tW and tZ' production at hadron colliders

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- **Soft-gluon corrections**
- **tW production**
- **tZ' production**

with Marco Guzzi (tZ') and Nodoka Yamanaka (tW)

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Soft-gluon corrections

They are important for top-quark processes
They approximate known exact results at NLO and NNLO very well

$$f_1(p_1) + f_2(p_2) \to t(p_t) + V \qquad (V = W \text{ or } Z')$$

define $s = (p_1 + p_2)^2$, $t = (p_1 - p_t)^2$, $u = (p_2 - p_t)^2$ **and** $s_4 = s + t + u - \sum_i m_i^2$

At partonic threshold $s_4 \to 0$

Soft corrections $\left[\frac{\ln^k(s_4/m^2)}{s_4}\right]_+$ **with** $k \leq 2n-1$ **for the order** α_s^n **corrections**

we set $m = m_t$ **for** tW **production and** $m = m_{Z'}$ **for** tZ' **production**

Resum these soft corrections for the double-differential cross section

At NNLL accuracy we need two-loop soft anomalous dimensions

At N^{3}LL accuracy we need three-loop soft anomalous dimensions

Finite-order expansions $\to$ no prescription needed

Approximate NNLO (aNNLO) and N^{3}LO (aN^{3}LO) predictions

for cross sections and differential distributions

Soft-gluon Resummation

moments of the partonic cross section with moment variable N:

$\hat{\sigma}(N) = \int (ds_4/s)\, e^{-Ns_4/s} \hat{\sigma}(s_4)$

factorized expression for the cross section

$$\sigma^{f_1 f_2 \to tV}(N) = \psi_1\left(N_1, \mu_F\right) \psi_2\left(N_2, \mu_F\right) H^{f_1 f_2 \to tV}\left(\alpha_s(\mu_R)\right) S^{f_1 f_2 \to tV}\left(\frac{m}{N\mu_F}, \alpha_s(\mu_R)\right)$$

ψ_1, ψ_2 $\to$ **collinear emission from incoming partons**

$H^{f_1 f_2 \to tV}$ **is hard function** $\to$ **short distance**

$S^{f_1 f_2 \to tV}$ **is soft function** $\to$ **noncollinear soft gluons**

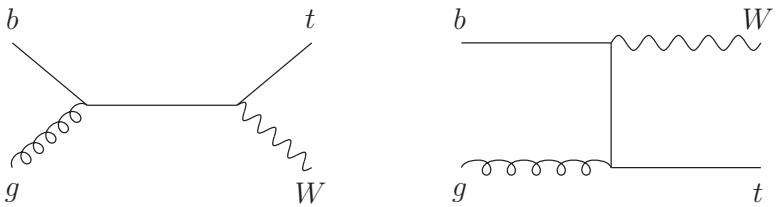
$S^{f_1 f_2 \to tV}$ **satisfies the renormalization group equation**

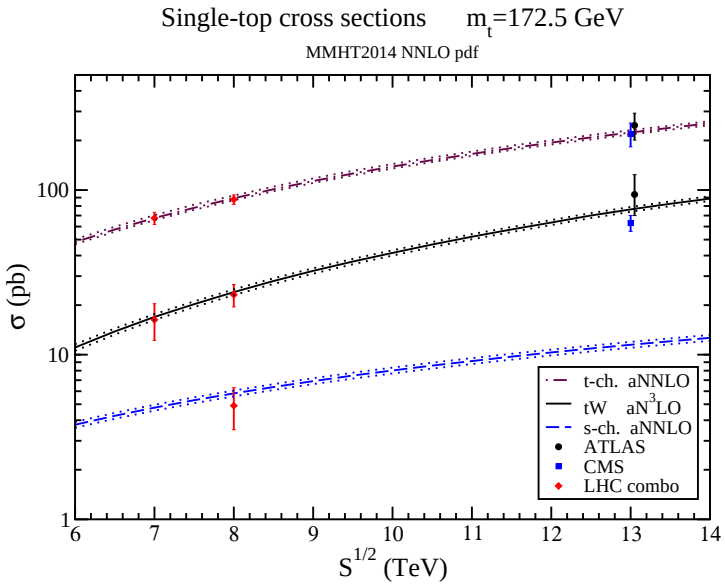
$$\left(\mu_R \frac{\partial}{\partial \mu_R} + \beta(g_s) \frac{\partial}{\partial g_s}\right) S^{f_1 f_2 \to tV} = -\Gamma_S^{\dagger\, f_1 f_2 \to tV} S^{f_1 f_2 \to tV} - S^{f_1 f_2 \to tV} \Gamma_S^{f_1 f_2 \to tV}$$

Soft anomalous dimension $\Gamma_S^{f_1 f_2 \to tV}$ controls the evolution of the soft function which gives the exponentiation of logarithms of N

tW production

leading-order diagrams





At one loop $\Gamma_S^{(1)\,bg\to tW} = C_F\left[\ln\left(\frac{m_t^2-t}{m_t\sqrt{s}}\right)-\frac{1}{2}\right]+\frac{C_A}{2}\ln\left(\frac{u-m_t^2}{t-m_t^2}\right)$

