Total and differential cross sections for Higgs and top-quark production

Nikolaos Kidonakis

- **Higher-order soft-gluon corrections**

- **Charged-Higgs production**

- **Single-top production and $t\bar{t}$ production**

College of Science and Mathematics
Department of Physics

ICNFP 2018

Higher-order corrections

QCD corrections are very significant for Higgs and top production

**Soft-gluon corrections are important
and they approximate exact results very well**

**We calculate/resum these soft corrections at NNLL accuracy
for the double-differential cross section**

Finite-order expansions

**Approximate NNLO (aNNLO) and N^3LO (aN^3LO) predictions
for cross sections and differential distributions**

Soft-gluon corrections

partonic processes
$$f_1(p_1) + f_2(p_2) \to t(p_t) + X$$

define

$s = (p_1 + p_2)^2$, $t = (p_1 - p_t)^2$, $u = (p_2 - p_t)^2$
and $s_4 = s + t + u - \sum m^2$

At partonic threshold $s_4 \to 0$

Soft corrections $\left[\dfrac{\ln^k(s_4/m_t^2)}{s_4} \right]_+$

For the order α_s^n **corrections** $k \leq 2n - 1$

Resum these soft corrections for the double-differential cross section

At NNLL accuracy we need two-loop soft anomalous dimensions

Soft-gluon Resummation

moments of the partonic cross section with moment variable N:
$\hat{\sigma}(N) = \int (ds_4/s) \, e^{-N s_4/s} \hat{\sigma}(s_4)$

factorized expression for the cross section in $4 - \epsilon$ dimensions

$$\sigma^{f_1 f_2 \to tX}(N, \epsilon) = H_{IL}^{f_1 f_2 \to tX}\left(\alpha_s(\mu_R)\right) S_{LI}^{f_1 f_2 \to tX}\left(\frac{m_t}{N \mu_F}, \alpha_s(\mu_R)\right)$$

$$\times \prod J_{\text{in}}\left(N, \mu_F, \epsilon\right) \prod J_{\text{out}}\left(N, \mu_F, \epsilon\right)$$

$H_{IL}^{f_1 f_2 \to tX}$ **is hard function and** $S_{LI}^{f_1 f_2 \to tX}$ **is soft function**

S_{LI} **satisfies the renormalization group equation**

$$\left(\mu \frac{\partial}{\partial \mu} + \beta(g_s) \frac{\partial}{\partial g_s}\right) S_{LI} = -(\Gamma_S^\dagger)_{LK} S_{KI} - S_{LK}(\Gamma_S)_{KI}$$

Soft anomalous dimension Γ_S controls the evolution of the soft function which gives the exponentiation of logarithms of N

tH^- production
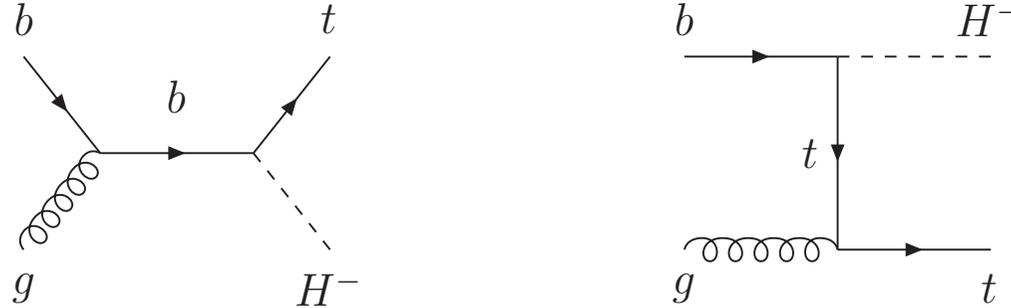
Born cross section for $bg \to tH^-$ $\propto \alpha\alpha_s(m_b^2 \tan^2 \beta + m_t^2 \cot^2 \beta)$

$\tan \beta = v_2/v_1$ **ratio of vevs of two Higgs doublets**

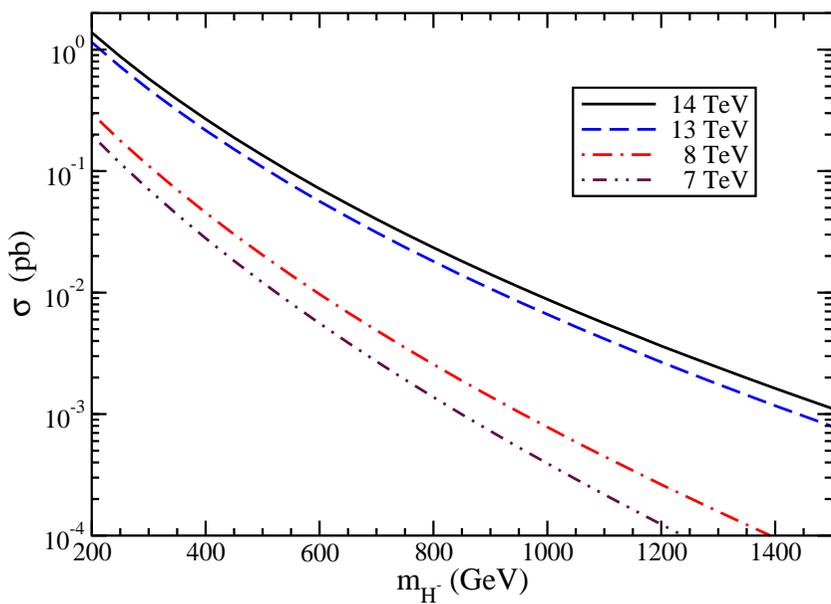$\Gamma_S^{bg \to tH^-} = (\alpha_s/\pi)\Gamma_S^{(1)} + (\alpha_s/\pi)^2\Gamma_S^{(2)} + \cdots$, **with**

$$\Gamma_S^{(1)} = C_F \left[\ln\left(\frac{m_t^2 - t}{m_t\sqrt{s}}\right) - \frac{1}{2}\right] + \frac{C_A}{2}\ln\left(\frac{m_t^2 - u}{m_t^2 - t}\right)$$

$$\Gamma_S^{(2)} = \left[C_A\left(\frac{67}{36} - \frac{\zeta_2}{2}\right) - \frac{5}{18}n_f\right]\Gamma_S^{(1)} + C_F C_A \frac{(1 - \zeta_3)}{4}$$

tH^- production

Total cross sections at aNNLO

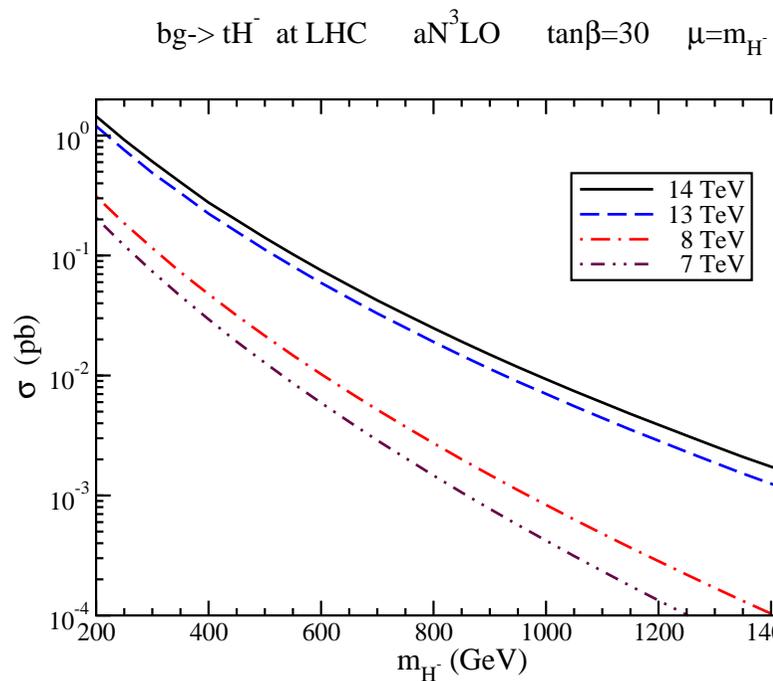bg-> tH⁻ at LHC   aNNLO   tanβ=30   μ=m$_{H^-}$

