tZ’ production at hadron colliders

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Intro/outline

- We study the production of a *top*-quark in association with a heavy extra *Z’* at hadron colliders in new physics models with and without flavor-changing neutral-current (FCNC) couplings.

- QCD soft-gluon resummation and threshold expansions used to calculate higher-order corrections for transverse-momentum distribution and total cross section.

- Impact of the uncertainties due to the structure of the proton and scale dependence.

Motivations

- HL-LHC and new generation facilities (e.g., FCC, SppC): new frontier of discovery

- Higher statistics: probe rare processes which may hint at or provide evidence of new physics

- Critical to identify/characterize particles with mass O(7-10) TeV if there

Motivations

$\mathrm{pp} \to tZ'$ is interesting:

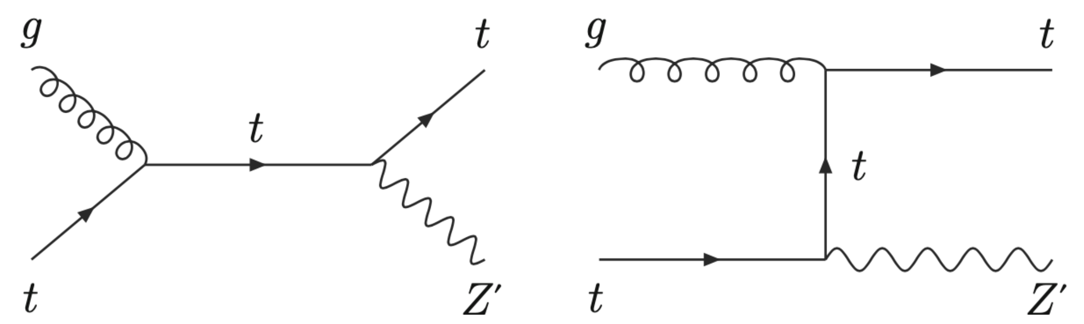
- kinematics of the final state and decay products relevant to investigate extensions of the Higgs sector (2HDM, SUSY, etc.), and of the EW sector with enlarged gauge symmetry.

- It can in principle be used to validate several BSM models

- Multiscale process with a non-trivial dynamics

- Can be generalized to any $\mathrm{pp} \to t + \ (Heavy)$

Non-trivial dynamics:



High energy reactions with $m_{Z'} \gg m_t$ Xsec affected by large (collinear) logarithms: $\alpha_s^n log^n\left(\frac{Q^2}{m_t^2}\right)$

where $Q \approx m_{Z'}$ (Dicus, Stelzer, Sullivan, Willenbrock PRD 1999)

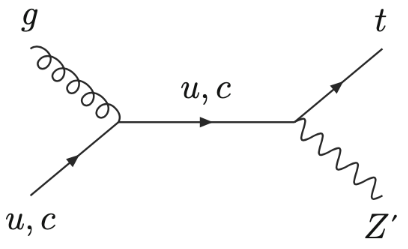
These logs need to be resummed using DGLAP evolution defining a top-quark PDF.
When $m_{Z'} \gg m_t \rightarrow$ top quark essentially massless: active flavor inside the proton.

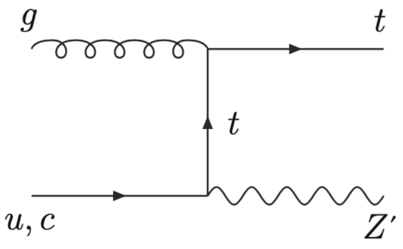
Factorization schemes with different number of flavors with consistent treatment of the top quark as a massless degree of freedom at high energies (Dawson, Ismail, Low PRD 2014; Han, Sayre, Westhoff JHEP2015)

Based on QCD factorization with initial-state heavy flavors, studied in previous literature (Aivazis, Collins, Olness, Tung PRD 1994; Collins PRD 1998; Kramer, Olness, Soper PRD 2000; Tung, Kretzer, Schmidt J.Phys. G 2002; M.G. Nadolsky, Lai, Yuan PRD 2012)

Effective Lagrangian contributions for two BSM models

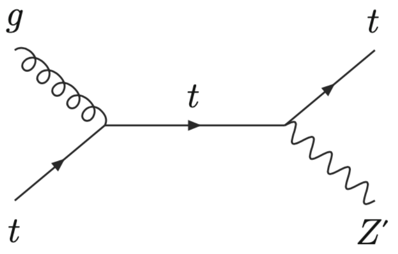
$$\mathcal{L}_{FCNC} = \frac{1}{\Lambda}\kappa_{tqZ'}\, e\, \bar{t}\, \sigma_{\mu\nu}\, q\, F^{\mu\nu}_{Z'} + h.c.,$$

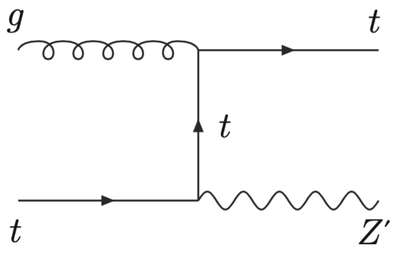




FCNC term in the Lagrangian includes anomalous couplings of a t, q pair to the Z'.
Λ effective new physics TeV-range scale.
We only consider tensor interactions here.
tZ' production @NLO with vector interactions previously studied (Adelman, Ferrando, White, JHEP 2013)

$$\mathcal{L}_{int} = \bar{t}_L N_L^{Z'} \gamma^\mu t_L Z'_\mu + \bar{t}_R N_R^{Z'} \gamma^\mu t_R Z'_\mu$$





Lagrangian for the top-quark sector in a string-inspired models (Corianò, Faraggi, M.G. PRD 2008; Faraggi, M.G., EPJC 2015)

$$N_L^{Z'} = -i\left(-g\cos\theta_W T_{3,L}\varepsilon + g_Y \sin\theta_W \frac{Y_{t,L}}{2}\varepsilon + g_{Z'}\frac{z_{t,L}}{2}\right)$$

$$N_R^{Z'} = -i\left(g_Y \sin\theta_W \frac{Y_{t,R}}{2}\varepsilon + g_{Z'}\frac{z_{t,R}}{2}\right)$$

Higher order corrections and soft gluons

Factorized cross section

$$S^2 \frac{d^2\sigma(S,T_1,U_1)}{dT_1\, dU_1} = \sum_{i,j=q,g} \int_{x_1^-}^1 \frac{dx_1}{x_1} \int_{x_2^-}^1 \frac{dx_2}{x_2} f_{i/p_1}(x_1,\mu_F^2) f_{j/p_2}(x_2,\mu_F^2) \times \hat{\sigma}_{ij\to tZ'}(s,t_1,u_1,m_t^2,m_{Z'}^2,\mu_F^2,\alpha_s(\mu_R^2))$$