At two loops $\Gamma_S^{(2)\,bg\to tW} = K_2\,\Gamma_S^{(1)\,bg\to tW}+\frac{1}{4}C_FC_A(1-\zeta_3)$

where $K_2 = C_A\left(\frac{67}{36}-\frac{\zeta_2}{2}\right)-\frac{5}{18}n_f$

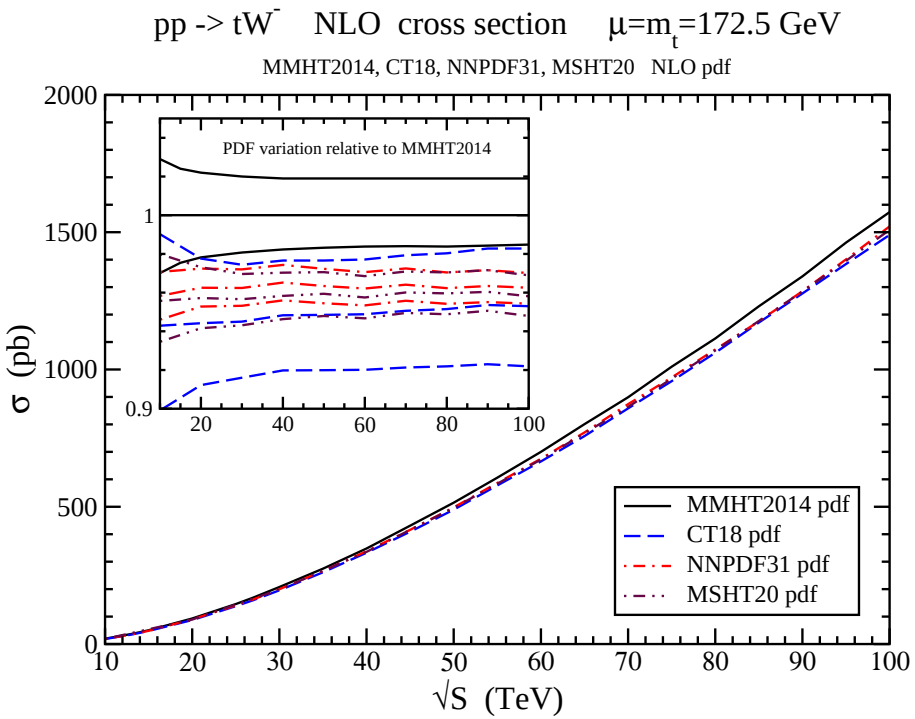
At three loops

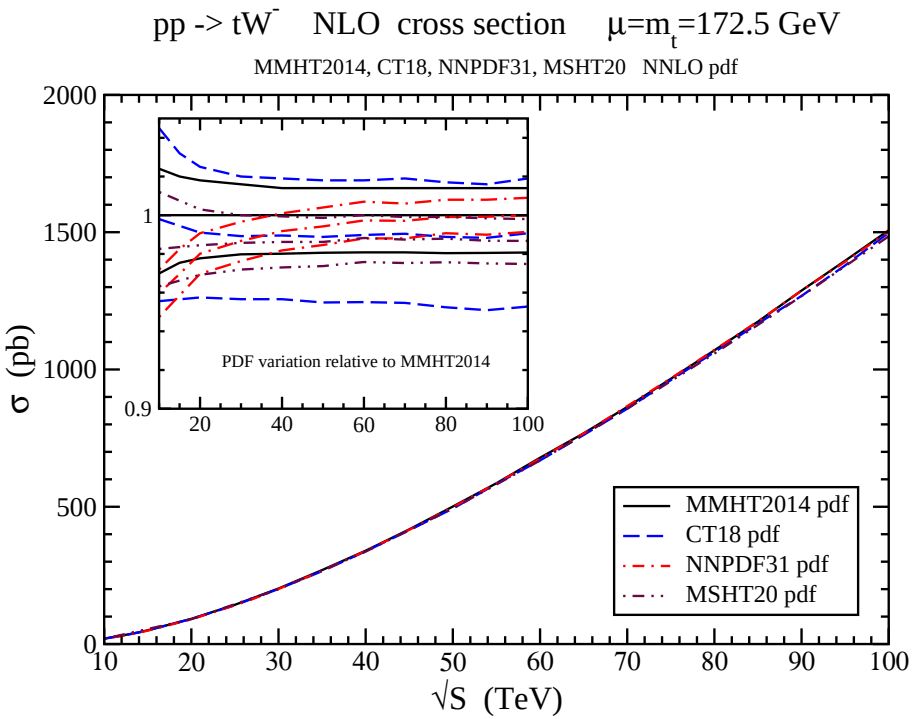
$$\Gamma_S^{(3)\,bg\to tW} = K_3\,\Gamma_S^{(1)\,bg\to tW}+\frac{1}{2}K_2C_FC_A(1-\zeta_3)+C_FC_A^2\left[-\frac{1}{4}+\frac{3}{8}\zeta_2-\frac{\zeta_3}{8}-\frac{3}{8}\zeta_2\zeta_3+\frac{9}{16}\zeta_5\right]$$

(same soft anomalous dimension for tZ' production)