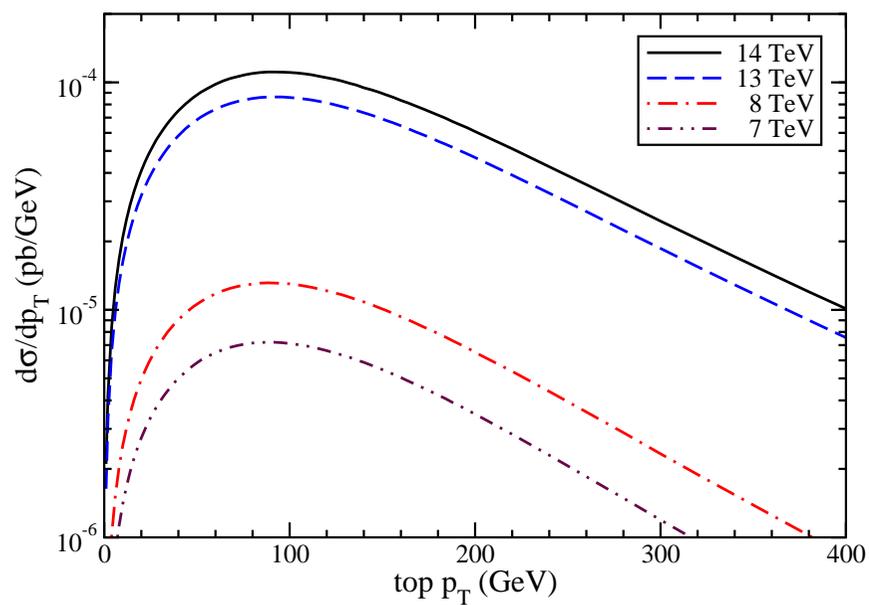bg-> tH⁻ at LHC   K-factor   μ=m$_{H^-}$

tH^- production

Total cross sections at aN^{3}LO

bg-> tH$^-$ at LHC   aN^{3}LO   tanβ=30   μ=m$_{H^-}$

bg-> tH$^-$ at LHC   aN^{3}LO K-factor   μ=m$_{H^-}$
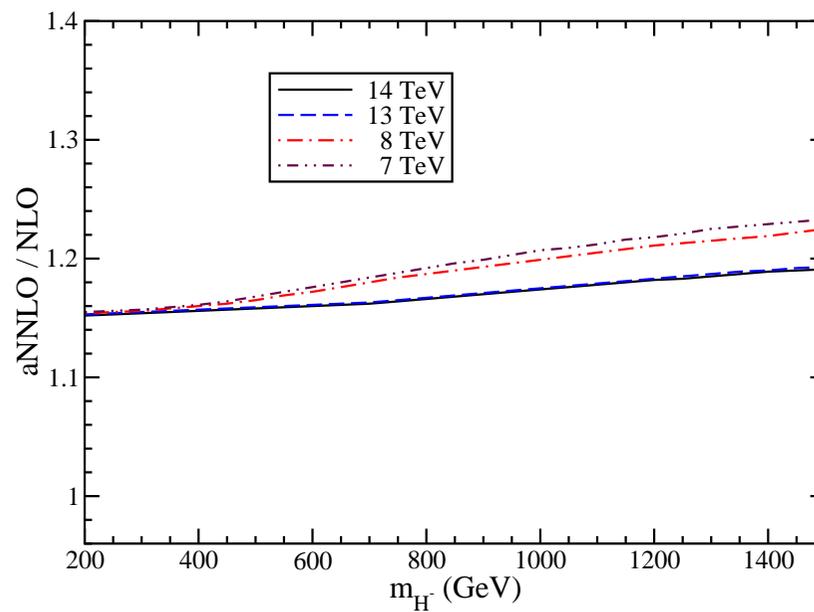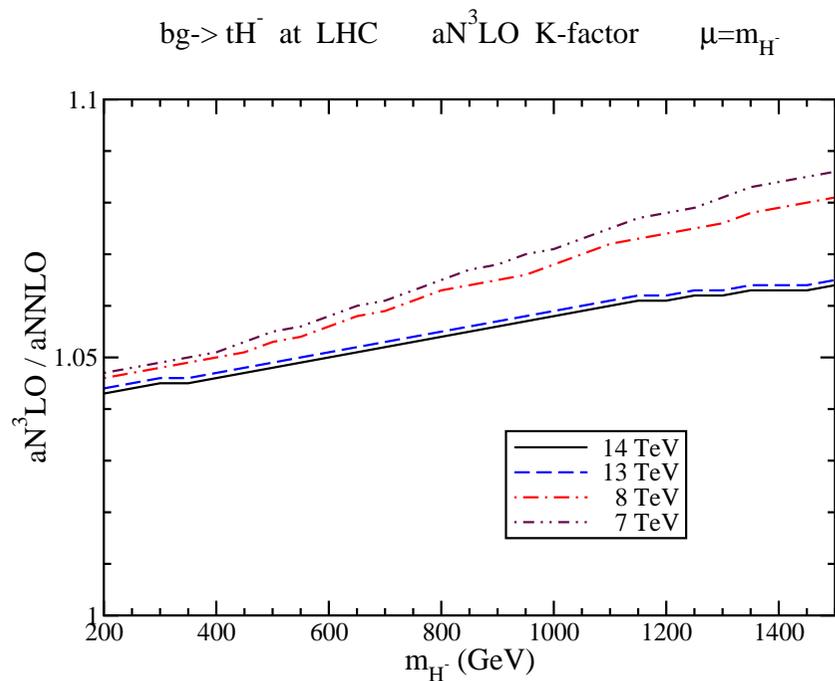
tH^- production

Top-quark p_T and rapidity distributions

bg-> tH$^-$ at LHC   top p_T aNNLO   tanβ=30 m_{H^-}=800 GeV

bg->tH$^-$ at LHC   top rapidity   aNNLO   tanβ=30 m_{H^-}=800 GeV

H^-W^+ **production**

Total cross sections

$b\,\bar{b} \rightarrow H^-\,W^+$ at LHC   aNNLO $\tan\beta=1$ $\mu=m_{H^-}$

aNNLO / LO

- 14 TeV
- 13 TeV
- 8 TeV
- 7 TeV

σ (pb)