Mandelstam variables at hadronic level $S=(P_1+P_2)^2\,,\quad T=(P_1-p_t)^2\,,\quad U=(P_2-p_t)^2\,,\quad S_4=S+T+U-m_t^2-m_{Z'}^2$

$$x_1^- = -\frac{U_1}{S+T_1}\,,\quad x_2^- = -\frac{x_1T_1}{x_1S+U_1} \qquad T_1=-\sqrt{S}\; m_T e^{-y}\,,\quad U_1=-\sqrt{S}\; m_T e^{y} \qquad m_T=\sqrt{p_T^2+m_t^2}$$

Soft gluons and refactorization of the hard-scattering Xsec $\hat{\sigma}(N)=\int (ds_4/s)\; e^{-Ns_4/s}\hat{\sigma}(s_4)$ Laplace transf.

$$\frac{d^2\hat{\sigma}_{gq\to tZ'}(N,\epsilon)}{dt\,du} = H_{gq\to tZ'}\left(\alpha_s(\mu)\right) S_{gq\to tZ'}\left(\frac{m_t}{N\mu},\alpha_s(\mu)\right) \prod_{i=g,q} J_i\left(N,\mu,\epsilon\right)$$

$s_4=s+t+u-m_t^2-m_{Z'}^2$

distance from threshold

$s_4=0$

Hard function
(short distance effects)

Soft function
(non-collinear soft gluons)

Jet function (dynamics of partons moving collinearly to the incoming partons)

Higher order corrections and soft gluons

The soft function obeys an RG equation

$$\left(\mu\frac{\partial}{\partial\mu}+\beta(g_s,\epsilon)\frac{\partial}{\partial g_s}\right) S_{gq\to tZ'} = -2\, S_{gq\to tZ'}\,\Gamma^S_{gq\to tZ'}$$

$$g_s^2 = 4\pi\alpha_s, \quad \beta(g_s,\epsilon) = -g_s\epsilon/2+\beta(g_s)$$

$\beta(g_s)$ = QCD beta-function

$$\Gamma^S_{gq\to tZ'} = \sum_{n=1}^{\infty}(\alpha_s/\pi)^n \Gamma^{S\,(n)}_{gq\to tZ'}$$

Soft anomalous dimension: controls the evolution of *S*

(Kidonakis, Sterman NPB 1997; Kidonakis PRL 2009; Kidonakis PRD 2019…)

Resummed Xsec

$$\frac{d^2\hat{\sigma}^{\rm resum}_{gq\to tZ}(N)}{dt\,du} = \exp\left[\sum_{i=g,q} E_i(N_i)\right] H_{gq\to tZ'}\left(\alpha_s(\sqrt{s})\right) S_{gq\to tZ'}\left(\alpha_s(\sqrt{s}/\tilde{N}')\right)\times\exp\left[2\int_{\sqrt{s}}^{\sqrt{s}/\tilde{N}'}\frac{d\mu}{\mu}\,\Gamma^S_{gq\to tZ'}\left(\alpha_s(\mu)\right)\right]$$

Upon expanding the resummed cross section to fixed order and inverting from the transform moment space back to momentum space, the logarithms of *N* produce “plus” distributions of logarithms of $s_4/m^2_{Z'}$, . The highest power of these logs is 1 at NLO and 3 at NNLO

$$\frac{d^2\hat{\sigma}_{gq\to tZ'}}{dt\,du} = \hat{\sigma}_0\frac{\alpha_s(\mu_R^2)}{\pi}\left\{A_{1,2}\left[\frac{\ln(s_4/m^2_{Z'})}{s_4}\right]_+ + A_{1,1}\left[\frac{1}{s_4}\right]_+ + A_{1,0}\delta(s_4)\right\}$$

$$+\,\hat{\sigma}_0\frac{\alpha_s^2(\mu_R^2)}{\pi^2}\left\{A_{2,3}\left[\frac{\ln^3(s_4/m^2_{Z'})}{s_4}\right]_+ + A_{2,2}\left[\frac{\ln^2(s_4/m^2_{Z'})}{s_4}\right]_+ + A_{2,1}\left[\frac{\ln(s_4/m^2_{Z'})}{s_4}\right]_+ + A_{2,0}\left[\frac{1}{s_4}\right]_+\right\}$$

