Soft-gluon corrections for single top quark production in association with electroweak bosons

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Effective Lagrangian and soft corrections

- **Effective Lagrangian**

$$\Delta\mathcal{L}^{eff} = \frac{1}{\Lambda}\,\kappa_{tqA}\, e\, \bar{t}\, \sigma_{\mu\nu}\, q\, F_A^{\mu\nu} + h.c.$$

- **Anomalous coupling- forbidden in SM without additional particles**

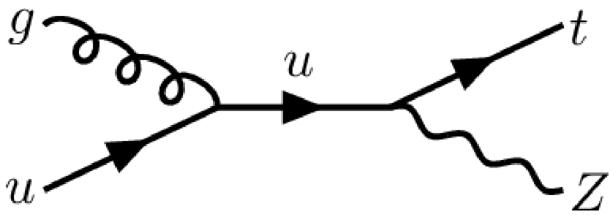
- **Corrections take the form of logarithmic "plus" distributions of a threshold variable, $s_4 = s + t + u - m_t^2 - m_A^2$.**

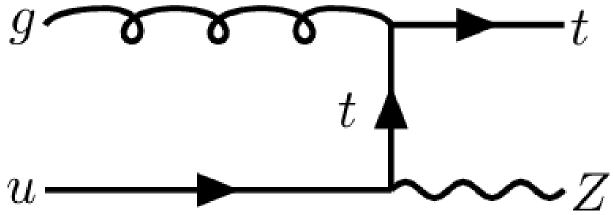
$$\int_0^{s_{4max}} ds_4 \left[\frac{\ln^k(s_4/m^2)}{s_4}\right]_+ f(s_4)\,, \qquad\qquad k \le 2n-1$$

$$= \int_0^{s_{4max}} ds_4 \frac{\ln^k(s_4/m^2)}{s_4}[f(s_4) - f(0)] + \frac{1}{k+1}\ln^{k+1}\left(\frac{s_{4max}}{m^2}\right) f(0)$$

$gq \to tZ$

- **Tree-level Feynman diagrams**





- **Leading order cross section**

$$\frac{d^2\hat{\sigma}_{gq\to tZ}}{dt\,du} = F_{LO}^{gq\to tZ}\,\delta(s_4)$$

$$\begin{aligned} F_{LO}^{gq\to tZ} \quad = \quad & \frac{e^2\alpha_s\kappa_{tqZ}^2}{6s^3\left(m_t^2-t\right)^2}\left\{2m_t^6 - m_t^4(3m_Z^2+4s+2t)\right. \\ & + m_t^2\left[2m_Z^4 - m_Z^2(2s+t) + 2(s^2+4st+t^2)\right] \\ & + 2m_Z^6 - 4m_Z^4 t + m_Z^2(s+t)(s+5t) - 2t(3s^2+6st+t^2) \\ & \left. - \frac{t}{m_t^2}\left[2m_Z^6 - 2m_Z^4(s+t) + m_Z^2(s+t)^2 - 4st(s+t)\right]\right\} \end{aligned}$$

$gq \to tZ$

- **NLO-NLL corrections**

$$\frac{d^2\hat{\sigma}^{(1)}_{gq\to tZ}}{dt\,du} = F^{gq\to tZ}_{LO}\frac{\alpha_s(\mu_R^2)}{\pi}\left\{c_3\left[\frac{\ln(s_4/m^2)}{s_4}\right]_+ + c_2\left[\frac{1}{s_4}\right]_+ + c_1\delta(s_4)\right\},$$

where

$$c_3 = 2(C_F + C_A)$$

$$c_2 = 2C_F\ln\left(\frac{u-m_t^2}{t-m_Z^2}\right) - C_F + C_A\ln\left(\frac{t-m_t^2}{u-m_t^2}\right) + C_A\ln\left(\frac{sm_t^2}{(u-m_Z^2)^2}\right) - (C_F+C_A)\ln\left(\frac{\mu_F^2}{m_t^2}\right)$$

$$c_1 = \left[C_F\ln\left(\frac{-t+m_Z^2}{m_t^2}\right) + C_A\ln\left(\frac{-u+m_Z^2}{m_t^2}\right) - \frac{3}{4}C_F\right]\ln\left(\frac{\mu_F^2}{m_t^2}\right) - \frac{\beta_0}{4}\ln\left(\frac{\mu_F^2}{\mu_R^2}\right).$$

- $C_F = \frac{4}{3}$ **and** $C_A = 3$ **are color factors, and** $\beta_0 = \frac{1}{3}(11C_A - 2n_f)$