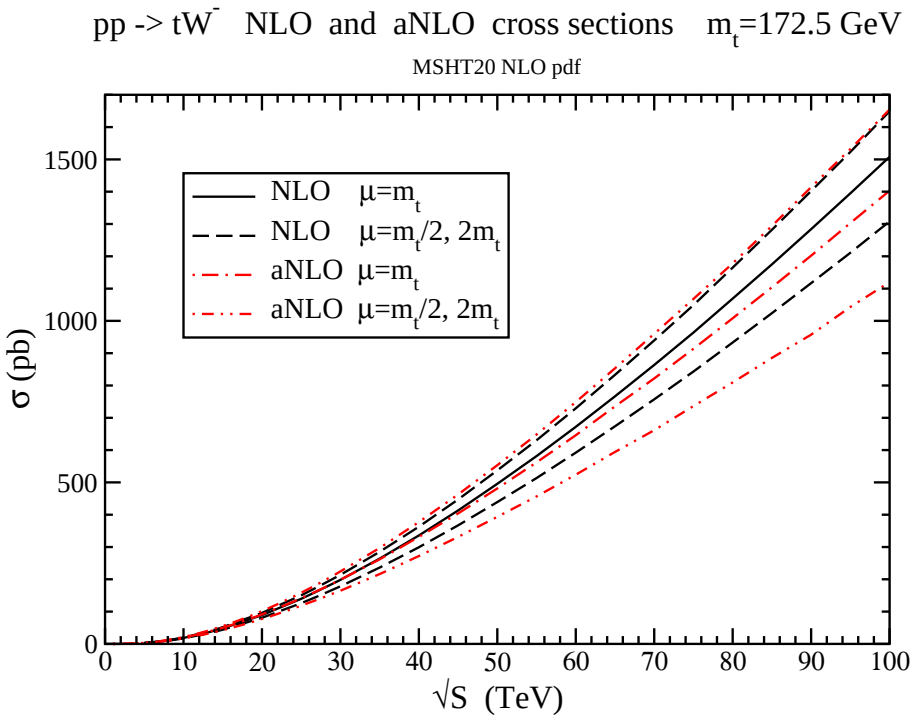
tW production at high-energy colliders

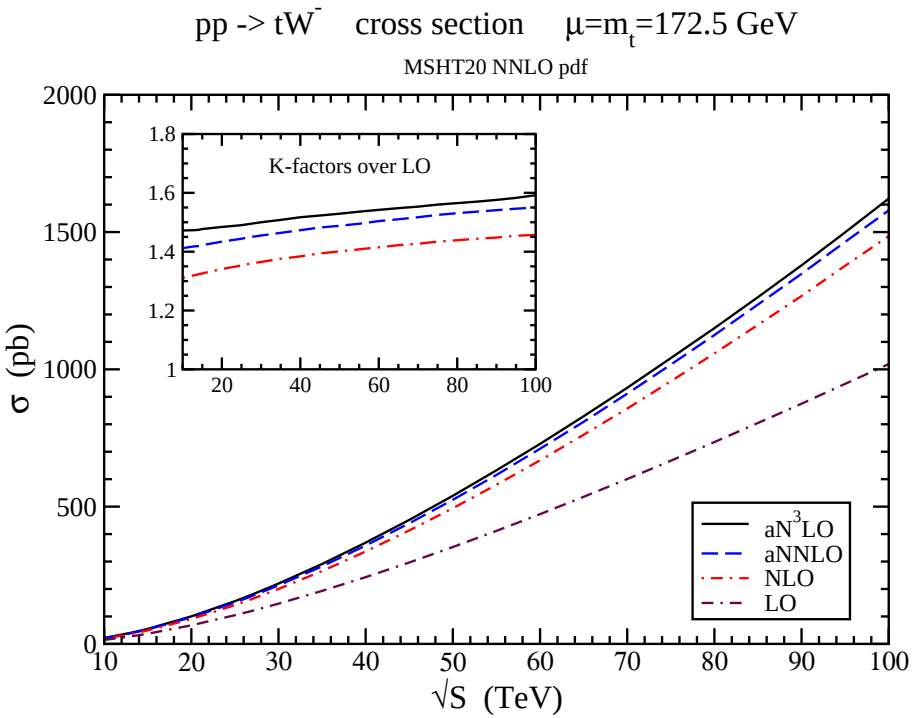
(with Nodoka Yamanaka, arXiv:2102.11300)