m_{H^-} (GeV)
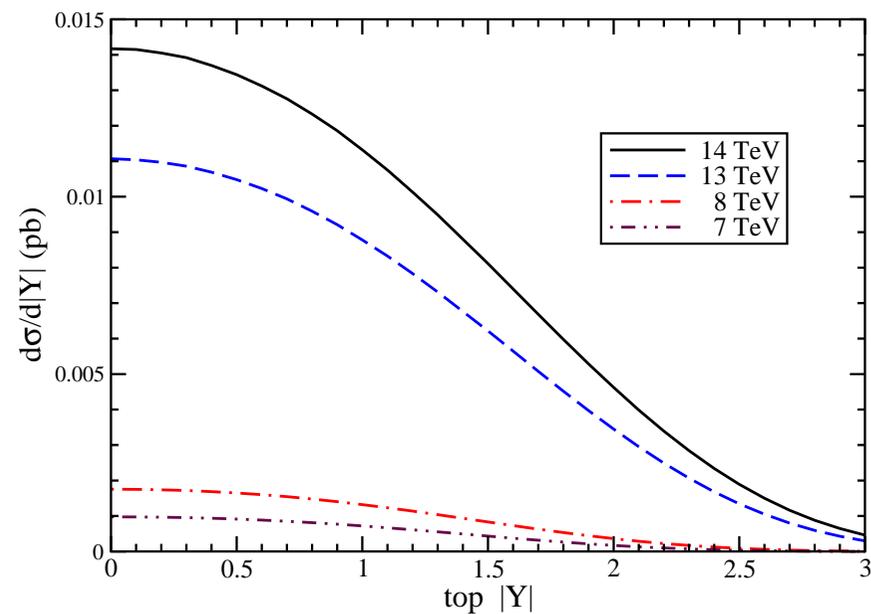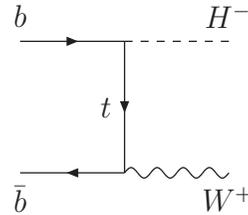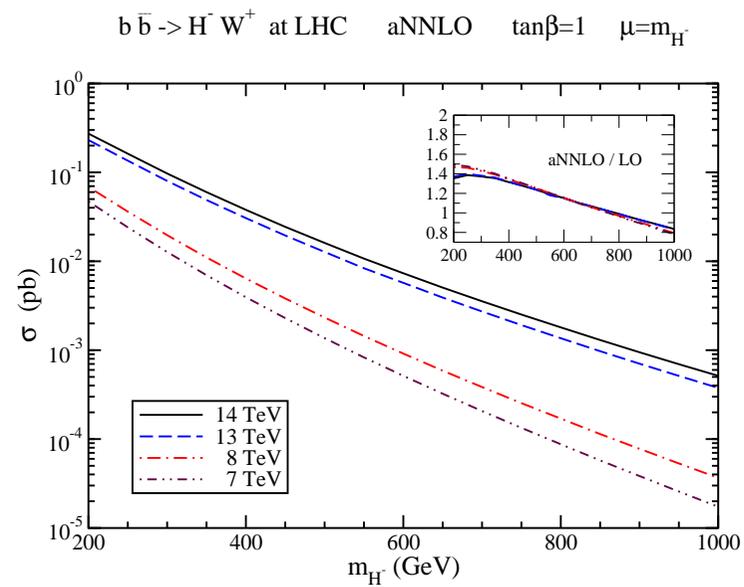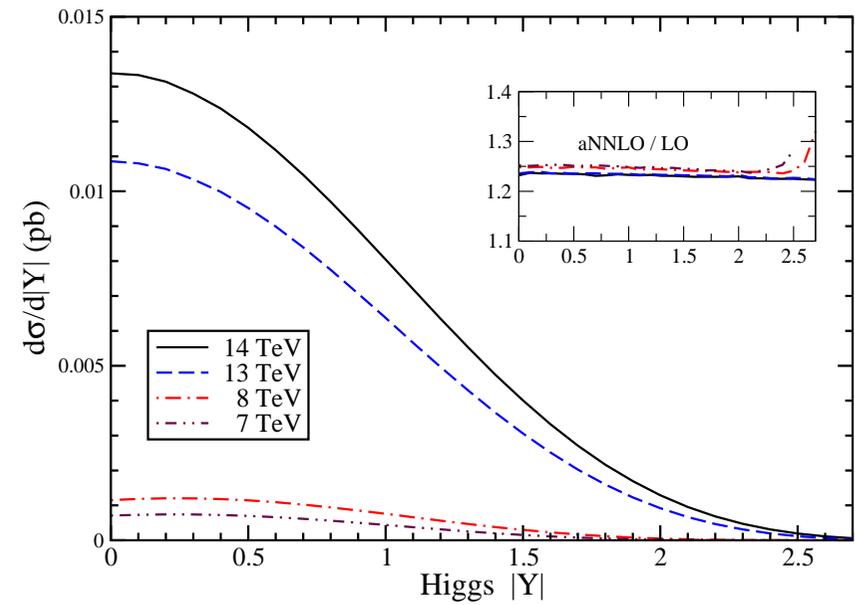
$H^- W^+$ production

Charged-Higgs p_T and rapidity distributions
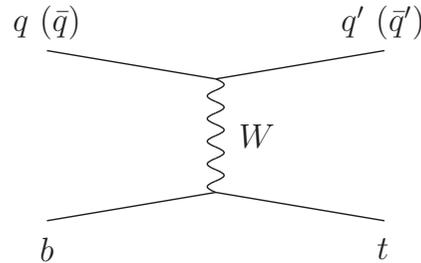
$b \bar{b} \rightarrow H^- W^+$ at LHC   aNNLO $\tan\beta=1$ m_{H^-}=500 GeV
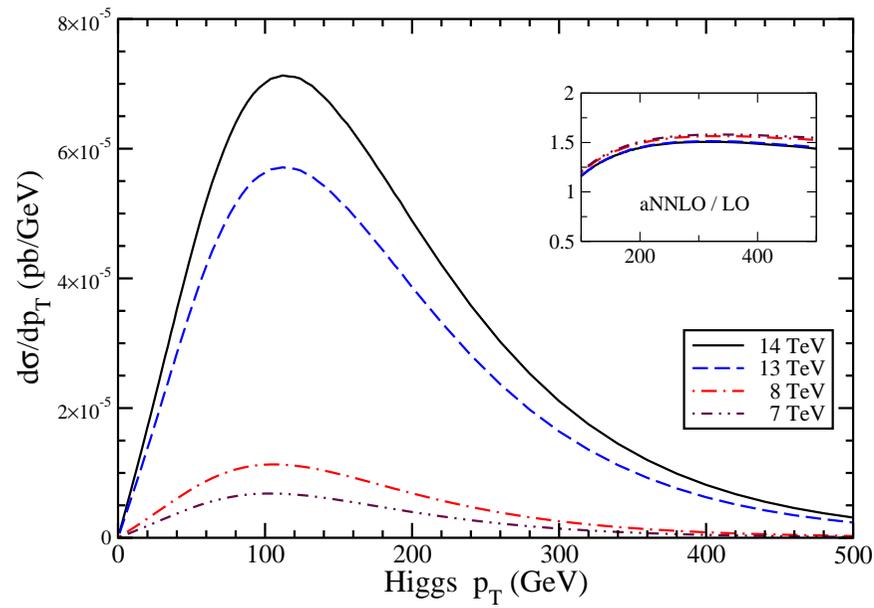
$b \bar{b} \rightarrow H^- W^+$ at LHC   aNNLO $\tan\beta=1$ m_{H^-}=500 GeV

