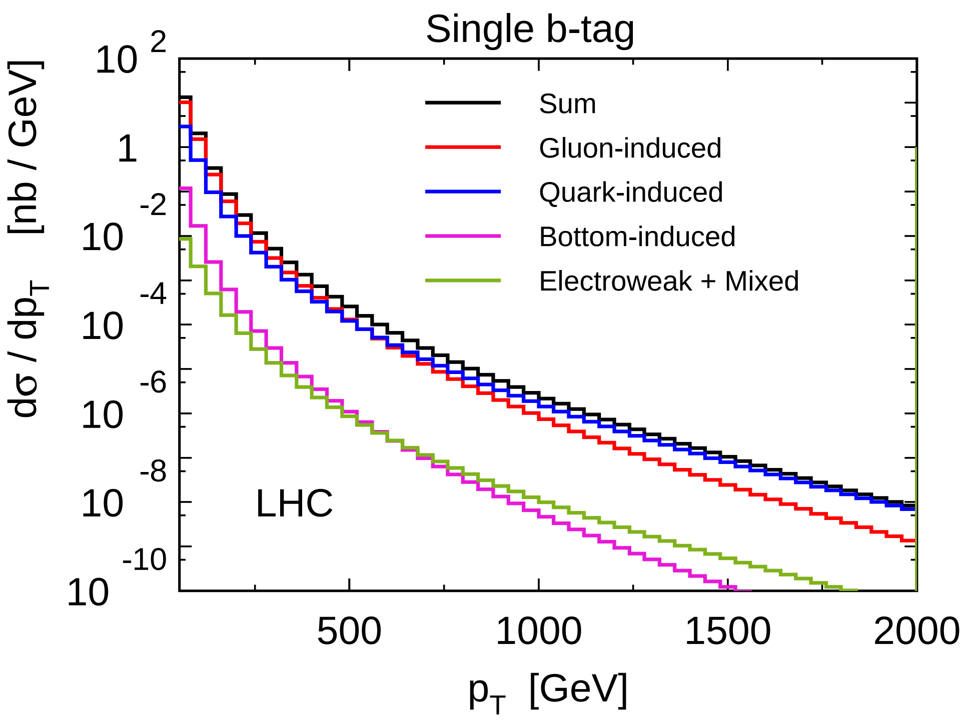
$M_{t\bar{t}}$ -dependence

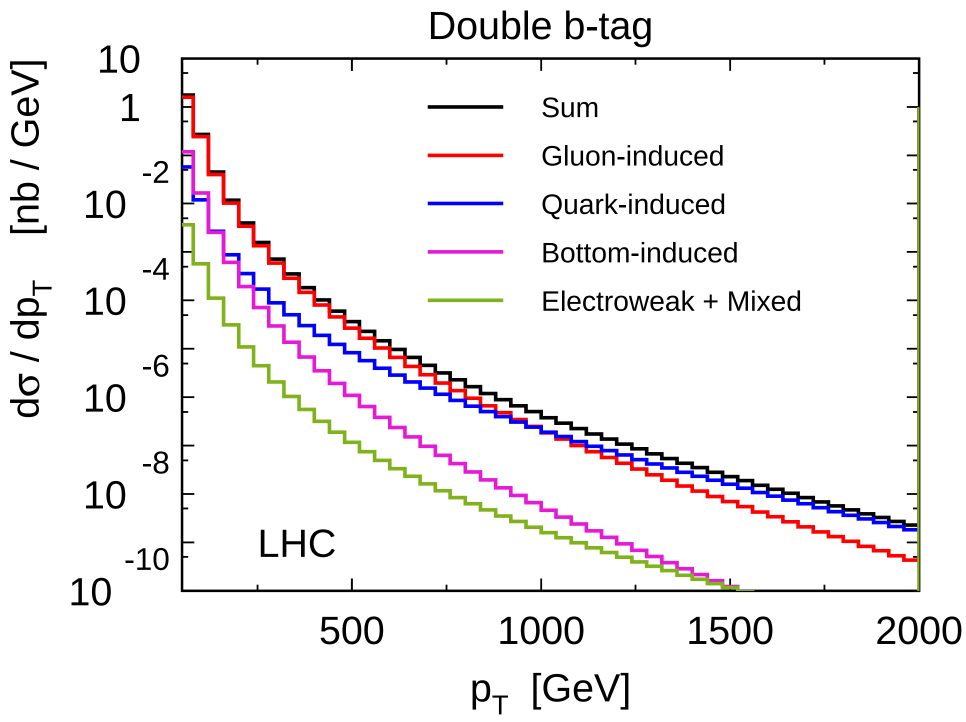


Bottom-Quarks

preliminary results

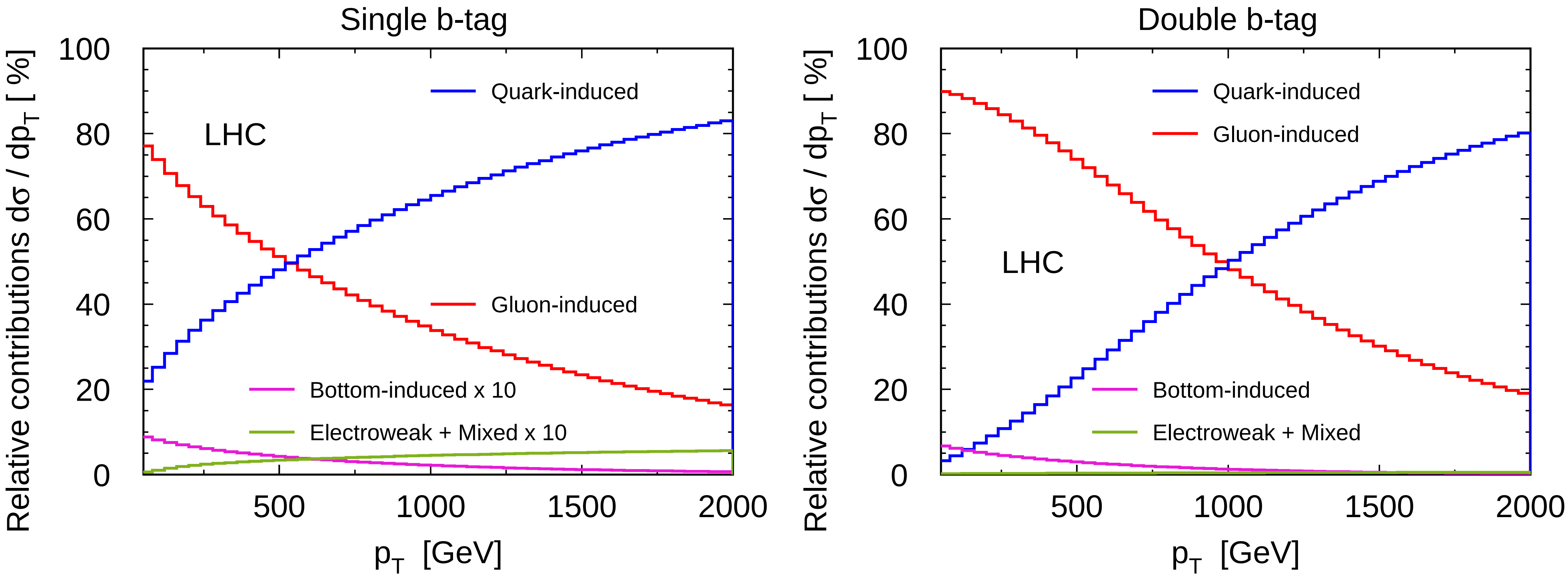
Bottom-Jet Production