smaller pdf-set dependence with NNLO pdf

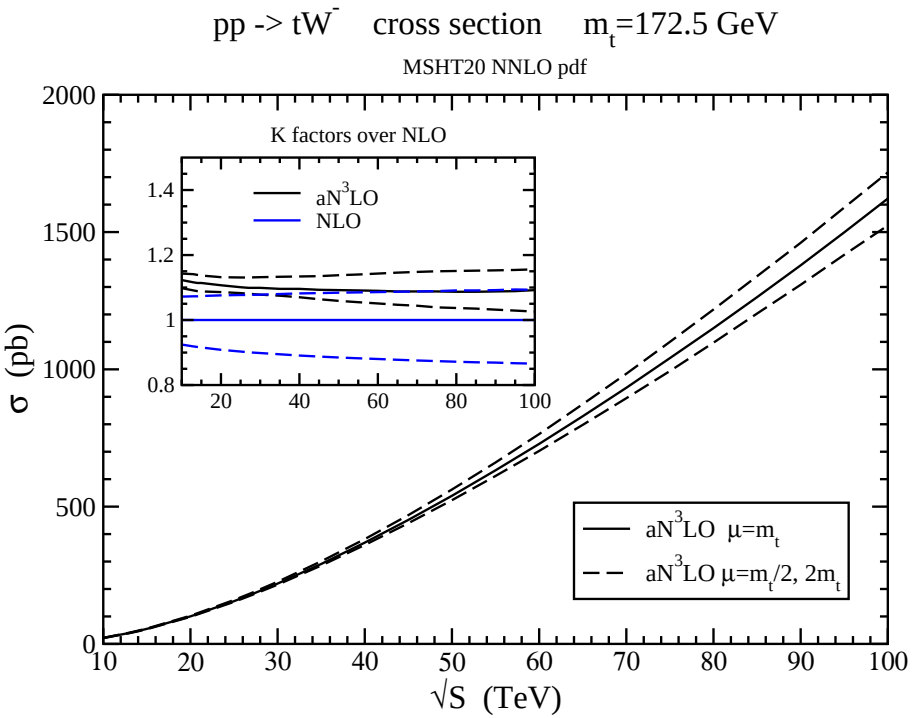


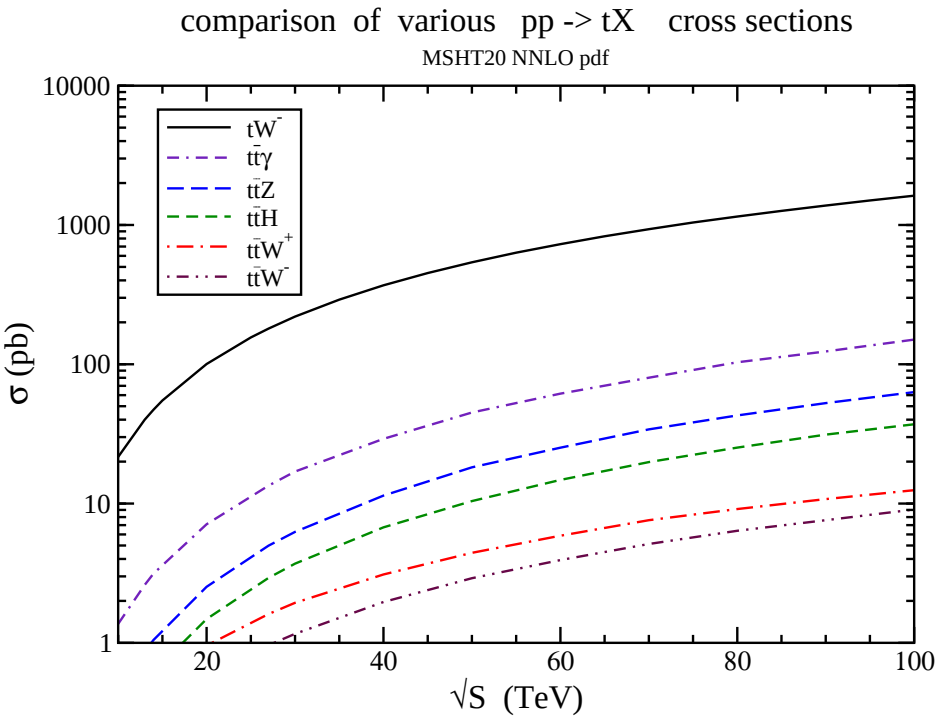


The aNLO cross section is a very good approximation to the complete NLO result for all forseeable collider energies
$\rightarrow$ the soft-gluon corrections are dominant

The aNNLO and aN^{3}LO corrections (at NNLL) are also significant

The aN^{3}LO cross section with scale and pdf (MSHT20) uncertainty is
at 13 TeV: $39.9 \pm 0.9^{+1.0}_{-0.7}$ **pb** **at 14 TeV** $47.1^{+1.1+1.1}_{-1.0-0.8}$ **pb**

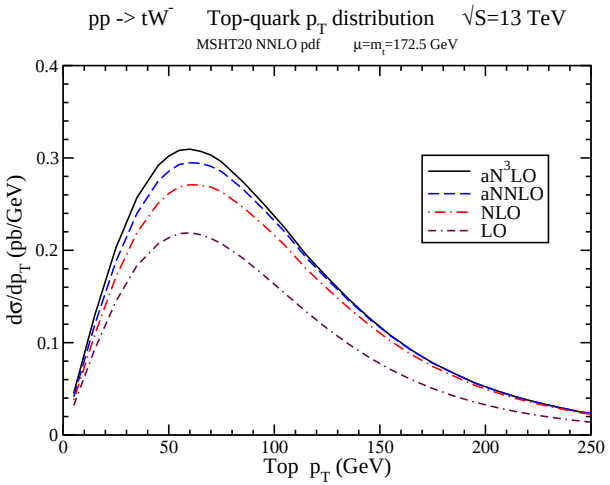


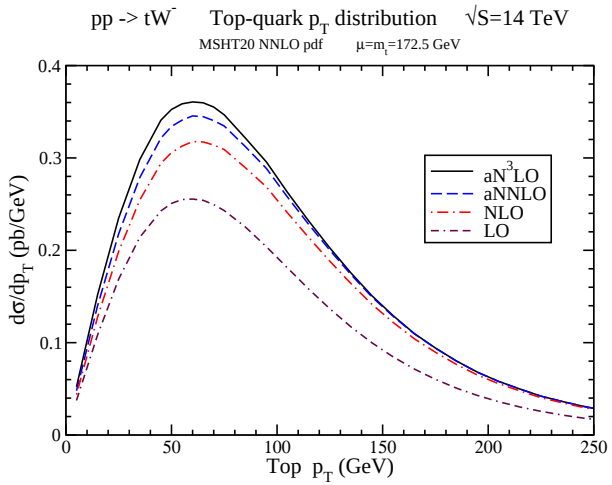


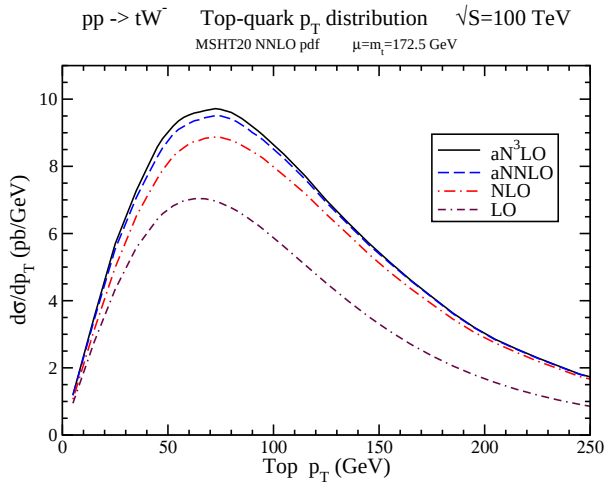
scale dependence at aN^{3}LO is reduced relative to NLO

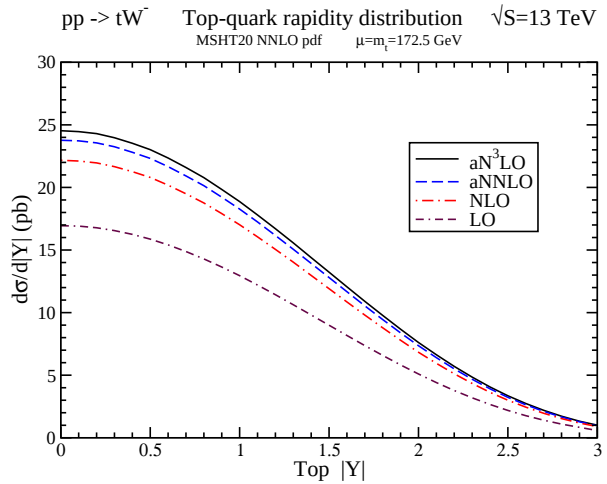
***tW* production cross sections are larger than for other top-quark processes with final-state electroweak and Higgs bosons**