Single-top t-channel production

At one loop

$$\Gamma_{S\,11}^{t\,(1)} = C_F \left[\ln\left(\frac{t(t-m_t^2)}{m_t s^{3/2}} \right) - \frac{1}{2} \right] \qquad \Gamma_{S\,12}^{t\,(1)} = \frac{C_F}{2N} \ln\left(\frac{u(u-m_t^2)}{s(s-m_t^2)} \right) \qquad \Gamma_{S\,21}^{t\,(1)} = \ln\left(\frac{u(u-m_t^2)}{s(s-m_t^2)} \right)$$
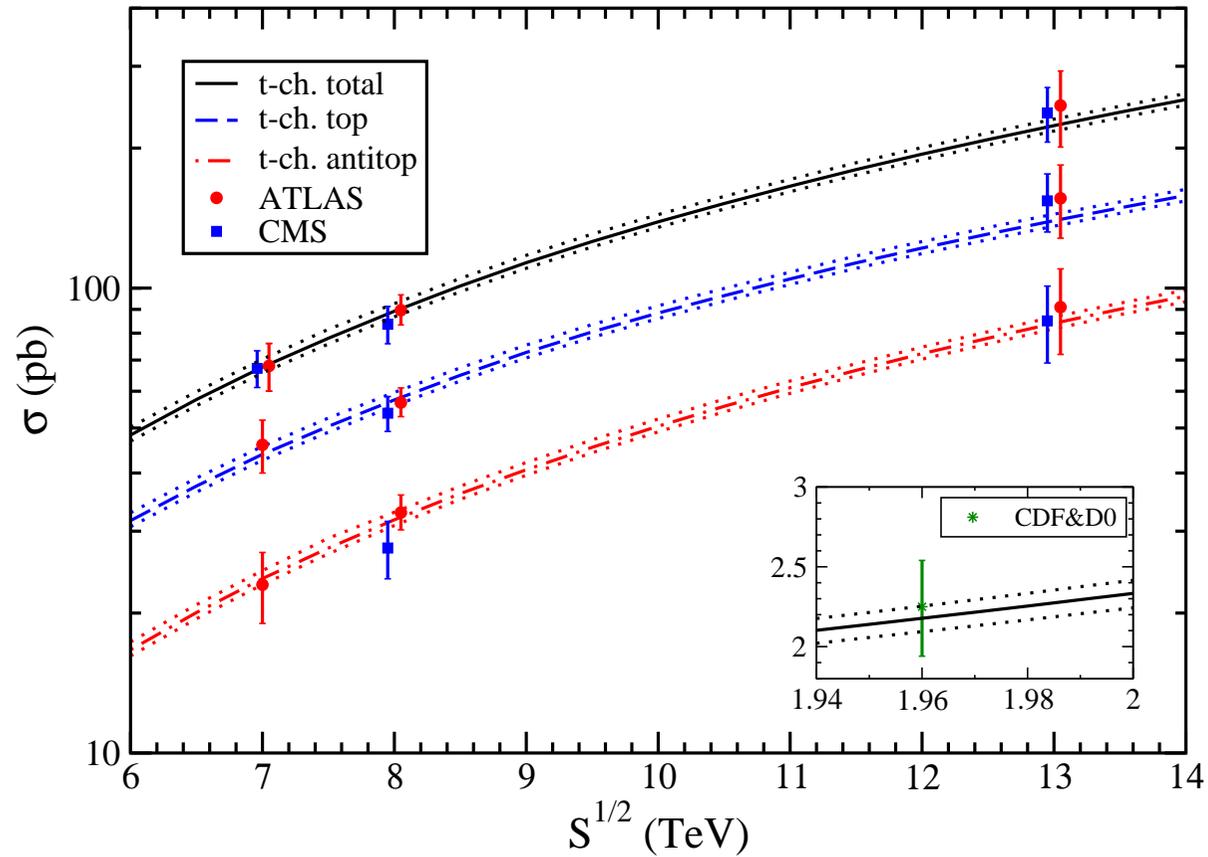
$$\Gamma_{S\,22}^{t\,(1)} = C_F \ln\left(\frac{s-m_t^2}{m_t \sqrt{s}} \right) - \frac{1}{2N} \ln\left(\frac{t(t-m_t^2)}{s(s-m_t^2)} \right) + \frac{(N^2-2)}{2N} \ln\left(\frac{u(u-m_t^2)}{s(s-m_t^2)} \right) - \frac{C_F}{2}$$
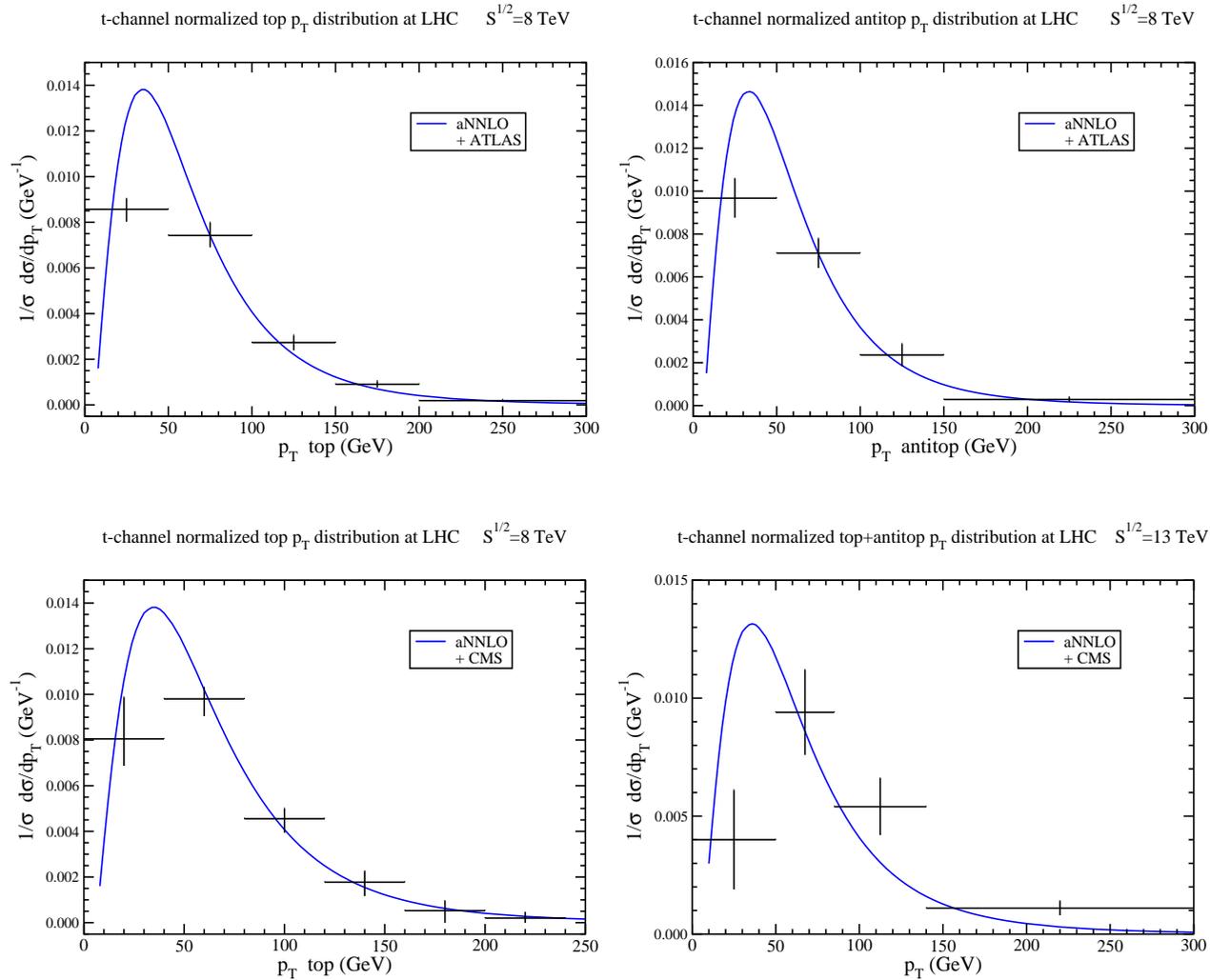
At two loops

$$\Gamma_{S\,11}^{t\,(2)} = \left[C_A \left(\frac{67}{36} - \frac{\zeta_2}{2} \right) - \frac{5}{18} n_f \right] \Gamma_{S\,11}^{t\,(1)} + C_F C_A \frac{(1-\zeta_3)}{4}$$
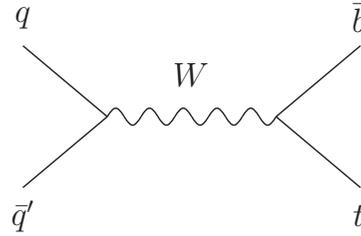
t-channel production at aNNLO