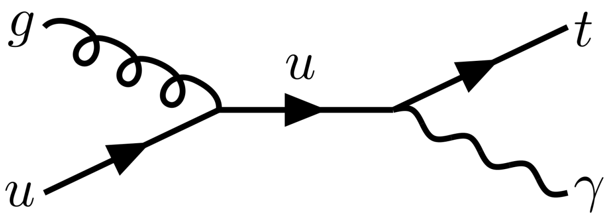
$gq \to tZ$

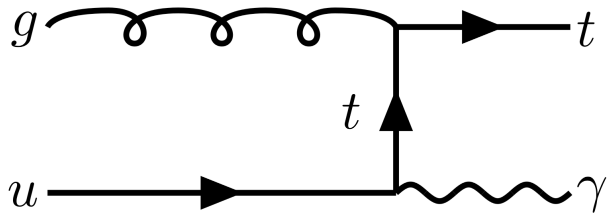
- **NNLO-NLL corrections**

$$\frac{d^2\hat{\sigma}^{(2)}_{gq\to tZ}}{dt\,du} = F_{LO}^{gq\to tZ}\frac{\alpha_s^2(\mu_R^2)}{\pi^2}\left\{\frac{1}{2}c_3^2\left[\frac{\ln^3(s_4/m^2)}{s_4}\right]_+ + \left[\frac{3}{2}c_3c_2 - \frac{\beta_0}{4}c_3\right]\left[\frac{\ln^2(s_4/m^2)}{s_4}\right]_+\right.$$
$$+\left[c_3c_1 - (C_F+C_A)^2\ln^2\left(\frac{\mu_F^2}{m_t^2}\right) - 2\,(C_F+C_A)\,c_2\ln\left(\frac{\mu_F^2}{m_t^2}\right)\right.$$
$$\left.+\frac{\beta_0}{4}c_3\ln\left(\frac{\mu_R^2}{m_t^2}\right)\right]\left[\frac{\ln(s_4/m^2)}{s_4}\right]_+$$
$$+\left[-(C_F+C_A)\,c_1\ln\left(\frac{\mu_F^2}{m_t^2}\right) - \frac{\beta_0}{4}(C_F+C_A)\ln\left(\frac{\mu_F^2}{m_t^2}\right)\ln\left(\frac{\mu_R^2}{m_t^2}\right)\right.$$
$$\left.\left.+(C_F+C_A)\frac{\beta_0}{8}\ln^2\left(\frac{\mu_F^2}{m_t^2}\right)\right]\left[\frac{1}{s_4}\right]_+\right\}$$