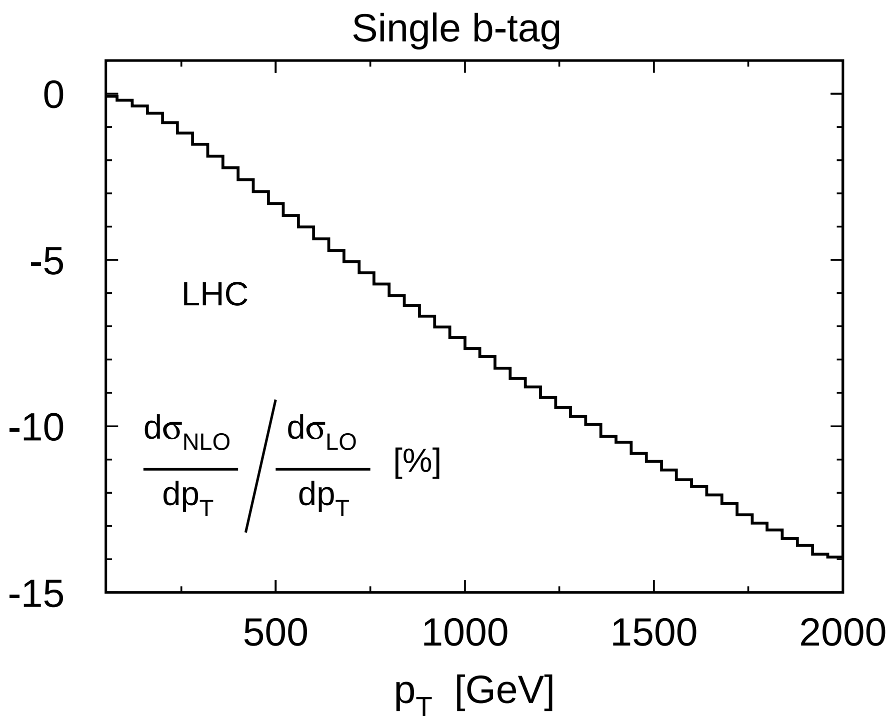
Bottom-Jet Production

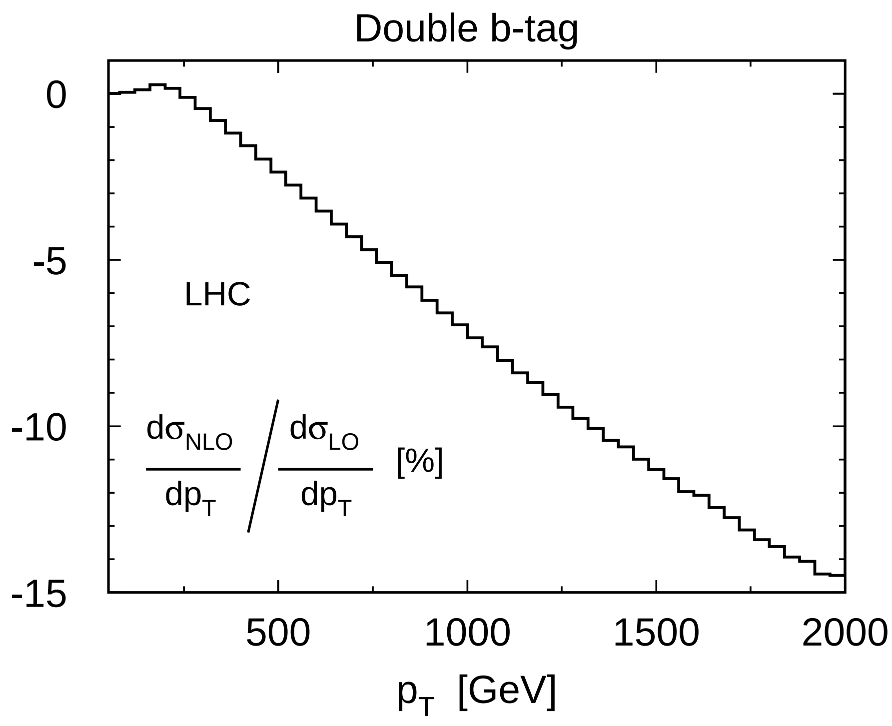
preliminary results



Bottom-Jet Production

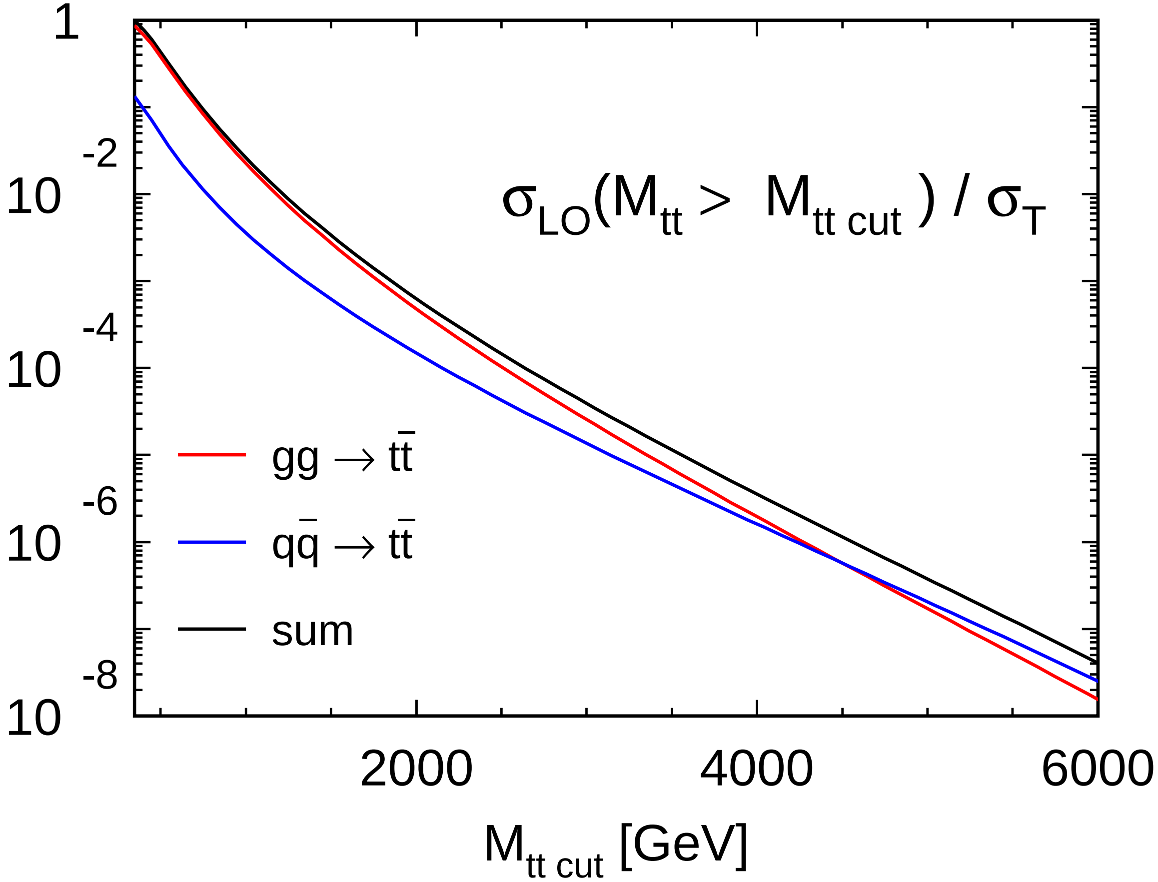
preliminary results





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
- two-loop terms might become relevant
- top-quark distributions at large $\hat{s}$ are strongly modified
- sizable m_H-dependence
- interplay between electroweak and QCD effects


1
10 -2
10 -4
10 -6
10 -8
$\sigma_{LO}(M_{tt} > M_{tt\,cut}) / \sigma_T$
$gg \to t\bar{t}$
$q\bar{q} \to t\bar{t}$
sum
2000
4000
6000
$M_{tt\,cut}$ [GeV]