Born

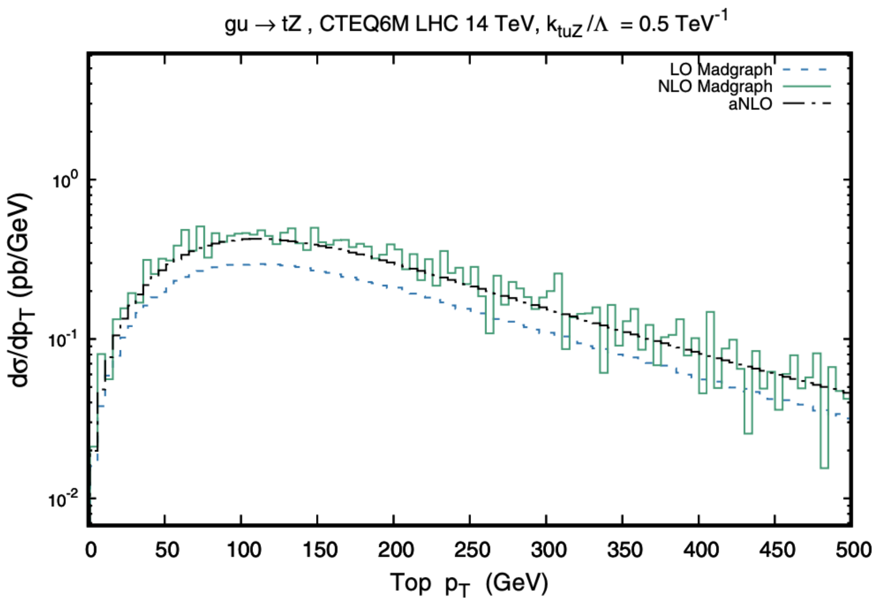
aNNLO

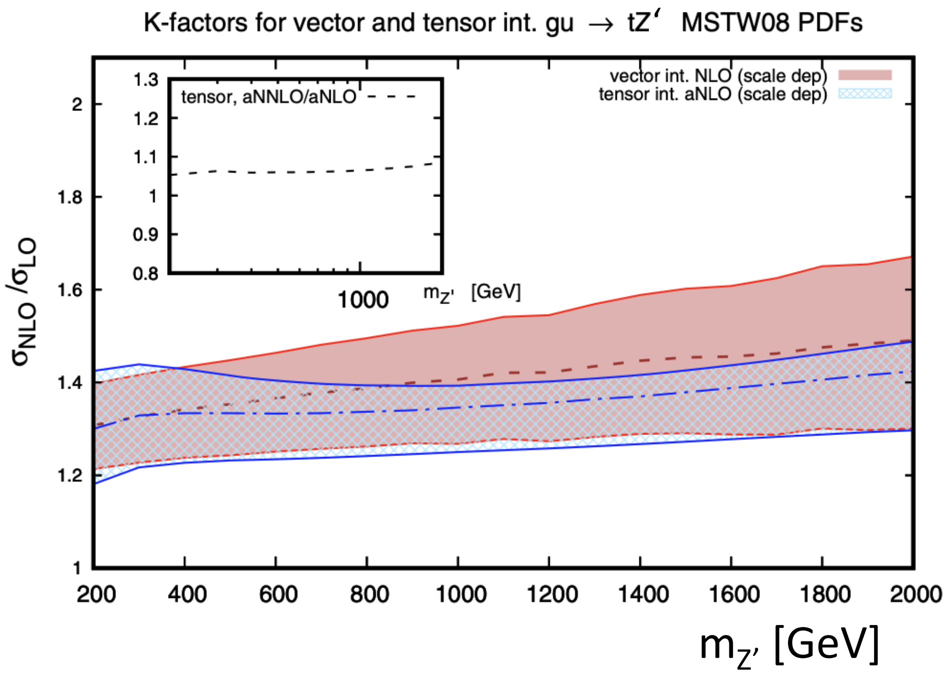
A few cross checks

Table 1 Total rate comparison for $gu \to tZ$ at the LHC 14 TeV: aNLO vs NLO from Ref. [50]. The cross section σ_0 is the default central value obtained using the central scale choice $\mu = m_Z + m_t$, i.e. $\sigma_0 = \sigma(\mu = m_Z + m_t)$. The scale dependence is obtained by varying μ up and down by a factor of 2, i.e. $(m_Z+m_t)/2 \le \mu \le 2(m_Z+m_t)$. CTEQ6M NLO PDFs [51] are used

(Li, Zhang, Li, Gao, Zhu PRD 2011)

σ_0^{aNLO}	σ_0^{NLO} (Ref. [50])	$(\sigma(\mu)/\sigma_0)_{\mathrm{aNLO}}$	$(\sigma(\mu)/\sigma_0)_{\mathrm{NLO}}$ (Ref. [50])
22.55 pb	22.5 pb	0.912 $\mu=2(m_Z+m_t)$ 1.103 $\mu=(m_Z+m_t)/2$	0.913 $\mu=2(m_Z+m_t)$ 1.112 $\mu=(m_Z+m_t)/2$





Right Figure: NLO K -factors for top FCNC with vector interactions and the aNLO K-factors for top FCNC with tensor interactions for the gu → t Z′ channel at the LHC at 7 TeV. Scale variation refers to (m Z ′ + mt)/4 ≤ μ ≤ mZ′ + mt. The inset plot also shows the aNNLO K- factors.

aNNLO matched to MadGraph5 NLO

- We match our aNNLO prediction to the exact NLO theory at fixed order in QCD. Our phenomenological results are shown at NLO and at matched aNNLO.

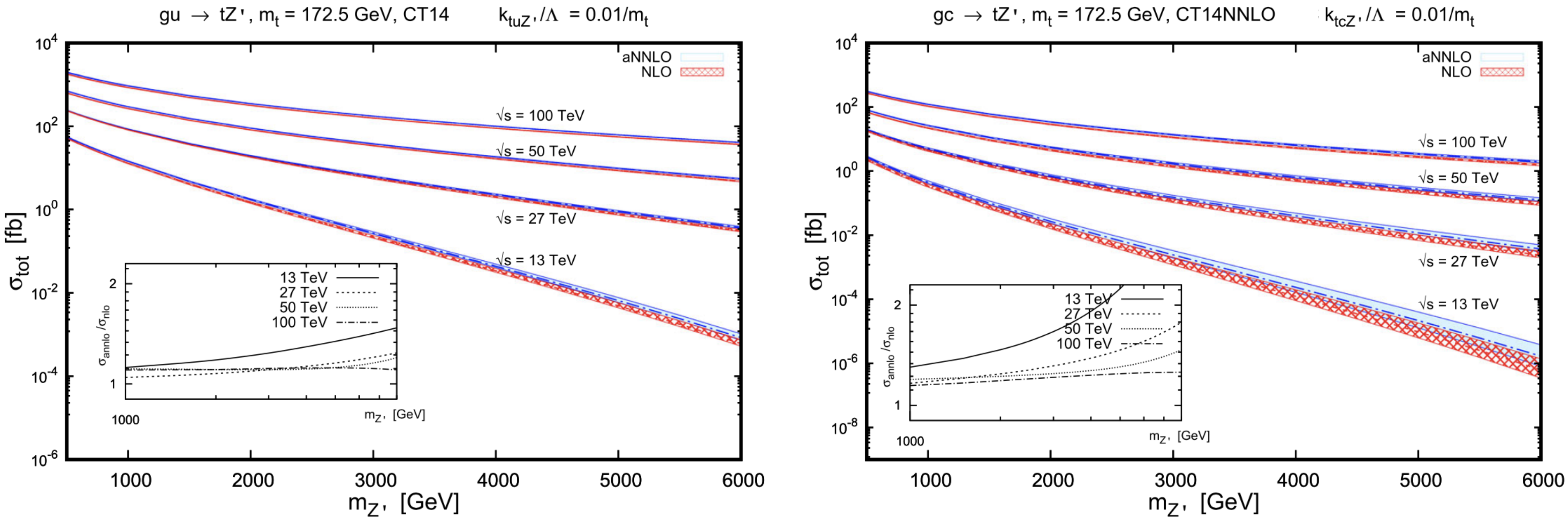
- The NLO fixed order theory predictions are obtained with MadGraph5_aMC@NLO- v2.7.2: used for total rate and the top-quark *pT* distribution. (Degrande, Maltoni, Wang, Zhang PRD 2015, G. Durieux, F. Maltoni and C. Zhang PRD 2015)

- The approximate aNNLO theory prediction is obtained by matching to the NLO as

$$\sigma_{aNNLO} = \left[\hat{\sigma}_{LO} + \hat{\sigma}_{NLO} + \hat{\sigma}_{aNNLO}\right]_{ij} \otimes f_i^{NNLO} \otimes f_j^{NNLO}$$