$gq \to t\gamma$

- **Tree-level Feynman diagrams**





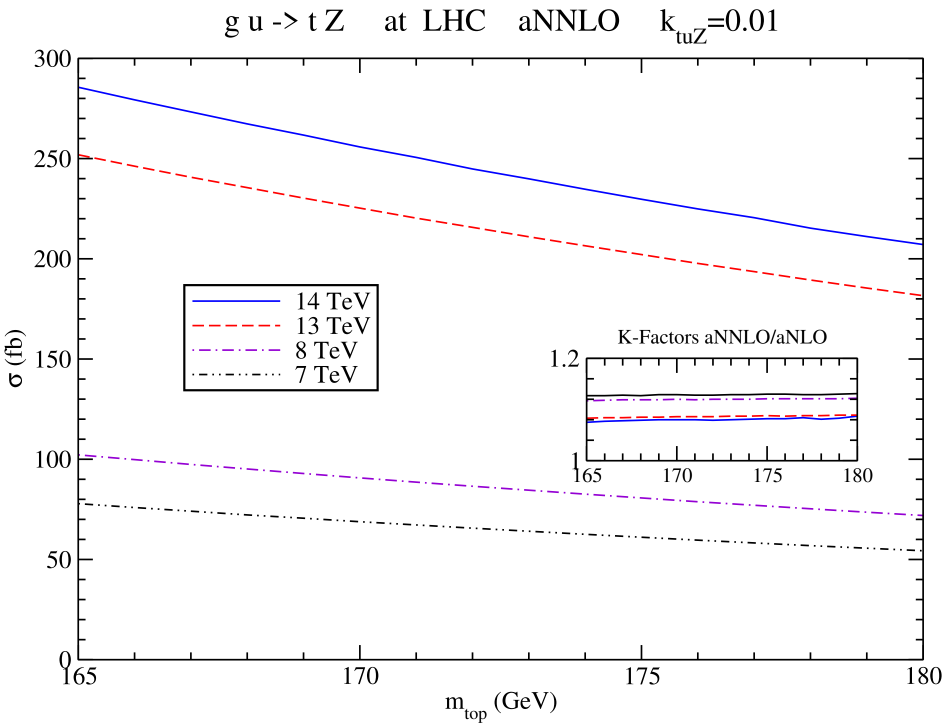
- **Leading order cross section**

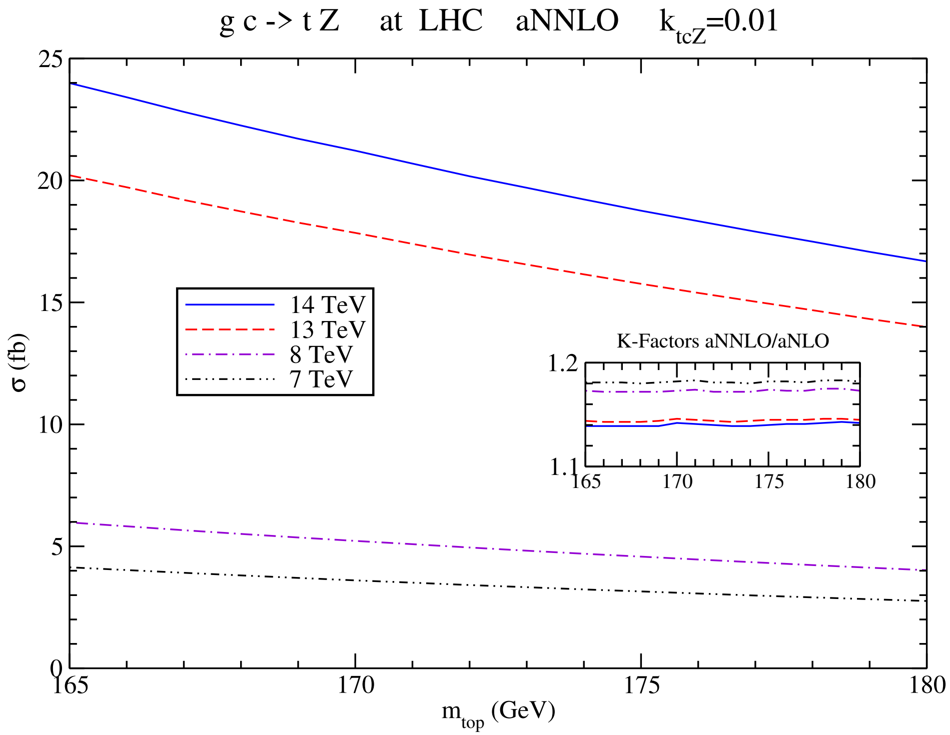
$$\frac{d^2\hat{\sigma}_{LO}^{gq\to t\gamma}}{dt\,du} = F_{LO}^{gq\to t\gamma}\delta(s_4)$$

$$F_{LO}^{gq\to t\gamma} = \frac{e^2\alpha_s\kappa_{tq\gamma}^2(m_t^2 - s - t)[m_t^6 - m_t^4 s - 2st^2 + m_t^2 t(3s+t)]}{3m_t^2 s^3(m_t^2 - t)^2}$$

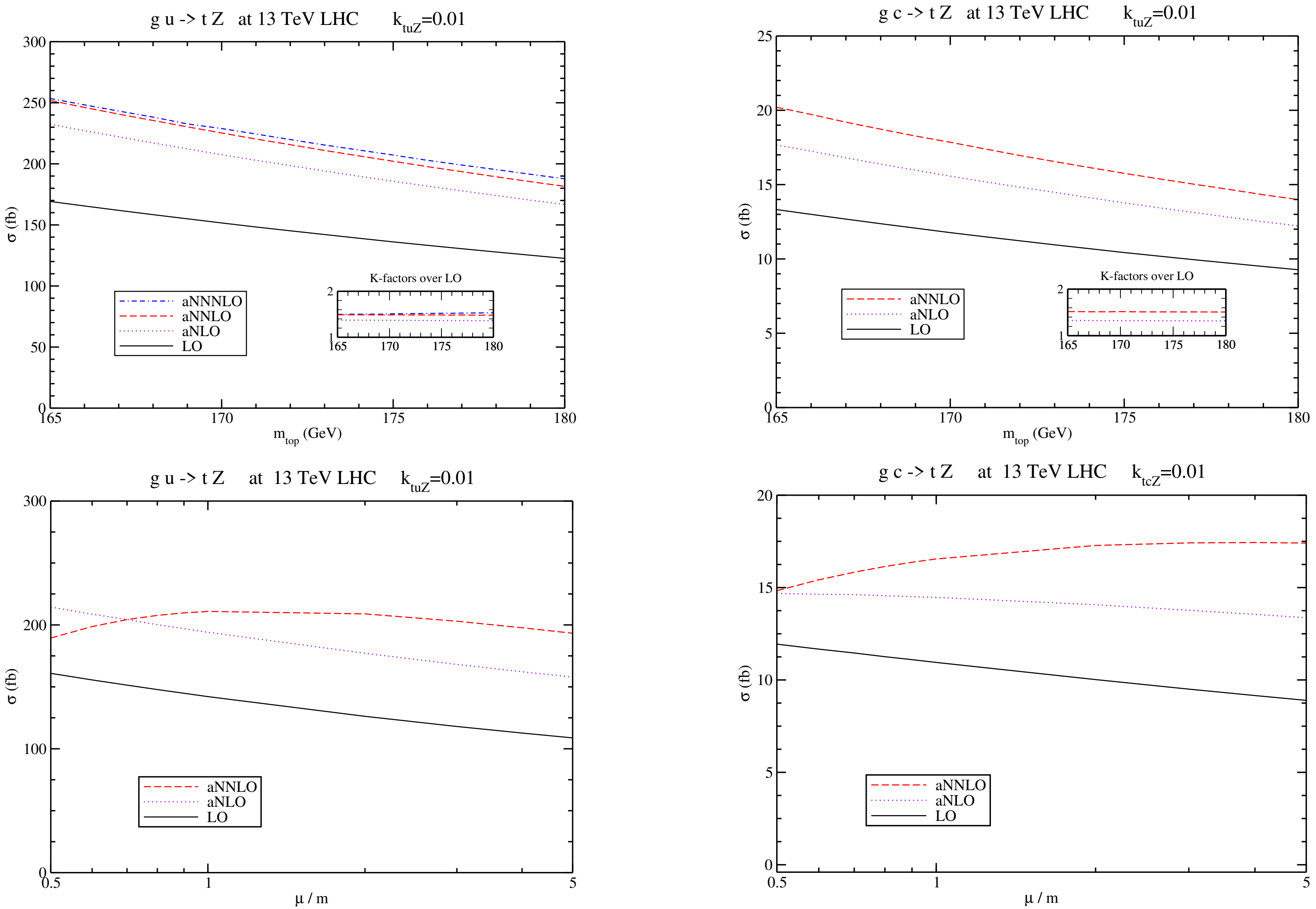
- **The NLO-NLL and NNLO-NLL corrections for $t\gamma$ production are analogous to those for tZ production, with $m_Z \to 0$ and the appropriate leading order expression.**