Single-top t-channel aNNLO cross sections m_t=172.5 GeV

Top p_T distributions in t-channel production at the LHC

t-channel normalized top p_T distribution at LHC $S^{1/2}$=8 TeV

t-channel normalized antitop p_T distribution at LHC $S^{1/2}$=8 TeV

t-channel normalized top p_T distribution at LHC $S^{1/2}$=8 TeV

t-channel normalized top+antitop p_T distribution at LHC $S^{1/2}$=13 TeV

Single-top s-channel production

At one loop

$$\Gamma^{s\,(1)}_{S\,11} = C_F \left[\ln\left(\frac{s - m_t^2}{m_t \sqrt{s}} \right) - \frac{1}{2} \right] \qquad \Gamma^{s\,(1)}_{S\,12} = \frac{C_F}{2N} \ln\left(\frac{u(u - m_t^2)}{t(t - m_t^2)} \right) \qquad \Gamma^{s\,(1)}_{S\,21} = \ln\left(\frac{u(u - m_t^2)}{t(t - m_t^2)} \right)$$
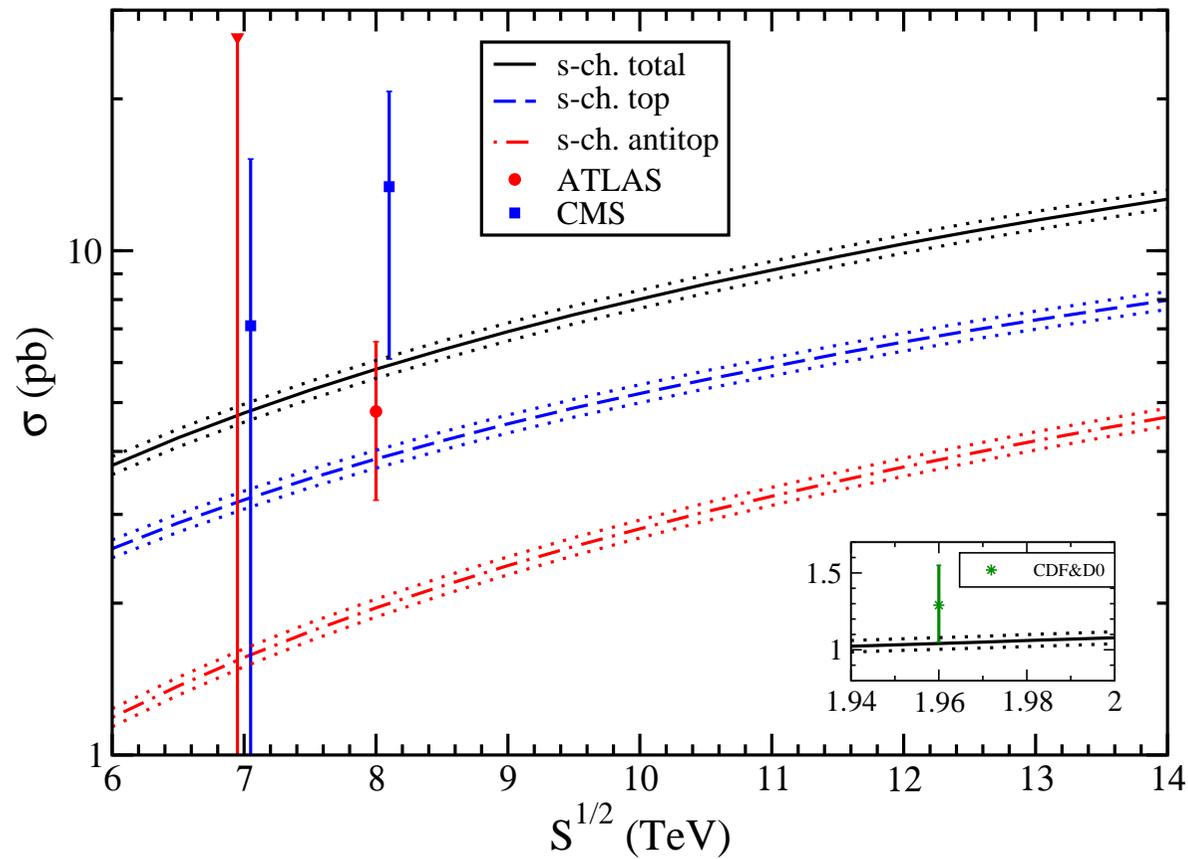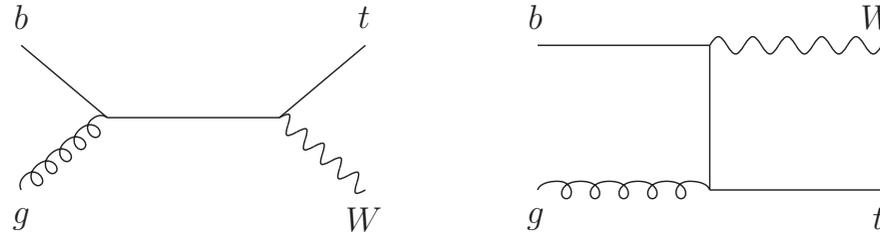
$$\Gamma^{s\,(1)}_{S\,22} = C_F \ln\left(\frac{s - m_t^2}{m_t \sqrt{s}} \right) - \frac{1}{N} \ln\left(\frac{u(u - m_t^2)}{t(t - m_t^2)} \right) + \frac{N}{2} \ln\left(\frac{u(u - m_t^2)}{s(s - m_t^2)} \right) - \frac{C_F}{2}$$

At two loops

$$\Gamma^{s\,(2)}_{S\,11} = \left[C_A \left(\frac{67}{36} - \frac{\zeta_2}{2} \right) - \frac{5}{18} n_f \right] \Gamma^{s\,(1)}_{S\,11} + C_F C_A \frac{(1 - \zeta_3)}{4}$$

s-channel production at aNNLO

Single-top s-channel aNNLO cross sections m_t=172.5 GeV

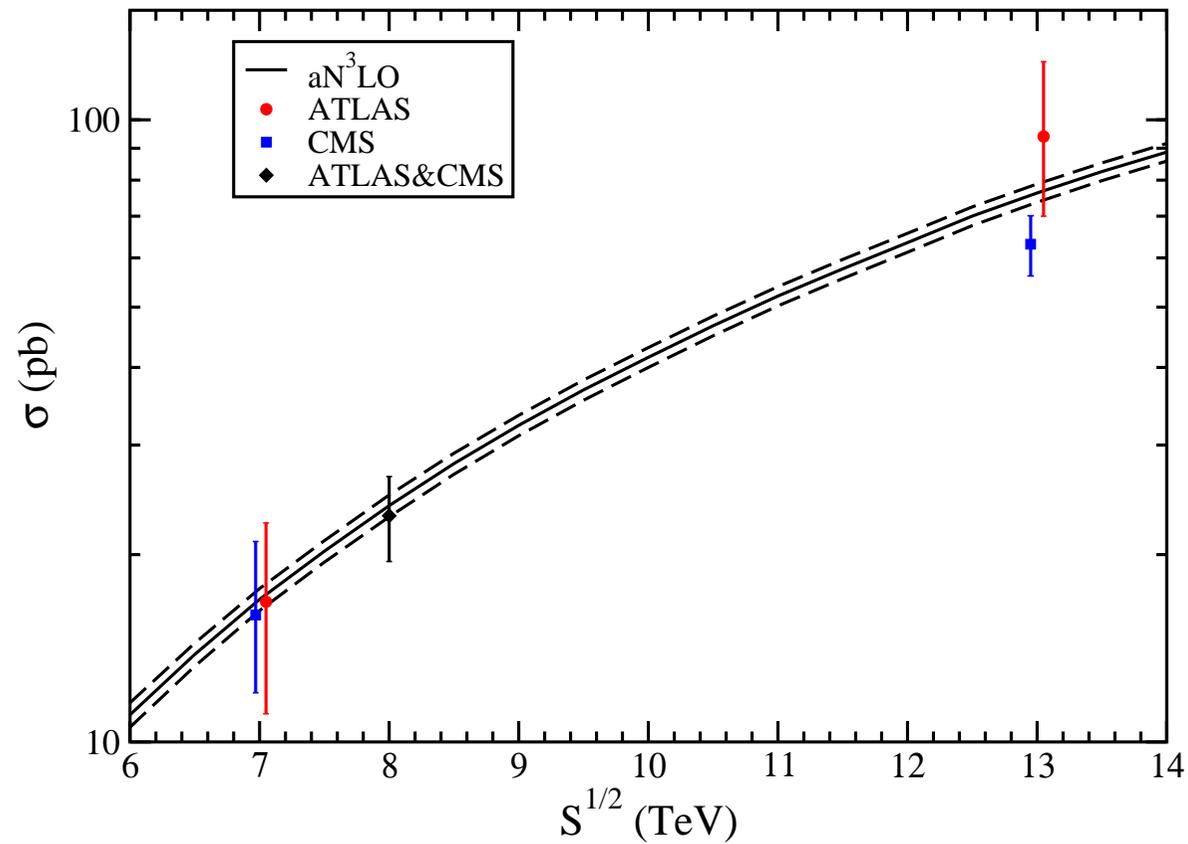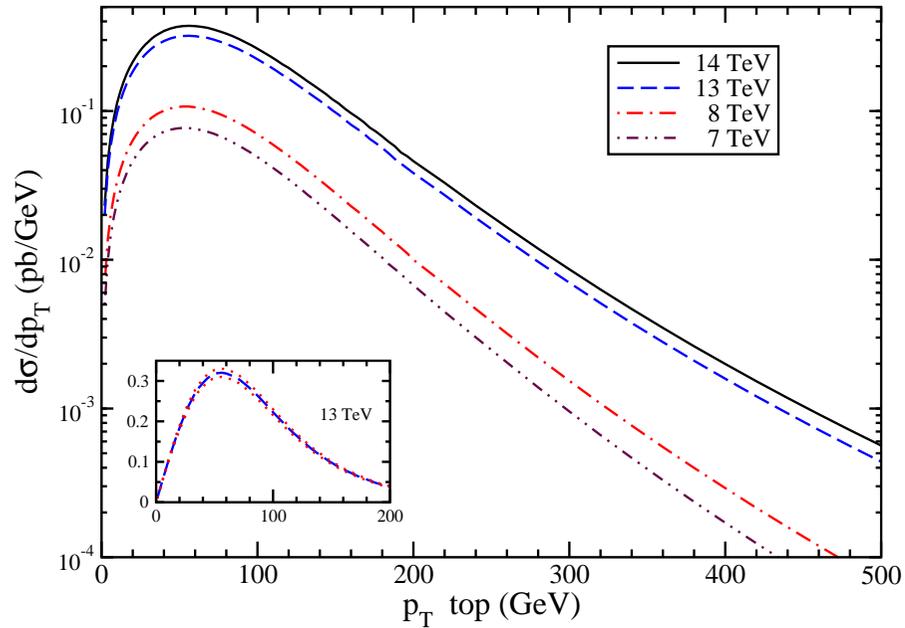# Associated tW production