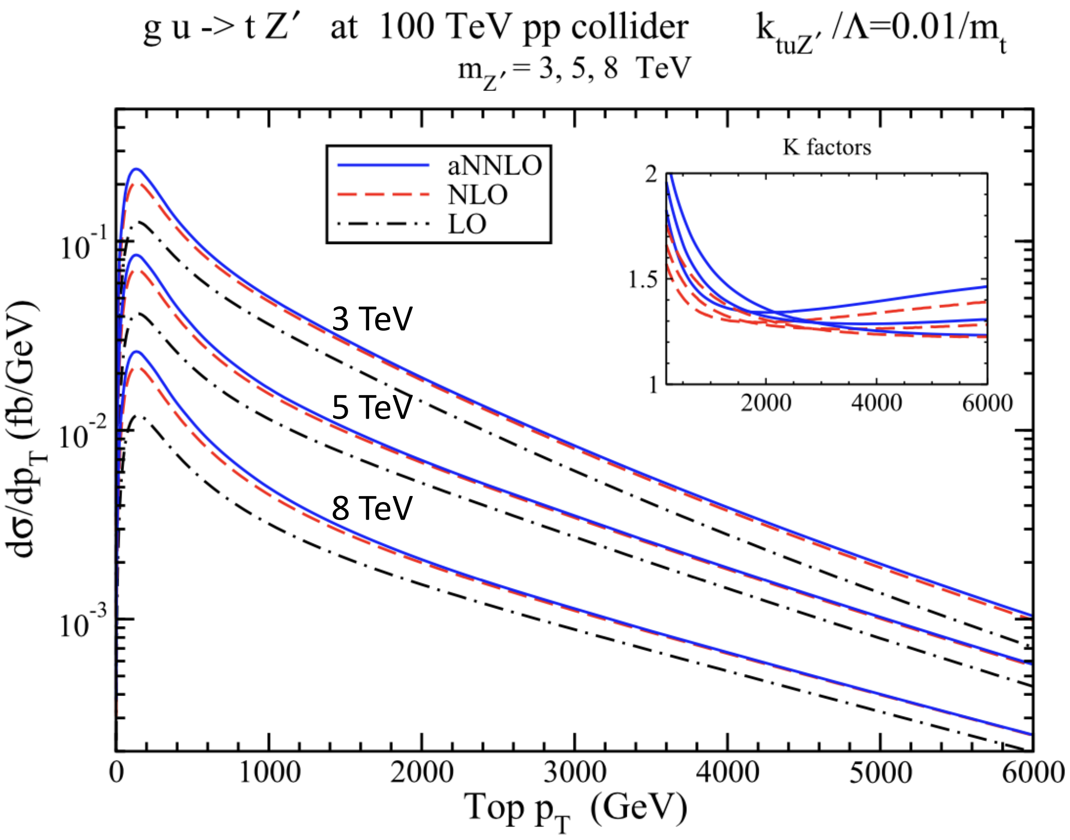
Phenomenological Results

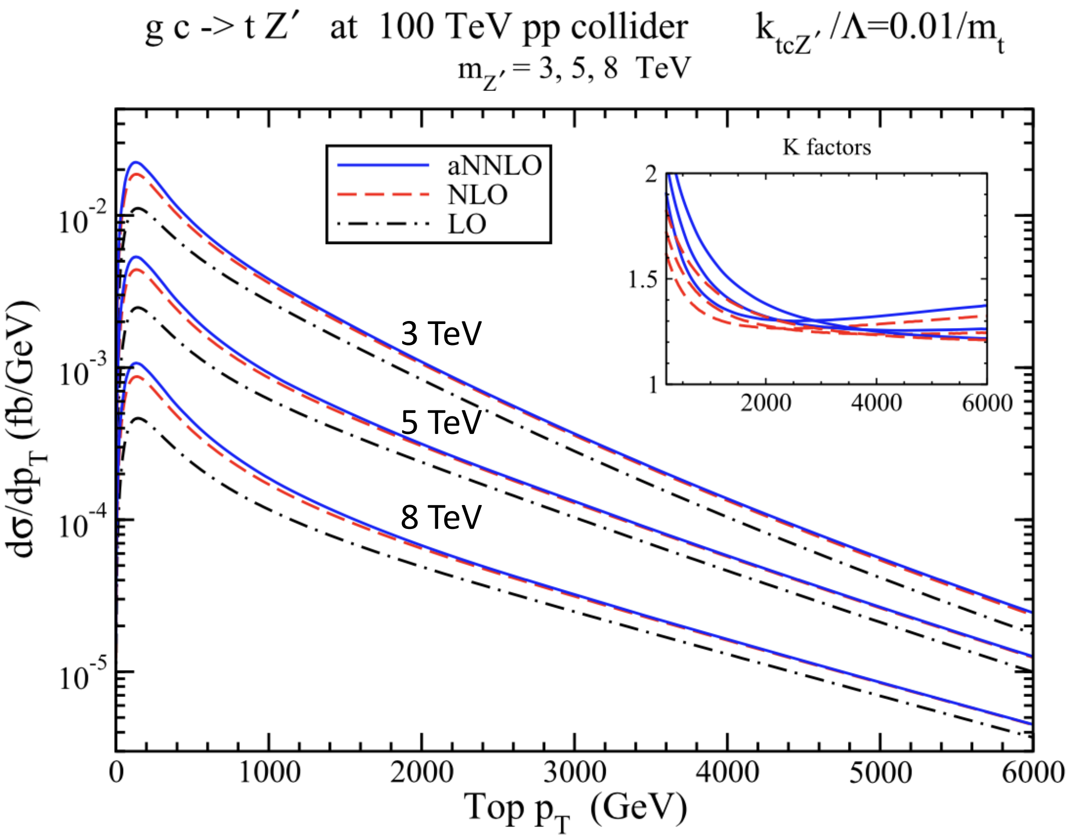
pp→ tZ' with FCNC total Xsec results at various center of mass energies for different $m_{Z'}$ values



aNNLO results obtained with CT14NNLO PDFs @68% C.L.; NLO results obtained with CT14NLO PDFs @68% C.L.

pp→ tZ' with FCNC top-pT spectrum at future collider energies for different $m_{Z'}$ values