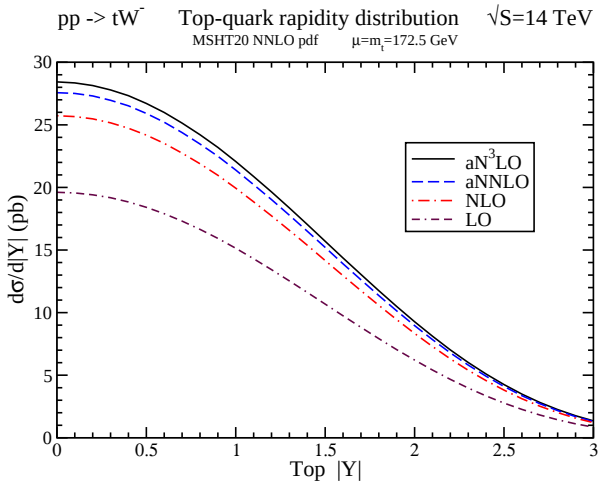
Top quark p_T and rapidity distributions in tW production

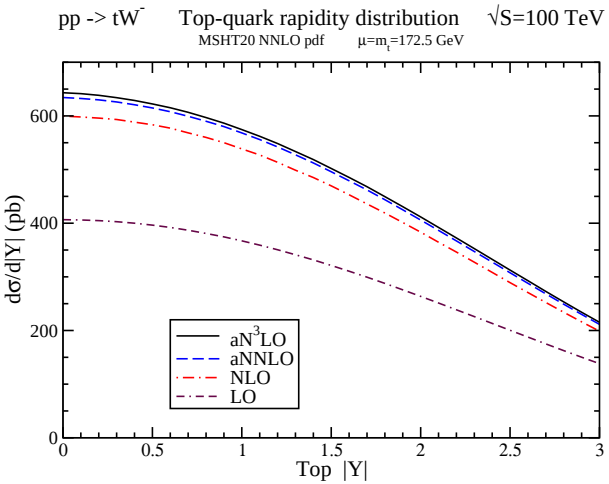






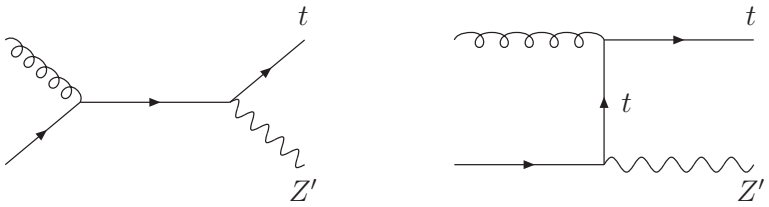






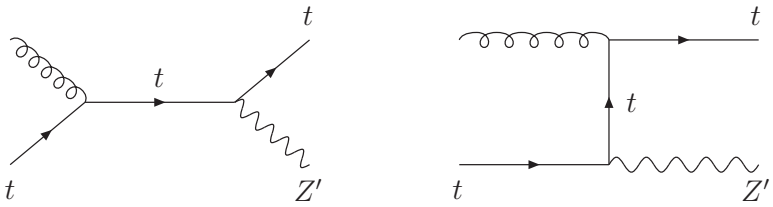
tZ' production in various models

(with Marco Guzzi, Eur. Phys. J. C 80, 467)



via anomalous t-u-Z' or t-c-Z' couplings

$$\mathcal{L}_{FCNC} = (\kappa_{tqZ'}/\Lambda)\, e\, \bar{t}\, \sigma_{\mu\nu}\, q\, F^{\mu\nu}_{Z'} + \text{h.c.}$$

