Theoretical results for top-quark cross sections and distributions

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- **Top-antitop pair production**
- **Single-top production**
- **Cusp anomalous dimension**

supported by NSF

Top-antitop pair production

QCD corrections are very significant for $t\bar{t}$

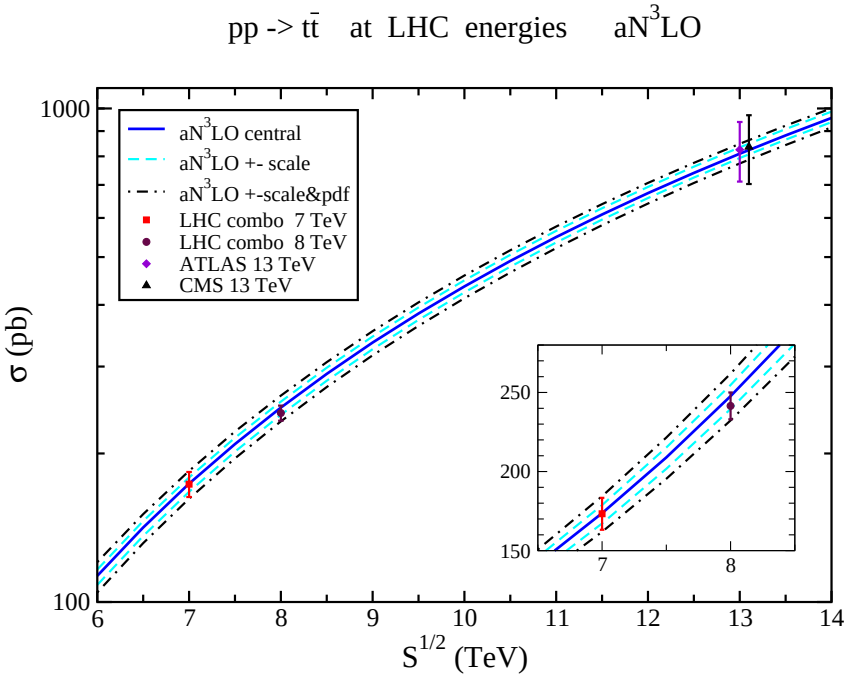
Soft-gluon corrections are important
and they approximate exact results very well

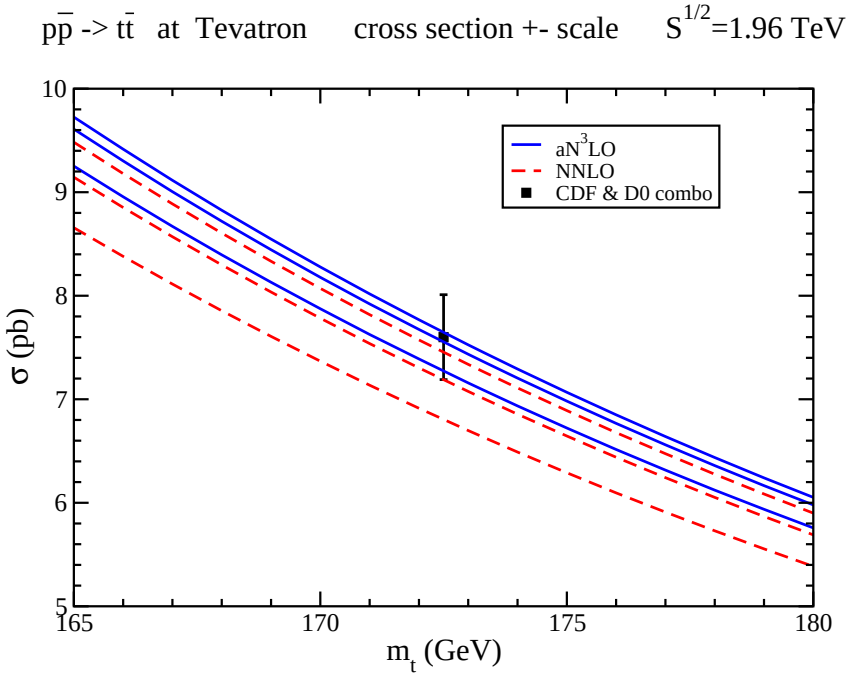
Calculate/resum these soft corrections at NNLL accuracy
for the double-differential cross section