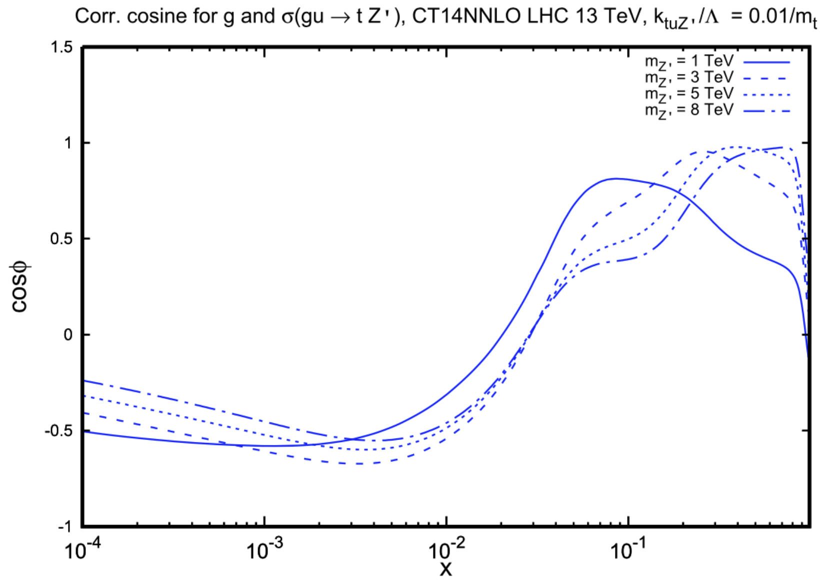


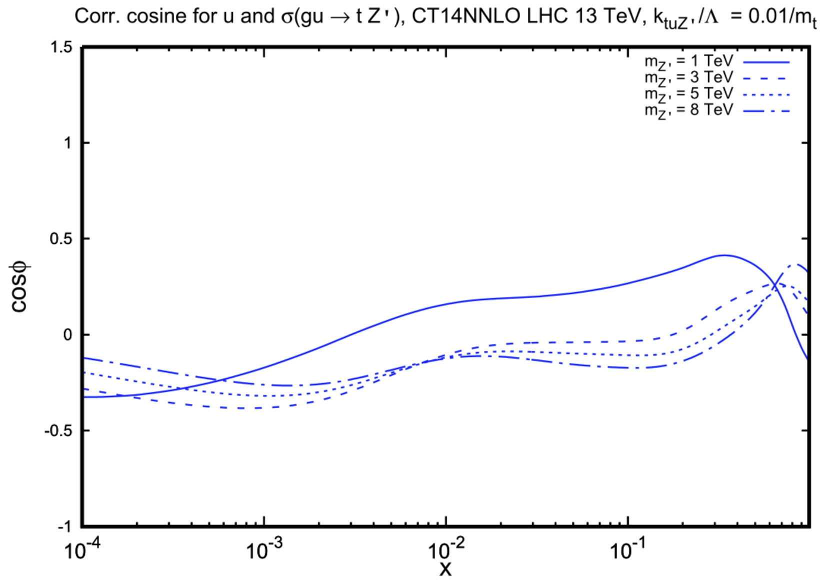


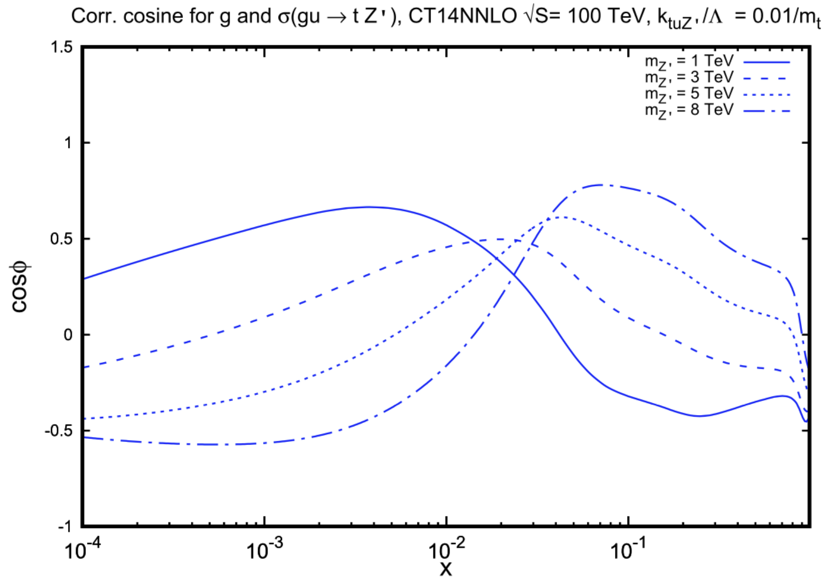
Results obtained with CT14NNLO PDFs

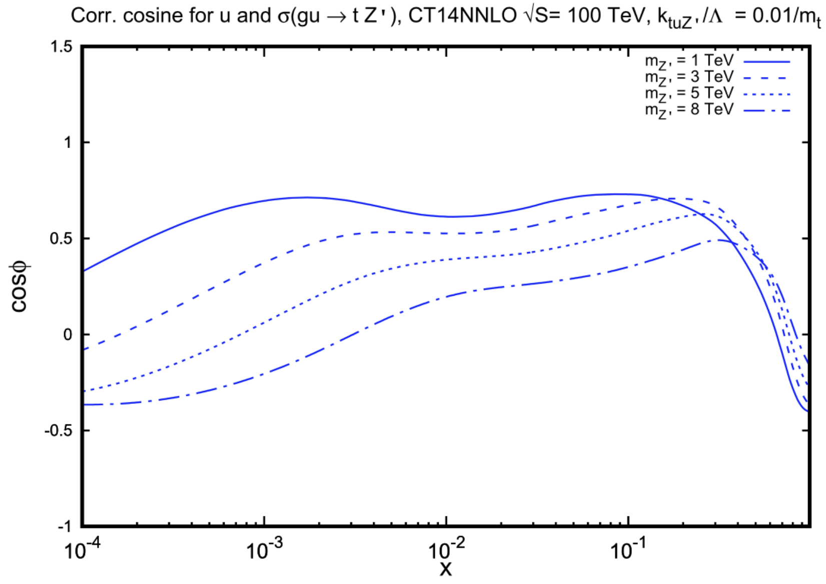
Inset plots: NLO/LO and aNNLO/LO K-factors