$gq \to tZ$ Total Cross Sections

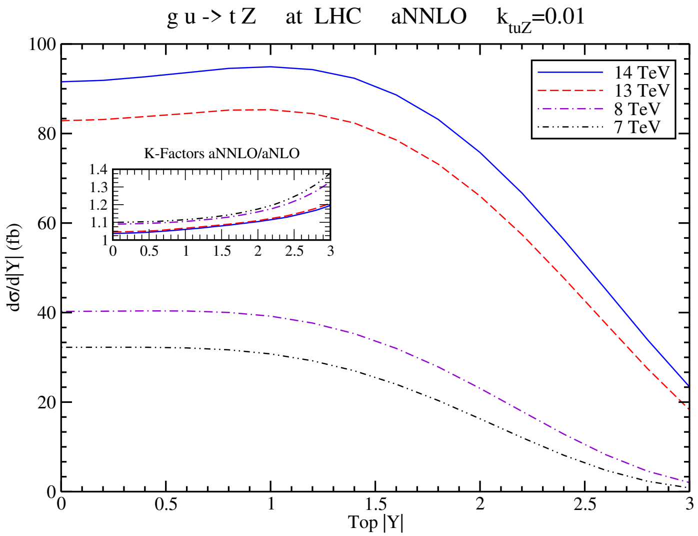


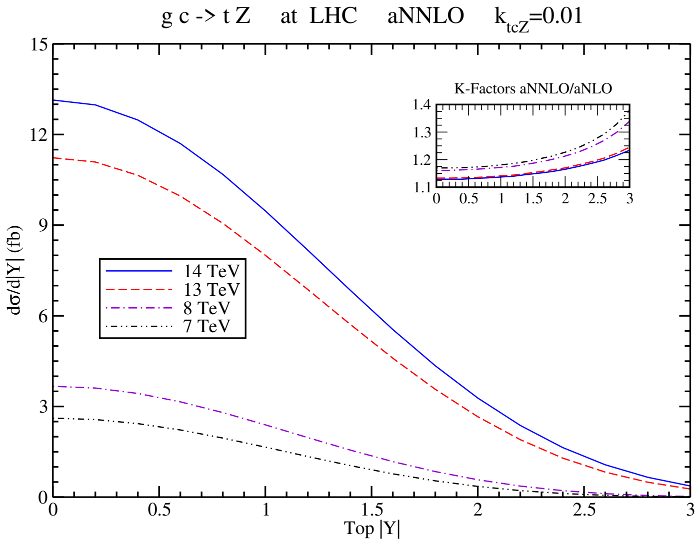


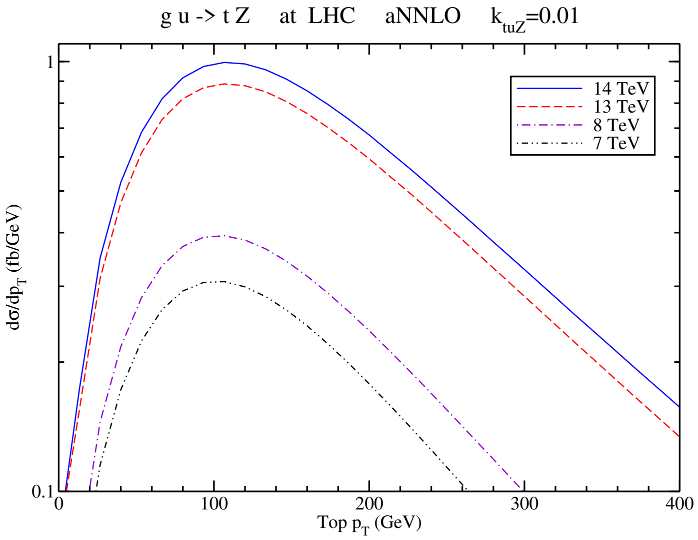
$gq \to tZ$ Total Cross Sections

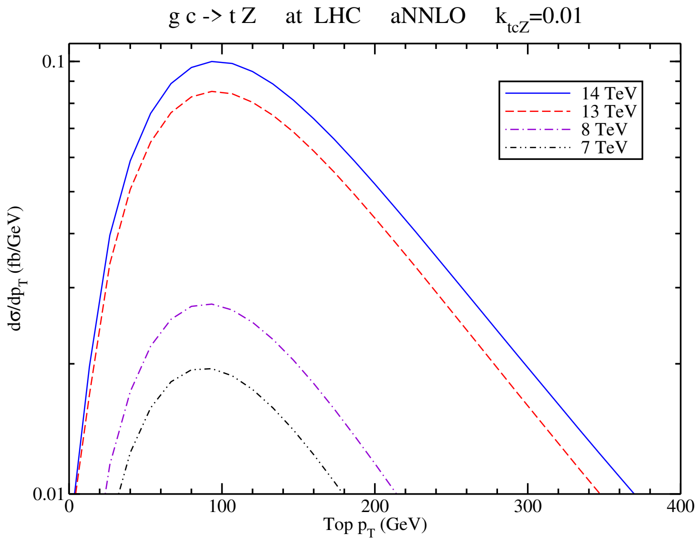


$gq \to tZ$ Differential Distributions

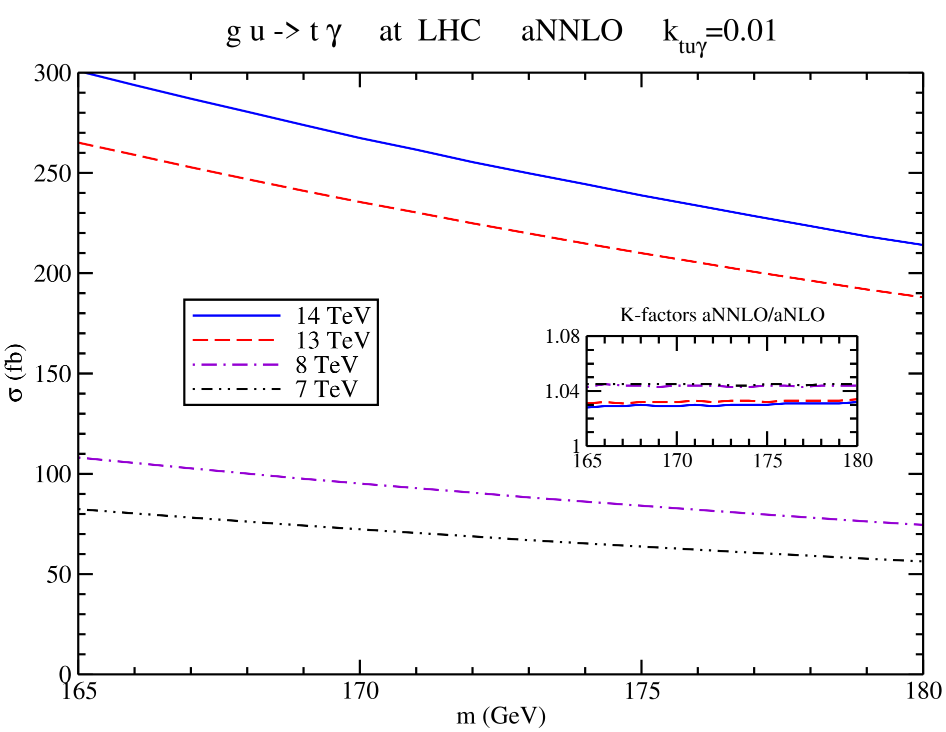


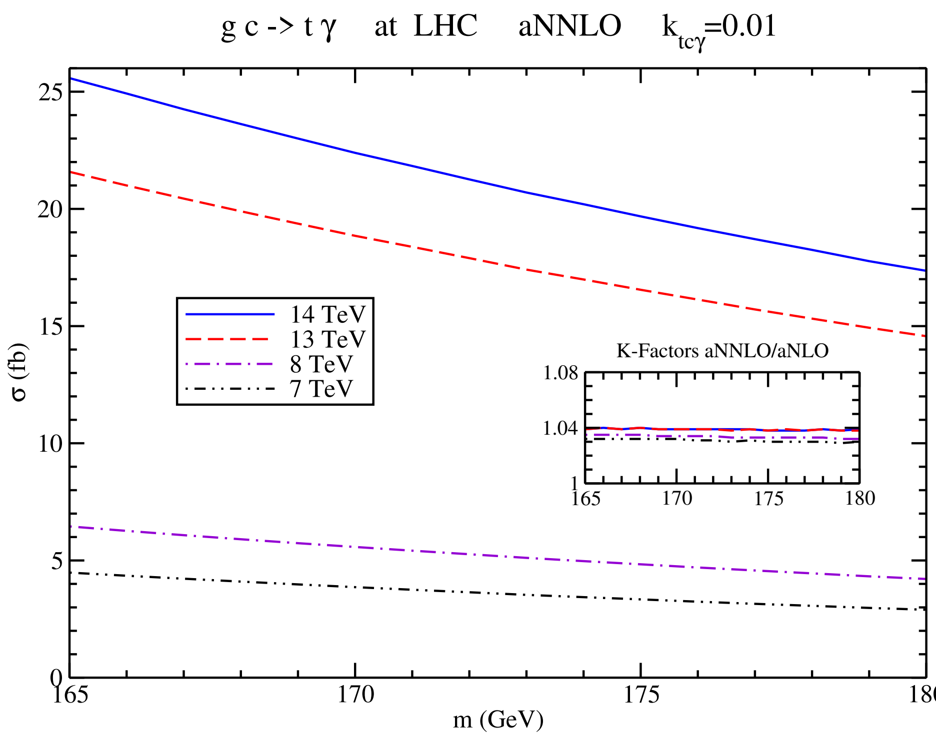




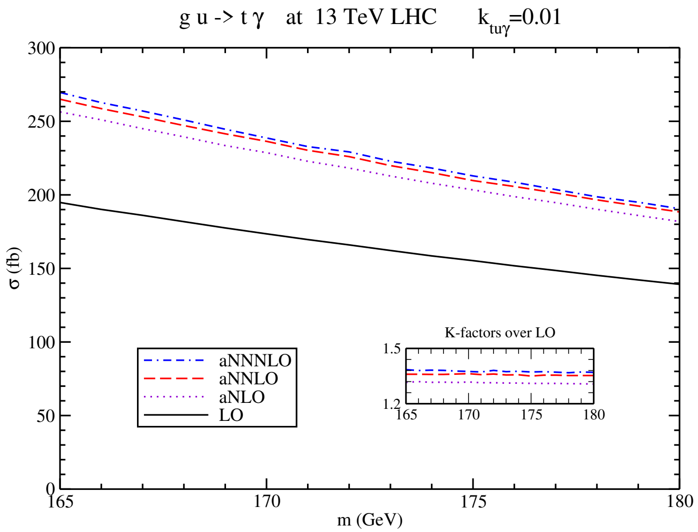