At one loop

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

At two loops

$$\Gamma_S^{tW^- \ (2)} = \left[C_A \left(\frac{67}{36} - \frac{\zeta_2}{2} \right) - \frac{5}{18} n_f \right] \Gamma_S^{tW^- \ (1)} + C_F C_A \frac{(1 - \zeta_3)}{4}$$

tW production at aN³LO

tW⁻ + t̄W⁺ aN³LO cross section m_t=172.5 GeV

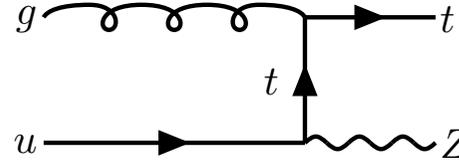# Top quark p_T and rapidity distributions in tW production
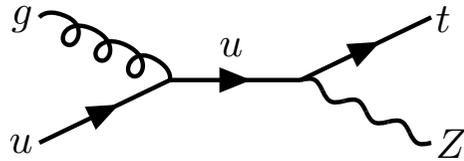
Top p_T distribution in tW$^-$ production at LHC   aN^{3}LO   m$_t$=173.3 GeV

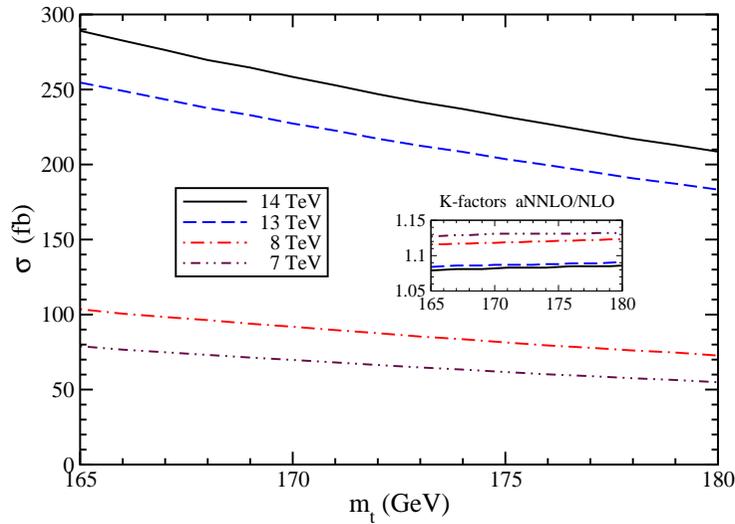Top rapidity distribution in tW$^-$ production at LHC   aN^{3}LO   m$_t$=173.3 GeV
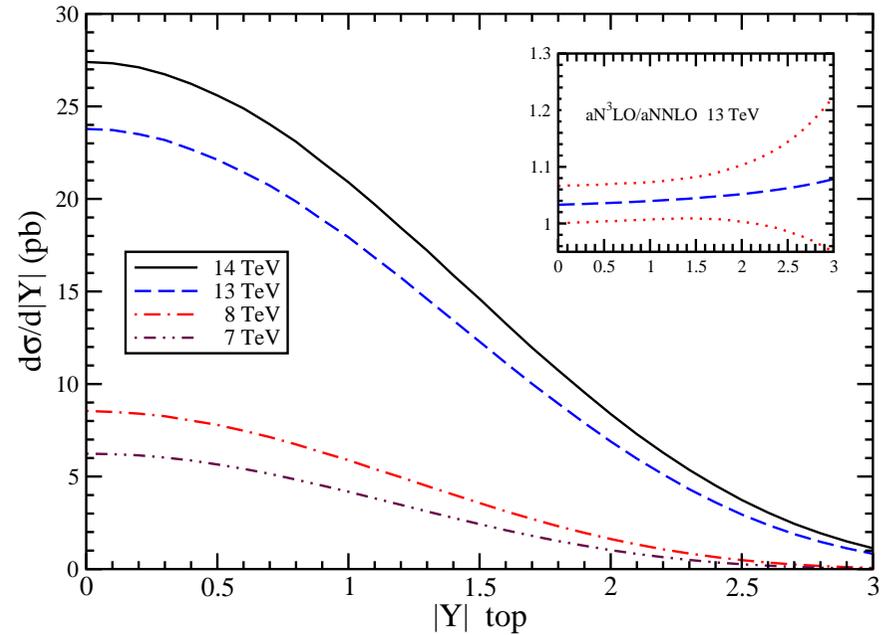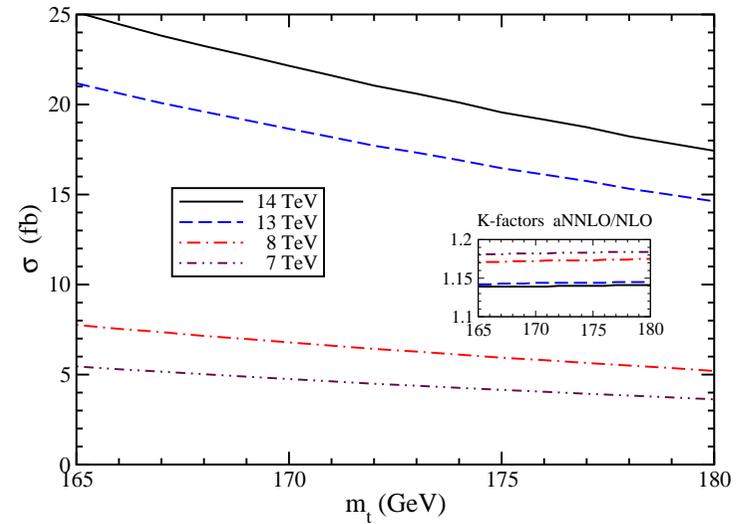
tZ production via anomalous couplings