Cross section and PDF correlations





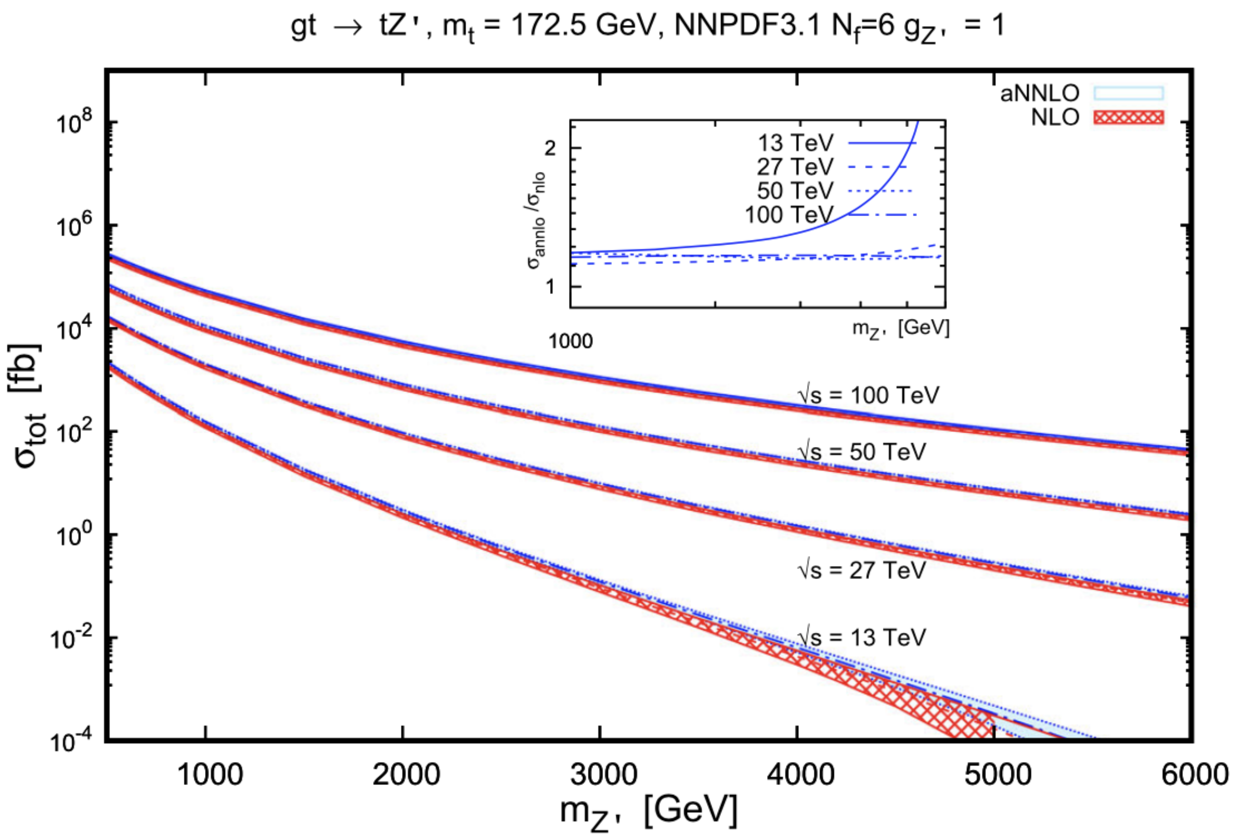


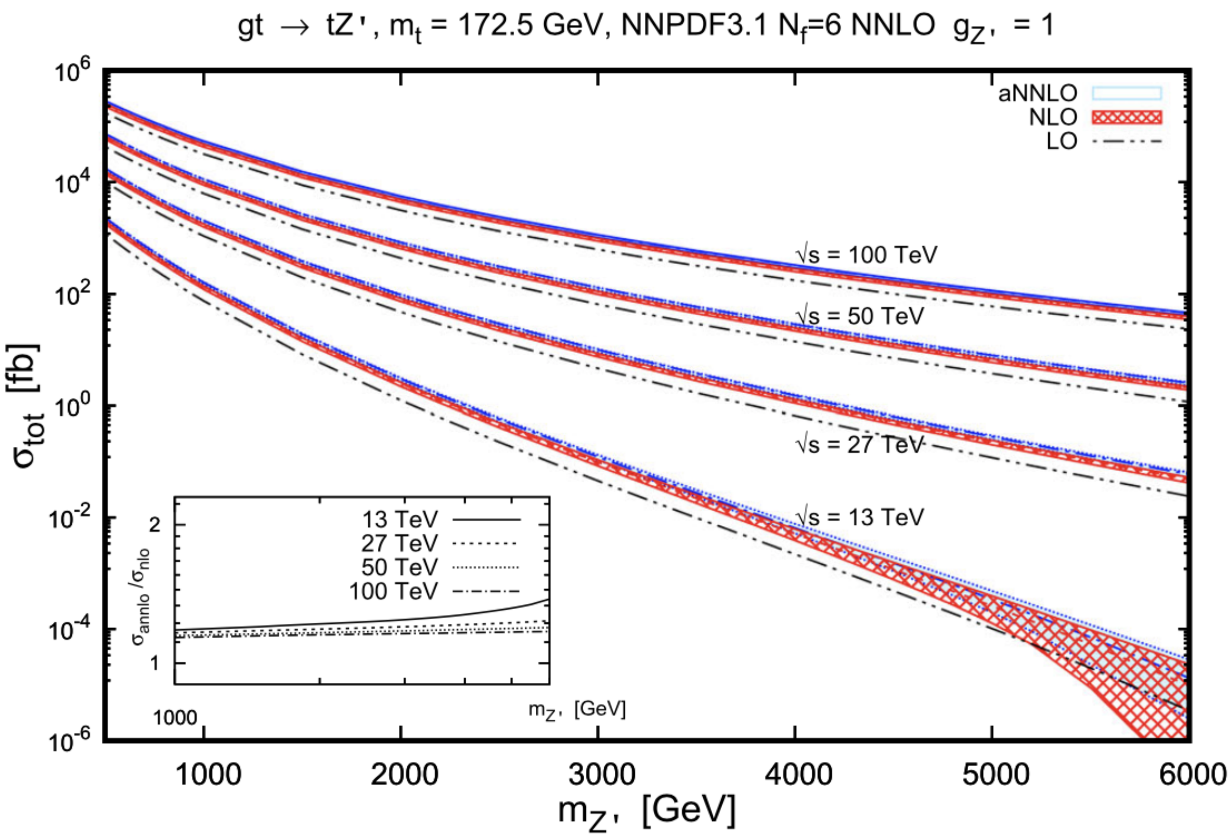


PDF correlations: they give us information about the kinematic region in which PDFs are probed and for example, they give us indication of the impact of the gluon at different values of the momentum fraction *x*.

In order to set tighter constraints on *Z'*s models it is important to understand how PDF uncertainties come into play and how to improve their precision through dedicated QCD global analyses.