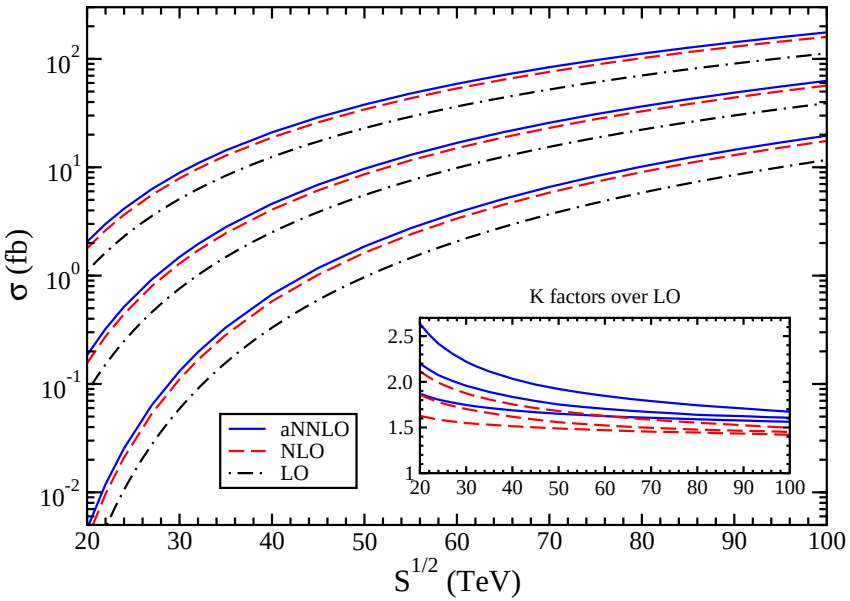


with initial-state top

$$\sum_{i=L,R} z_{t,i}\, g_{Z'}\, \bar{t}_i \gamma^\mu t_i Z'_\mu$$

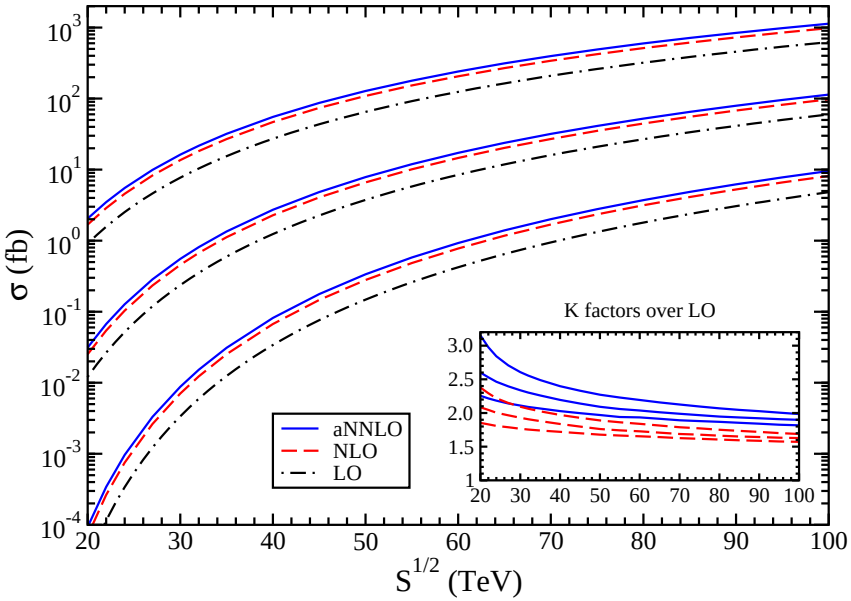
gu -> tZ´ in pp collisions $m_{Z'}$=3, 5, 8 TeV $k_{tuZ'}/\Lambda$=0.01/m_t

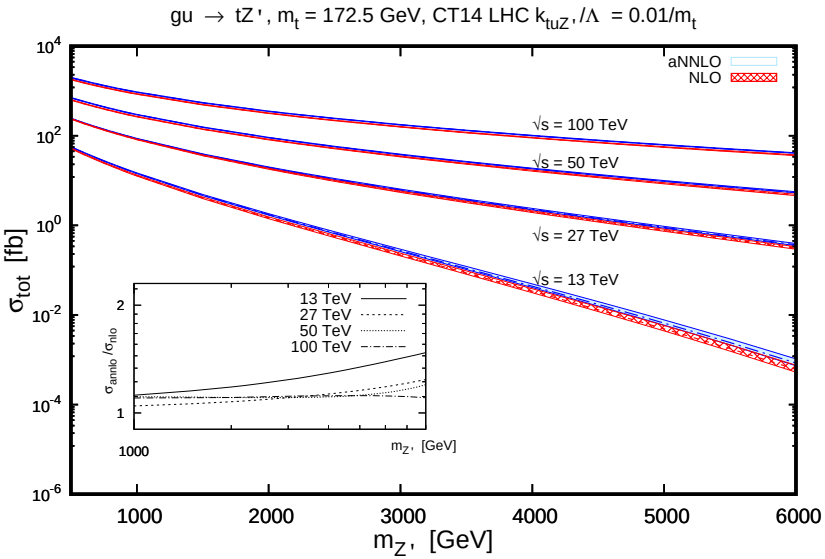
CT14 NNLO pdf $\mu=m_{Z'}$ m_t=172.5 GeV