$$\Delta\mathcal{L}^{eff} = \frac{1}{\Lambda}\,\kappa_{tqZ}\,e\,\bar{t}\,(i/2)(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)\,q\,F_Z^{\mu\nu} + h.c.$$
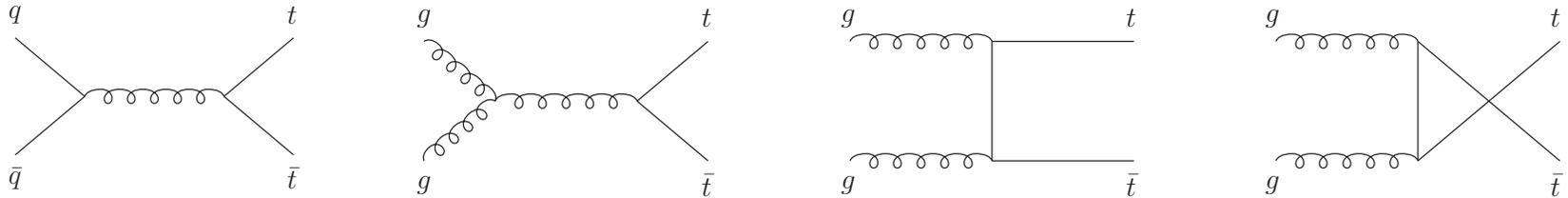

g u -> t Z   at LHC   aNNLO   k$_{tuZ}$=0.01

g c -> t Z   at LHC   aNNLO   k$_{tcZ}$=0.01

Top-antitop pair production

At one loop for $q\bar{q} \to t\bar{t}$

$$\Gamma_{11}^{q\bar{q}\,(1)} = \Gamma_{\text{cusp}}^{(1)}, \quad \Gamma_{12}^{q\bar{q}\,(1)} = \frac{C_F}{C_A} \ln\left(\frac{t_1}{u_1}\right), \quad \Gamma_{21}^{q\bar{q}\,(1)} = 2\ln\left(\frac{t_1}{u_1}\right)$$

$$\Gamma_{22}^{q\bar{q}\,(1)} = \left(1 - \frac{C_A}{2C_F}\right)\Gamma_{\text{cusp}}^{(1)} + 4C_F \ln\left(\frac{t_1}{u_1}\right) - \frac{C_A}{2}\left[1 + \ln\left(\frac{s m_t^2 t_1^2}{u_1^4}\right)\right]$$
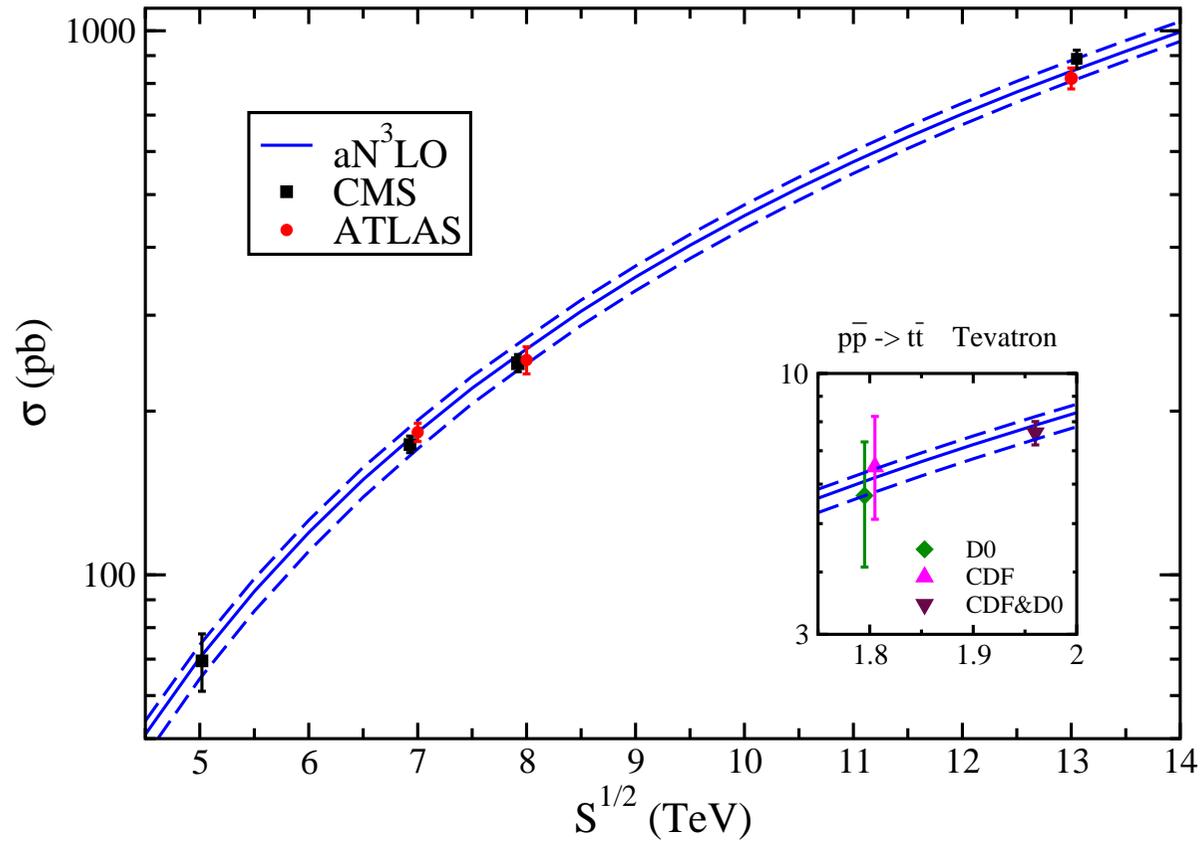
At two loops for $q\bar{q} \to t\bar{t}$

$$\Gamma_{11}^{q\bar{q}\,(2)} = \Gamma_{\text{cusp}}^{(2)}, \quad \Gamma_{12}^{q\bar{q}\,(2)} = \left(\frac{K}{2} - \frac{C_A}{2}N_{2l}\right)\Gamma_{12}^{q\bar{q}\,(1)}, \quad \Gamma_{21}^{q\bar{q}\,(2)} = \left(\frac{K}{2} + \frac{C_A}{2}N_{2l}\right)\Gamma_{21}^{q\bar{q}\,(1)}$$

$$\Gamma_{22}^{q\bar{q}\,(2)} = \frac{K}{2}\Gamma_{22}^{q\bar{q}\,(1)} + \left(1 - \frac{C_A}{2C_F}\right)\left(\Gamma_{\text{cusp}}^{(2)} - \frac{K}{2}\Gamma_{\text{cusp}}^{(1)}\right)$$
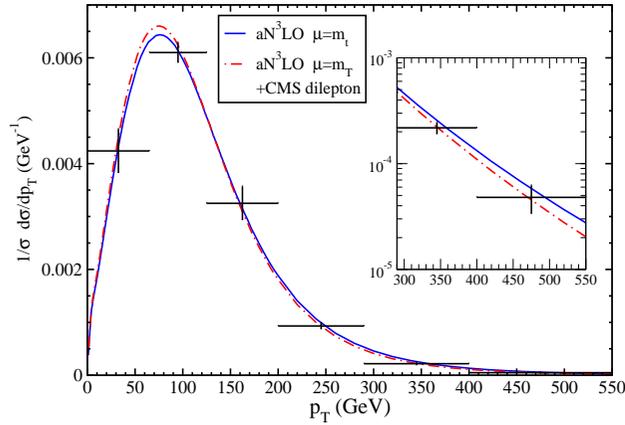
3×3 matrix for $gg \to t\bar{t}$