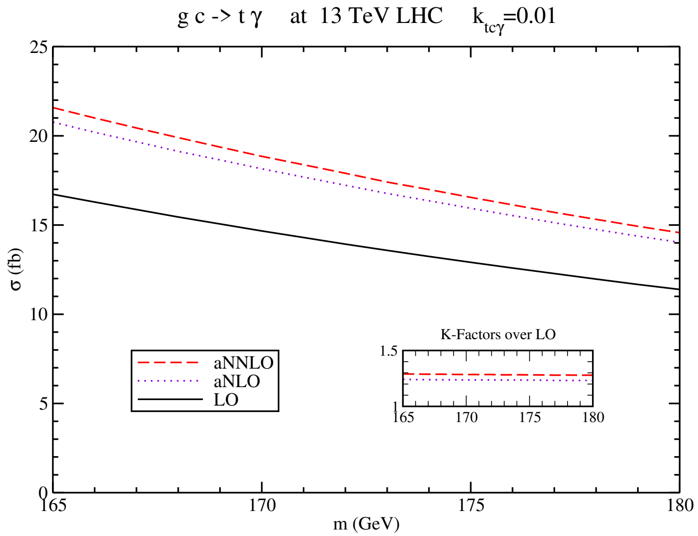
$gq \to t\gamma$ Total Cross Sections

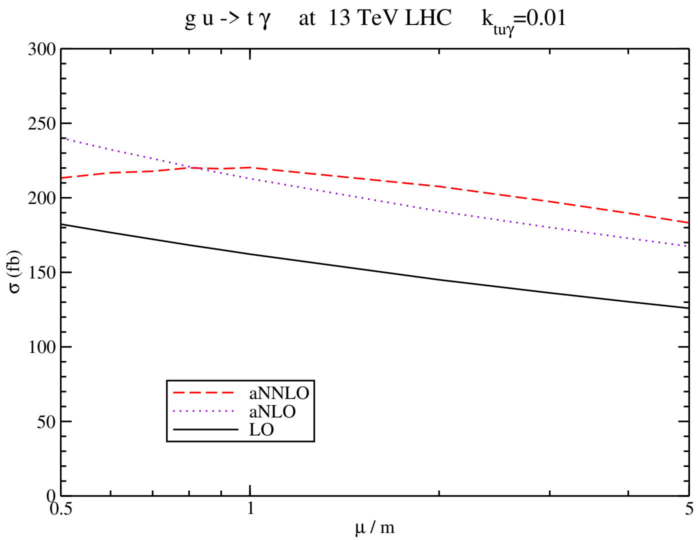


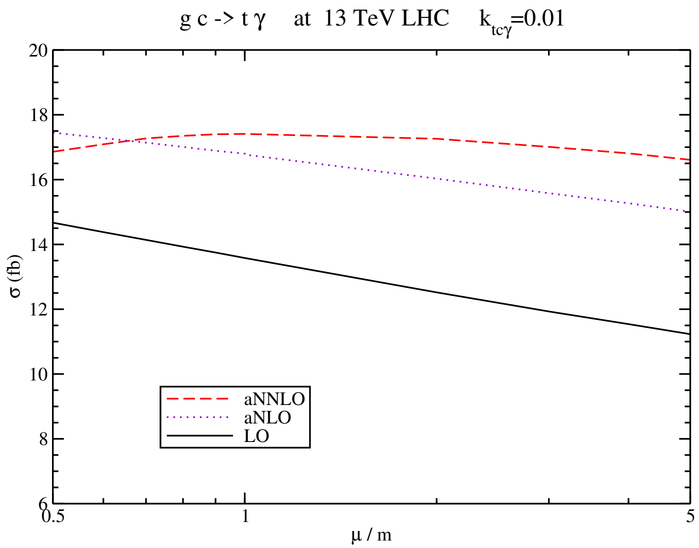


$gq \to t\gamma$ Total Cross Sections

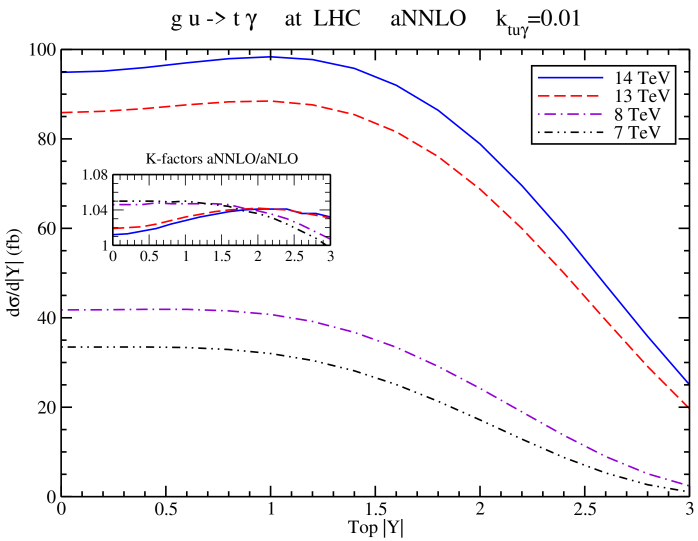


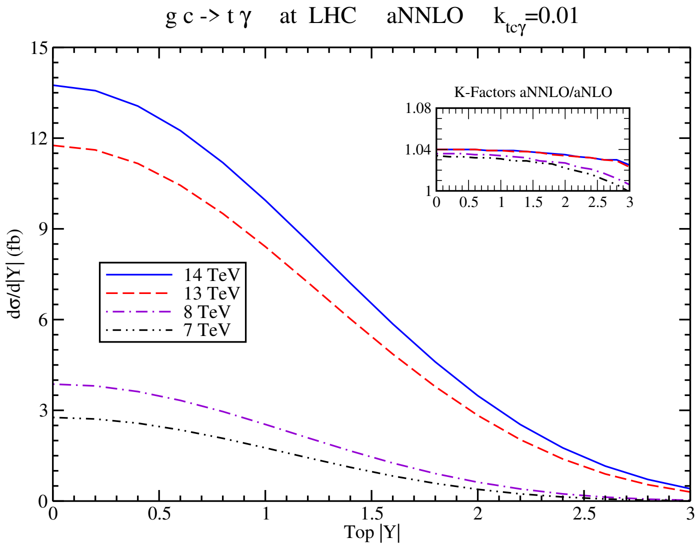


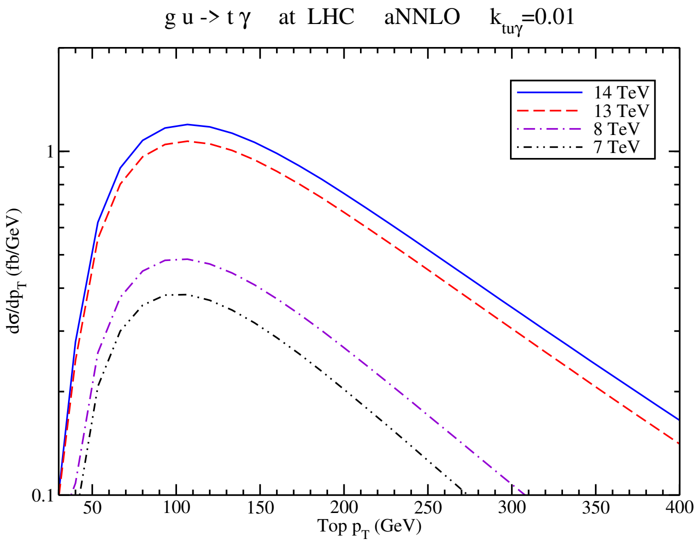


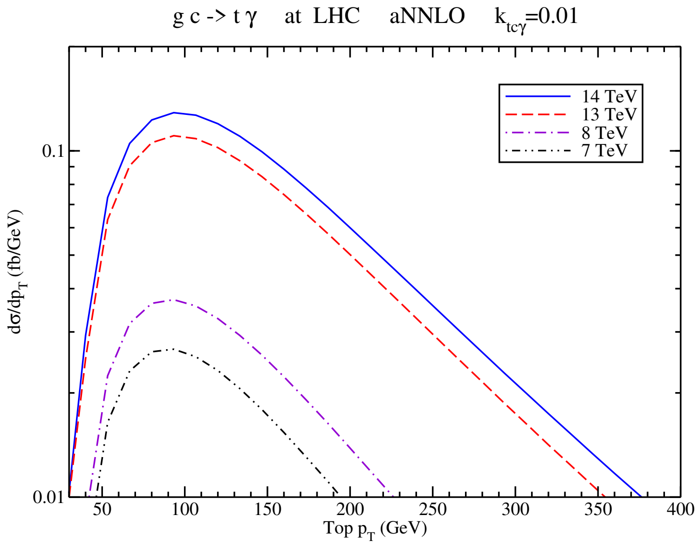


$gq \to t\gamma$ Differential Distributions