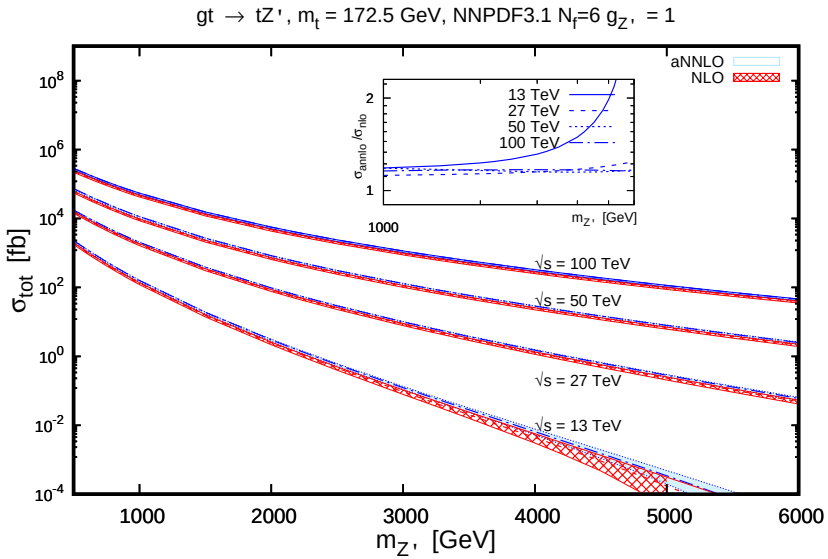


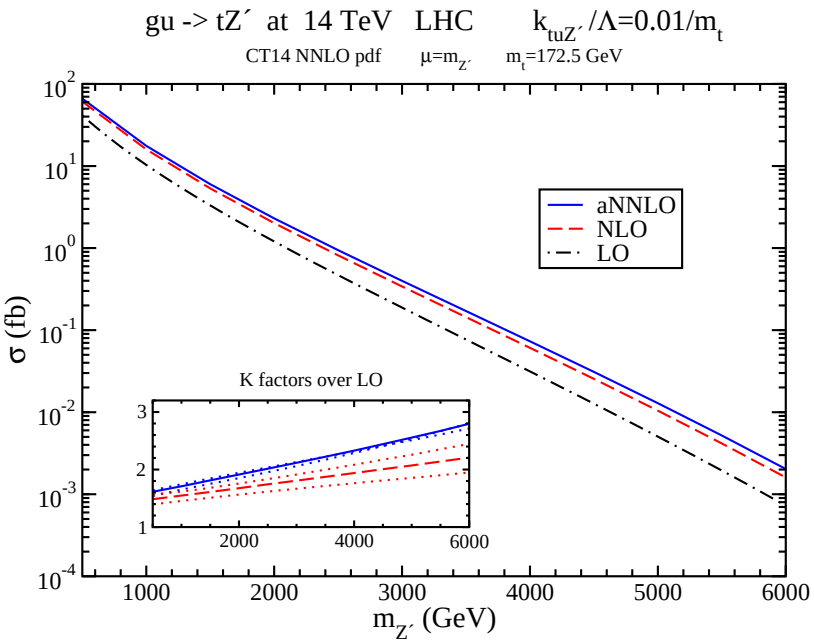
gt -> tZ´ in pp collisions $m_{Z'}$=3, 5, 8 TeV $g_{Z'}$=1

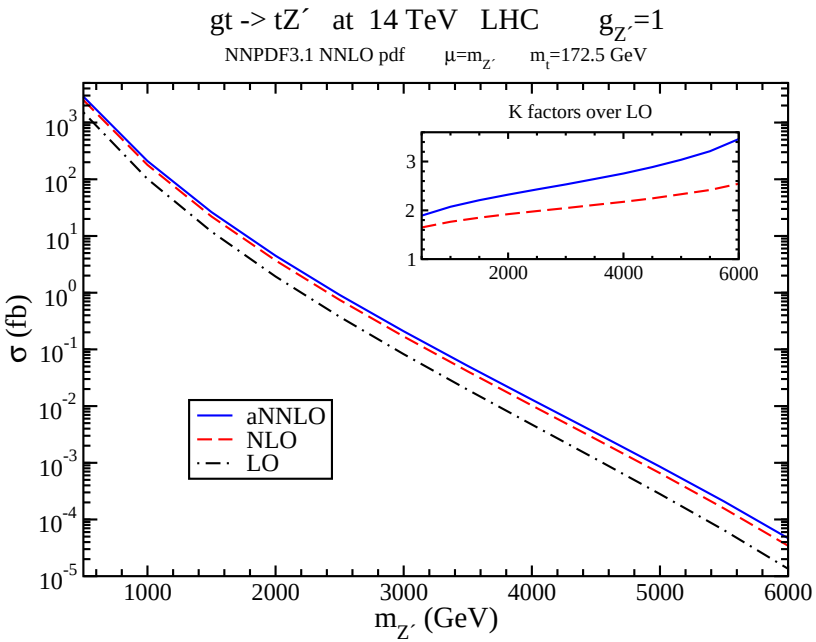
NNPDF3.1 NNLO pdf $\mu=m_{Z'}$ m_t=172.5 GeV

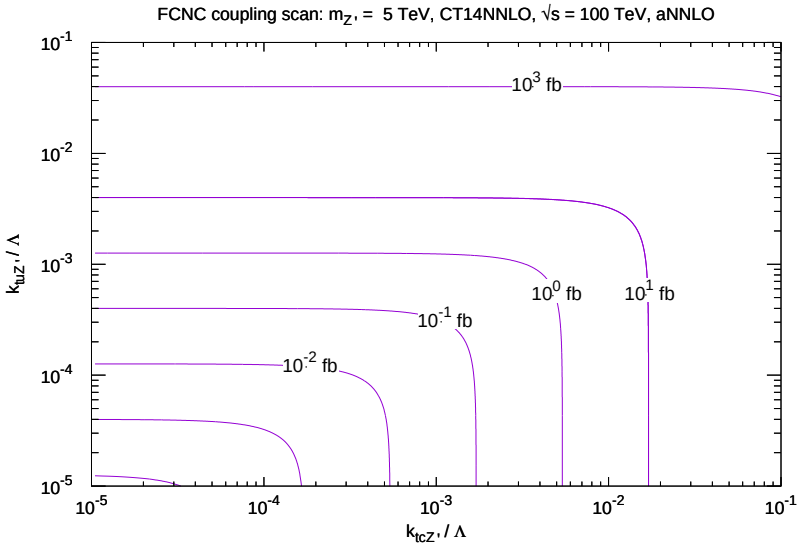


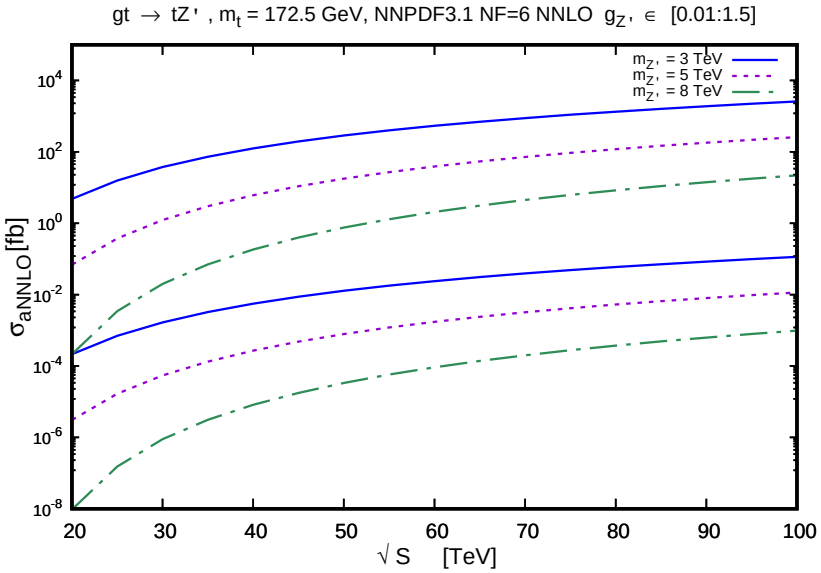

gu → tZ', m_t = 172.5 GeV, CT14 LHC k_tuZ'/Λ = 0.01/m_t
aNNLO
NLO
√s = 100 TeV
√s = 50 TeV
√s = 27 TeV
√s = 13 TeV
σ_tot [fb]
m_Z' [GeV]
13 TeV
27 TeV
50 TeV
100 TeV
σ_annlo /σ_nlo