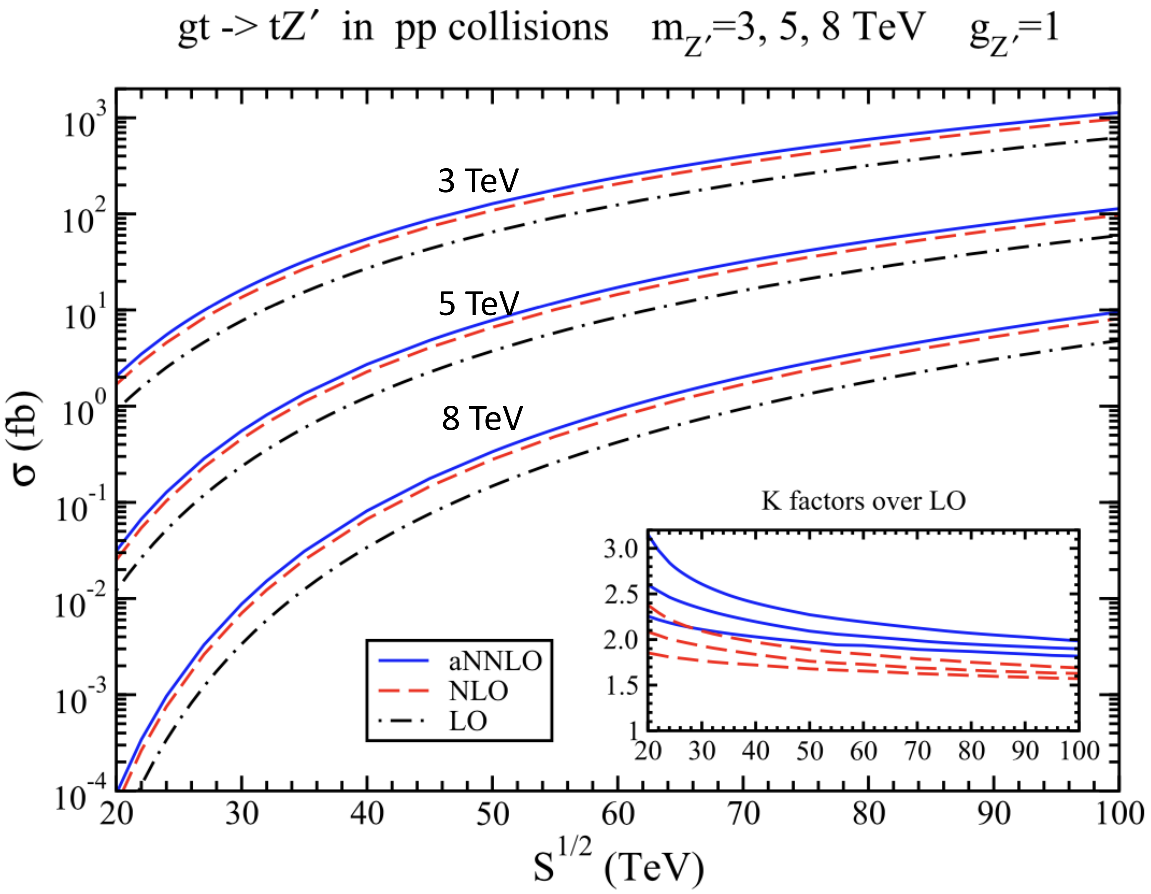
pp→ tZ' in string-inspired models: total Xsec results at various center of mass energies for different $m_{Z'}$ values

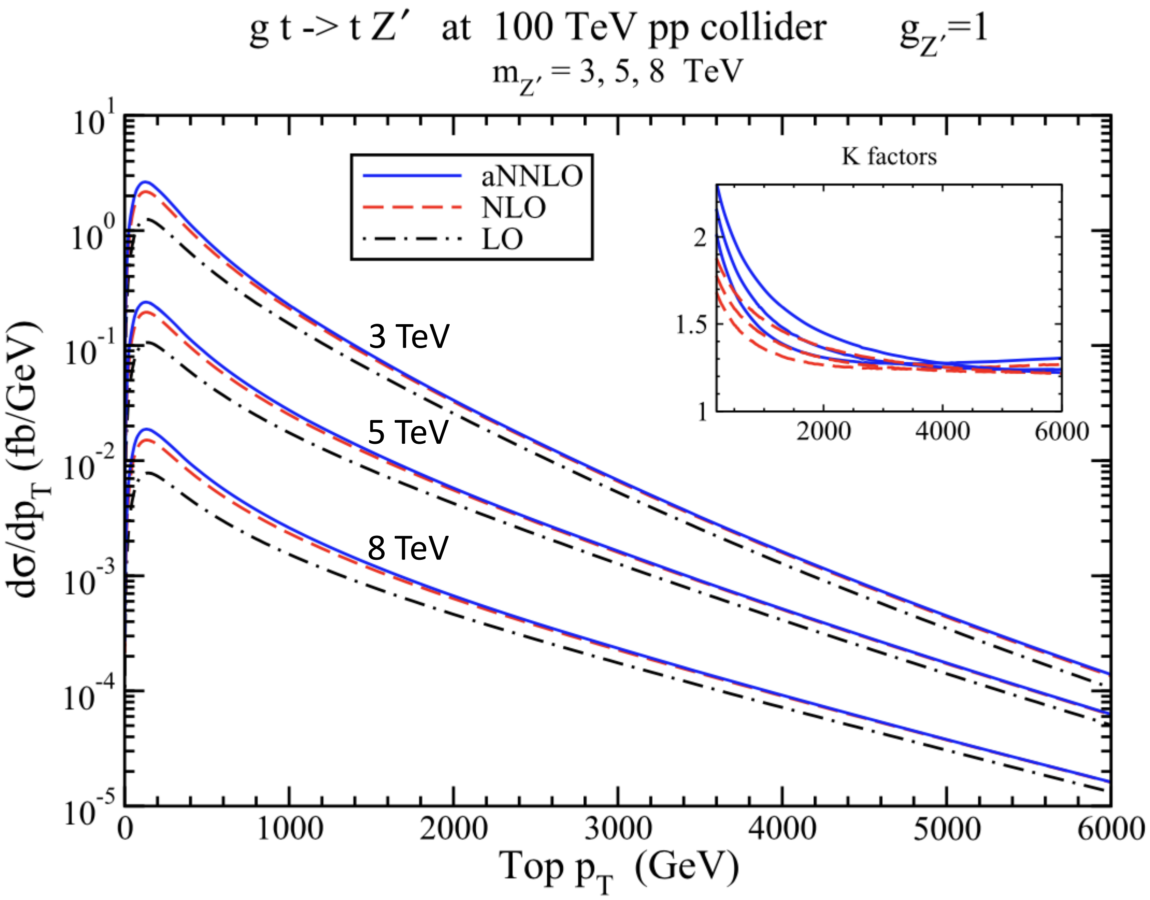




aNNLO results obtained with NNPDF3.1NNLO Nf=6 PDFs @68% C.L.; NLO results obtained with NNPDF3.1NLO Nf=6

pp→ tZ' in string-inspired models: total Xsec results vs center of mass energy for different $m_{Z'}$ values and top-pT spectrum





Results obtained with NNPDF3.1NNLO Nf=6 PDFs

Inset plots: NLO/LO and aNNLO/LO K-factors

Summary and Conclusion

- We have studied tZ' production in various BSM models at hadron colliders. We performed a phenomenological QCD analysis where we scrutinized tZ' production in the presence of FCNC and in the case in which the extra Z' is generated within a low-energy realization of string theory models.

- We have calculated theoretical predictions for cross sections and top-quark *pT* distributions that include higher-order soft-gluon corrections.

- Theory predictions obtained at aNNLO in QCD by extending the soft-gluon resummation formalism to the case in which a top quark is produced in association with a heavy neutral vector boson in *pp* collisions at energies relevant for future new-generation hadron colliders like FCC-hh and SppC.

- We have found that QCD corrections due to soft-gluon emissions are considerable and need to be included in future precision studies.