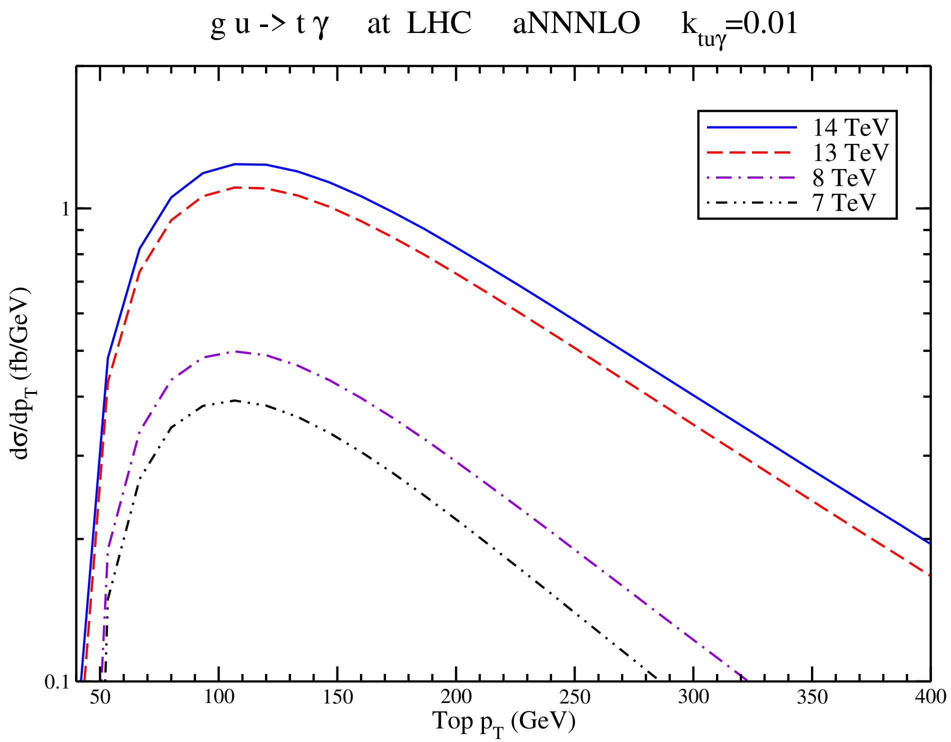


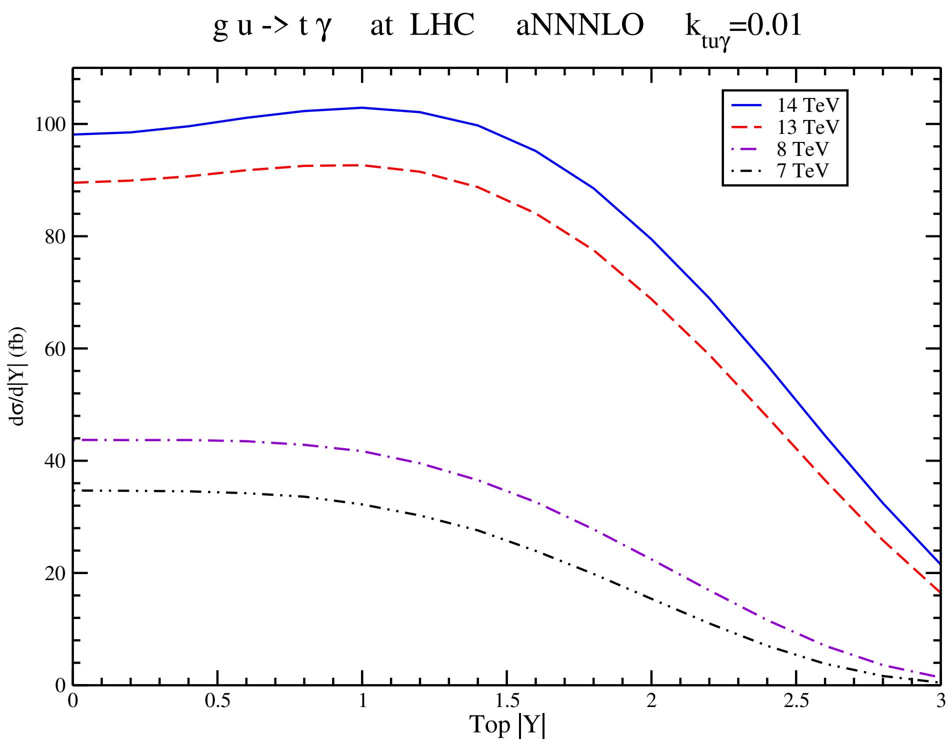






$gu \to t\gamma$ aN^{3}LO Differential Distributions





Future work

- **With tZ and $t\gamma$ production, most $2 \to 2$ processes' soft gluon corrections have been computed to at least NLL accuracy.**

- **Logical next step is to extend results to $2 \to 3$ processes.**

- **For $2 \to 2$ corrections, take 2 particle phase space and change to 3 particle phase space, requiring an additional integration (s_4)**

- **For $2 \to 3$ processes, change to 4 particle phase space, requiring 3 additional integrations.**

- **Determining proper definitions of the invariants and for the threshold variable becomes challenging.**

- **Expression for LO cross section is also much more complicated, making results less numerically stable.**

Summary

- **Soft-gluon corrections take the form of logarithmic "plus" distributions**
- **Results are scale dependent- but scale uncertainty is less at aNNLO**
- **Soft gluon radiative corrections dominate full corrections**
- **NLO and NNLO corrections contribute significantly to the total cross section**
- **Future work will extend method to processes with three particle final states**