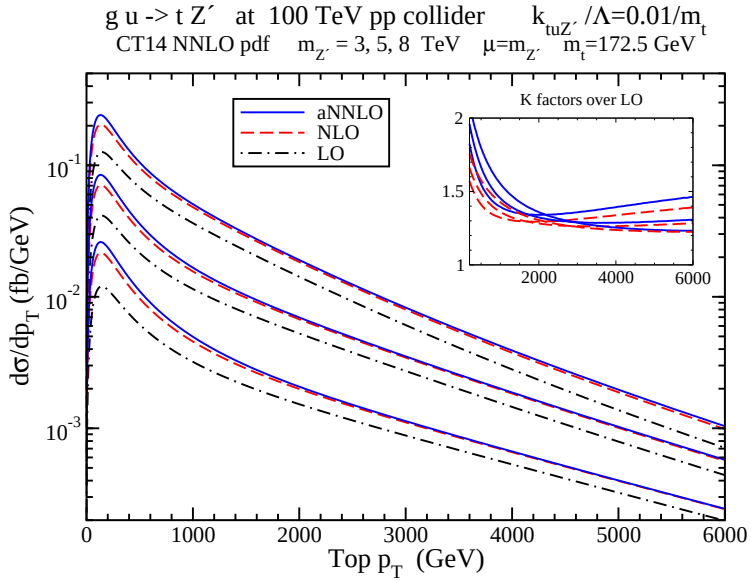

gt → tZ', m_t = 172.5 GeV, NNPDF3.1 N_f=6 g_Z' = 1
aNNLO
NLO
√s = 100 TeV
√s = 50 TeV
√s = 27 TeV
√s = 13 TeV
σ_tot [fb]
m_Z' [GeV]
13 TeV
27 TeV
50 TeV
100 TeV
σ_annlo /σ_nlo


gu -> tZ´ at 14 TeV LHC k_tuZ´/Λ=0.01/m_t
CT14 NNLO pdf μ=m_Z´ m_t=172.5 GeV
aNNLO
NLO
LO
K factors over LO
σ (fb)
m_Z´ (GeV)


gt -> tZ´ at 14 TeV LHC g_Z´=1
NNPDF3.1 NNLO pdf μ=m_Z´ m_t=172.5 GeV
K factors over LO
aNNLO
NLO
LO
σ (fb)
m_Z´ (GeV)


FCNC coupling scan: $m_{Z'}$ = 5 TeV, CT14NNLO, √s = 100 TeV, aNNLO
10^3 fb
10^0 fb
10^1 fb
10^{-1} fb
10^{-2} fb
$k_{tuZ'}/\Lambda$
$k_{tcZ'}/\Lambda$


gt → tZ', m_t = 172.5 GeV, NNPDF3.1 NF=6 NNLO $g_{Z'}$ ∈ [0.01:1.5]
$m_{Z'}$ = 3 TeV
$m_{Z'}$ = 5 TeV
$m_{Z'}$ = 8 TeV
σ_{aNNLO}[fb]
√ S [TeV]


g u -> t Z´ at 100 TeV pp collider $k_{tuZ'}/\Lambda$=0.01/m_t
CT14 NNLO pdf $m_{Z'}$ = 3, 5, 8 TeV μ=$m_{Z'}$ m_t=172.5 GeV
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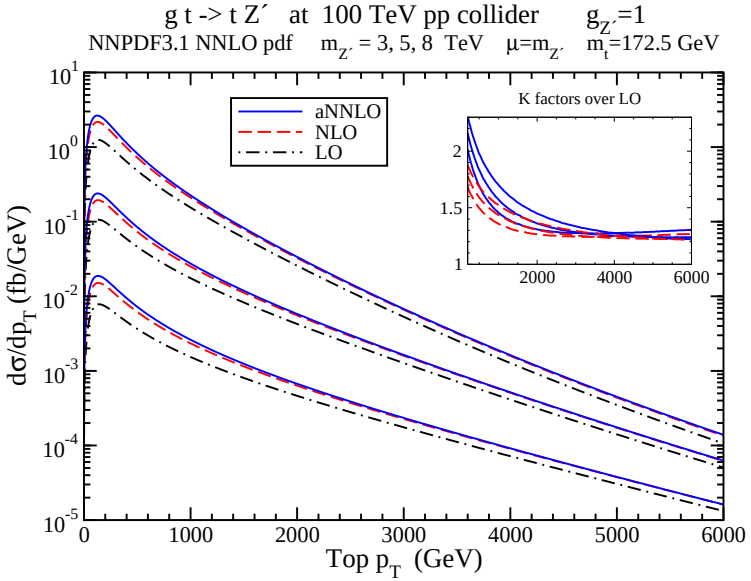
K factors over LO
$d\sigma/dp_T$ (fb/GeV)
Top p_T (GeV)


g t -> t Z´ at 100 TeV pp collider $g_{Z'}$=1
NNPDF3.1 NNLO pdf $m_{Z'}$ = 3, 5, 8 TeV μ=$m_{Z'}$ m_t=172.5 GeV
aNNLO
NLO
LO
K factors over LO
$d\sigma/dp_T$ (fb/GeV)
Top p_T (GeV)

Summary

- **soft-gluon corrections and resummation**
- **tW production at aN^{3}LO**
- **soft-gluon corrections are dominant**
- **tZ' production in various models**
- **high-order corrections are very significant**