- This can in principle be applied to $\mathrm{pp} \rightarrow t + \ (Heavy)$

BACK UP

Additional results: scale and PDF uncertainties

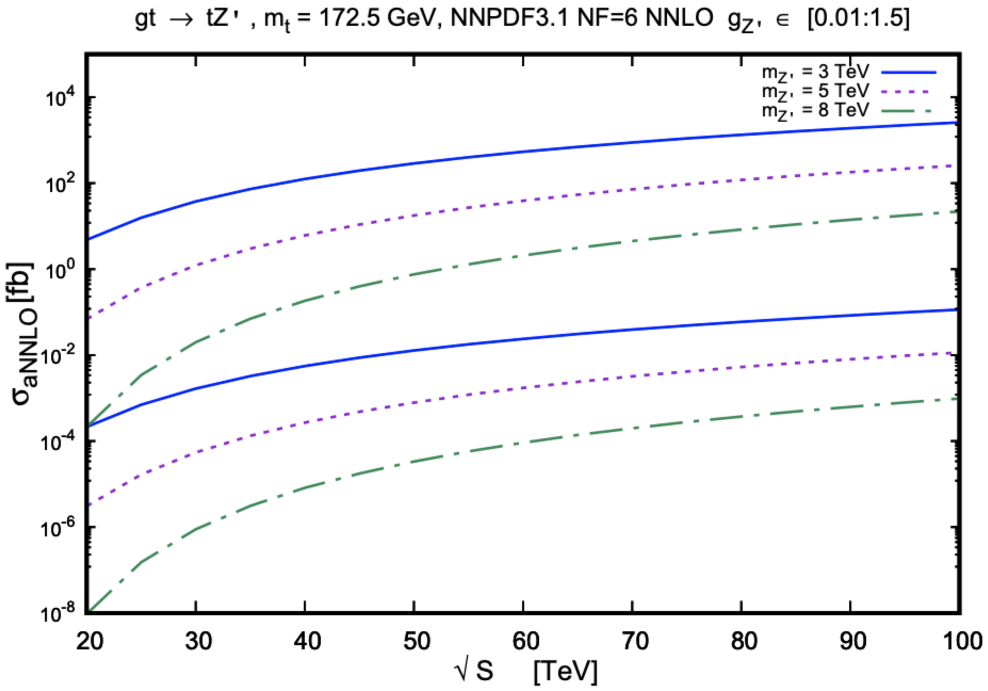
Table 2 aNNLO cross sections and aNNLO/LO K-factors for $gu \to tZ'$ with $k_{tuZ'}/\Lambda = 0.01/m_t$ and $m_t = 172.5$ GeV at 13 TeV LHC collider energy. The CT14NNLO PDF uncertainties are calculated at the 68% C.L. The scale uncertainties are obtained by taking up and down variations of the factorization scale μ, $m_{Z'}/2 < \mu < 2m_{Z'}$

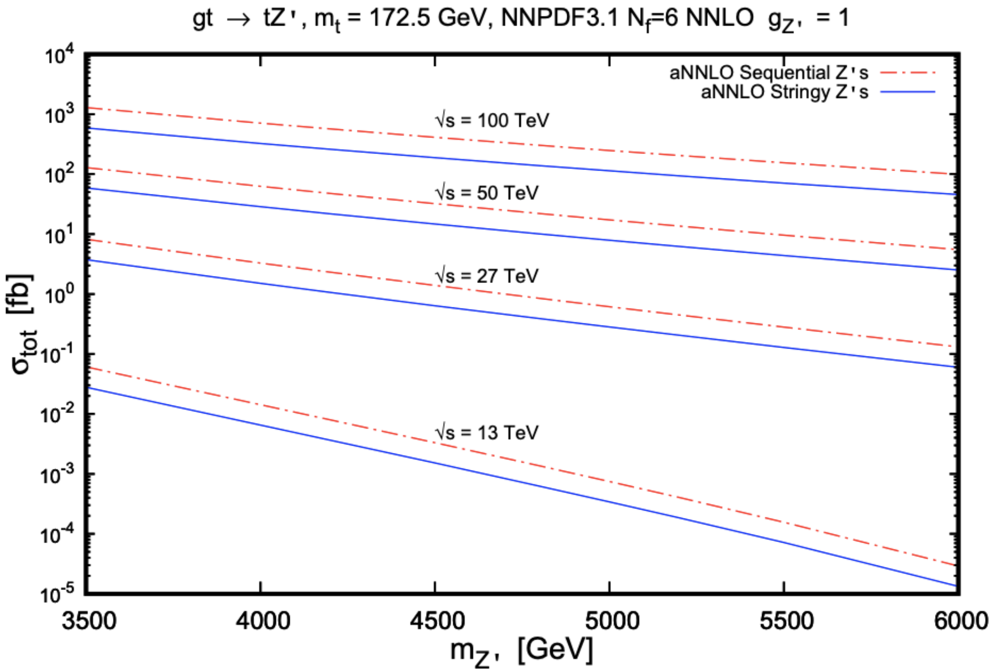
$m_{Z'}$ (TeV)	σ_{aNNLO} (fb)	δPDF (CT14NNLO)	δscale	K-factor
1	14.4	± 0.3	$^{+0.3}_{-0.4}$	1.74
3	0.272	$^{+0.025}_{-0.062}$	$^{+0.001}_{-0.006}$	2.24
5	0.00659	$^{+0.00134}_{-0.00086}$	$^{+0.00001}_{-0.00018}$	2.78

Table 3 aNNLO cross sections and aNNLO/LO K-factors for $gt \to tZ'$ with $g_{Z'} = 1$ and $m_t = 172.5$ GeV at 13 TeV LHC collider energy. The NNPDF3.1 $n_f = 6$ PDF uncertainties are determined at the 1-σ C.L. The scale uncertainties are obtained by taking up and down variations of the factorization scale μ, $m_{Z'}/2 < \mu < 2m_{Z'}$

$m_{Z'}$ (TeV)	σ_{aNNLO} (fb)	δPDF(NNPDF3.1)	δscale	K-factor
1	157	± 16	$^{+56}_{-60}$	2.12
3	0.122	± 0.018	$^{+0.021}_{-0.026}$	2.66
5	3.34×10^{-4}	$\pm 1.88 \times 10^{-4}$	$^{+3.7\times 10^{-5}}_{-5.3\times 10^{-5}}$	3.33

Additional results: comparison with sequential Z’ models





Left: Scan of the gZ’ parameter for the gt → tZ’ process. The plot shows results of the total cross section at aNNLO as a function of collider energy. Bands with different dashing represent Z ’ mass values of 3, 5, and 8 TeV.
Right: Comparison between string-inspired Z ’ s and sequential Z ’ s for different values of the collider energy at aNNLO.