Top-antitop pair production

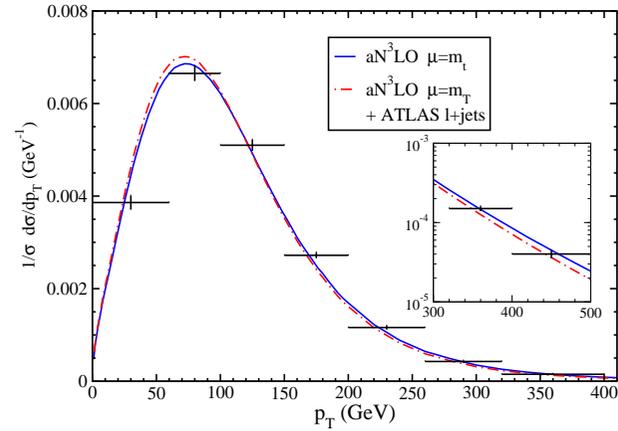pp -> $t\bar{t}$ at LHC energies aN^3LO m_t=172.5 GeV

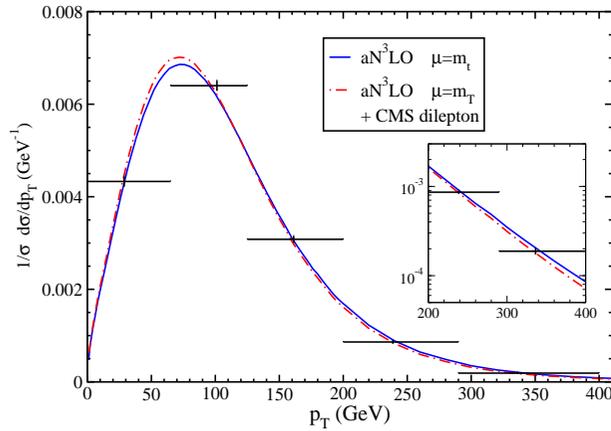# Top p_T distributions in $t\bar{t}$ production


Normalized top p_T distribution at the LHC $S^{1/2}$=13 TeV

Normalized top p_T distribution at the LHC $S^{1/2}$=8 TeV

Normalized top p_T distribution at the LHC $S^{1/2}$=8 TeV

Normalized top p_T distribution at the LHC $S^{1/2}$=8 TeV
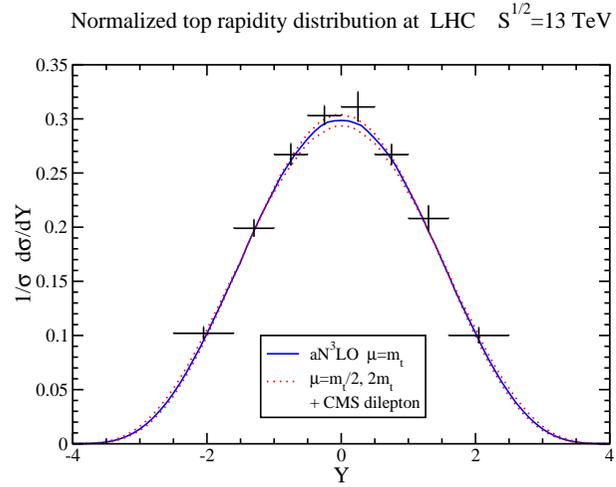
Top rapidity distributions in $t\bar{t}$ production

Normalized top rapidity distribution at LHC $S^{1/2}$=13 TeV

Normalized top rapidity distribution at LHC $S^{1/2}$=8 TeV

Normalized top rapidity distribution at LHC $S^{1/2}$=8 TeV
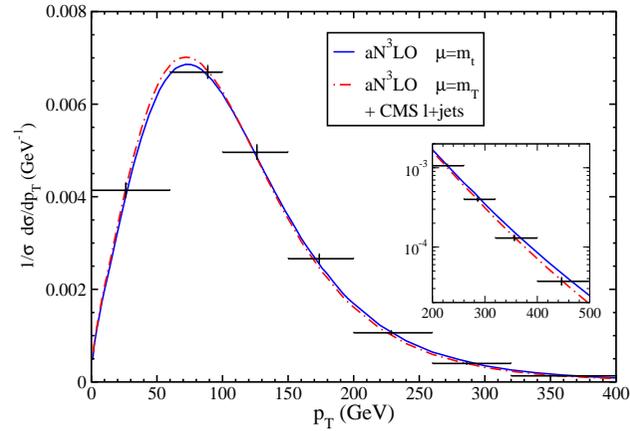
Normalized top rapidity distribution at LHC $S^{1/2}$=8 TeV
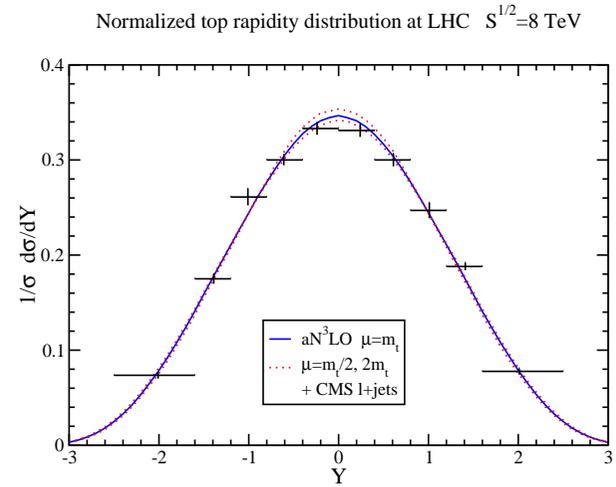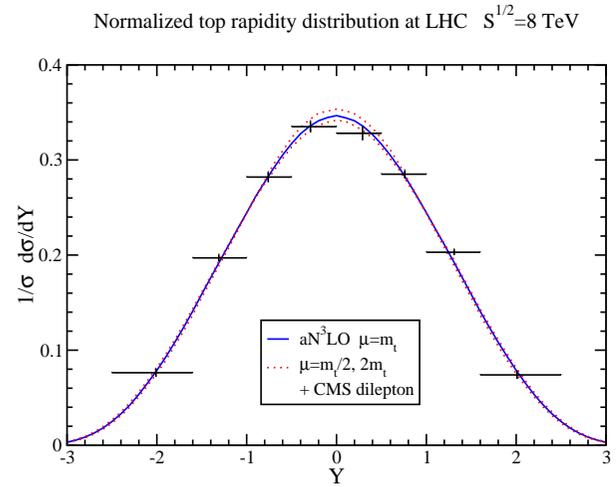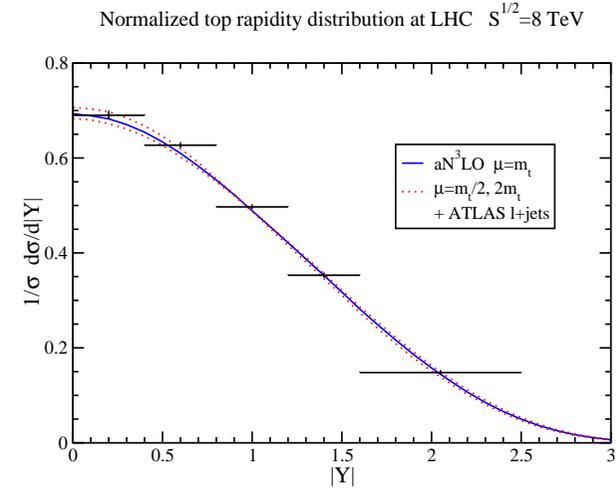
Summary

- **cross sections and distributions for Higgs and top production**

- **soft-gluon corrections**

- tH^- **and** H^-W^+ **production at aNNLO and beyond**

- t**-channel and** s**-channel single top at aNNLO**

- tW **production at aN^{3}LO**

- tZ **production via anomalous couplings**

- $t\bar{t}$ **production at aN^{3}LO**

- **excellent agreement with collider data**

- **high-order corrections are very significant**