Approximate N^{3}LO (aN^{3}LO) predictions for cross sections are derived by adding third-order soft corrections to fixed-order results

aN^{3}LO = LO + NLO + NNLO + approx N^{3}LO corrections

Top-pair cross sections at the LHC and the Tevatron





aN^{3}LO total $t\bar{t}$ cross sections $\pm$ scale $\pm$ pdf uncertainties

LHC 13 TeV: 826^{+24+14}_{-16-18} **pb**

LHC 14 TeV: 975^{+28+16}_{-19-20} **pb**

$m_t = 173.3$ **GeV and MMHT2014 pdf**

Relative size of perturbative corrections

$$\sigma^{\rm aN^3LO} = \sigma^{(0)} \left[1 + \frac{\sigma^{(1)}}{\sigma^{(0)}} + \frac{\sigma^{(2)}}{\sigma^{(0)}} + \frac{\sigma^{(\rm a3)}}{\sigma^{(0)}} \right]$$

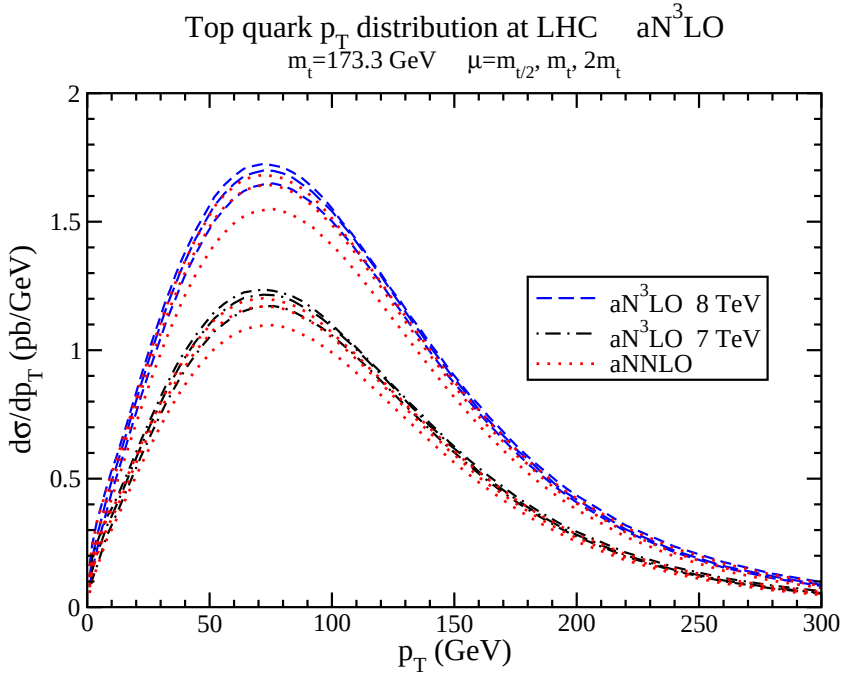
Fractional contributions to the perturbative series for the $t\bar{t}$ cross section					
corrections	Tevatron 1.96 TeV	LHC 7 TeV	LHC 8 TeV	LHC 13 TeV	LHC 14 TeV
$\sigma^{(1)}/\sigma^{(0)}$	0.236	0.470	0.476	0.493	0.496
$\sigma^{(2)}/\sigma^{(0)}$	0.106	0.178	0.177	0.172	0.170
$\sigma^{(\rm a3)}/\sigma^{(0)}$	0.068	0.066	0.059	0.045	0.043
$\sigma^{\rm aN^3LO}/\sigma^{(0)}$	1.410	1.714	1.712	1.710	1.709

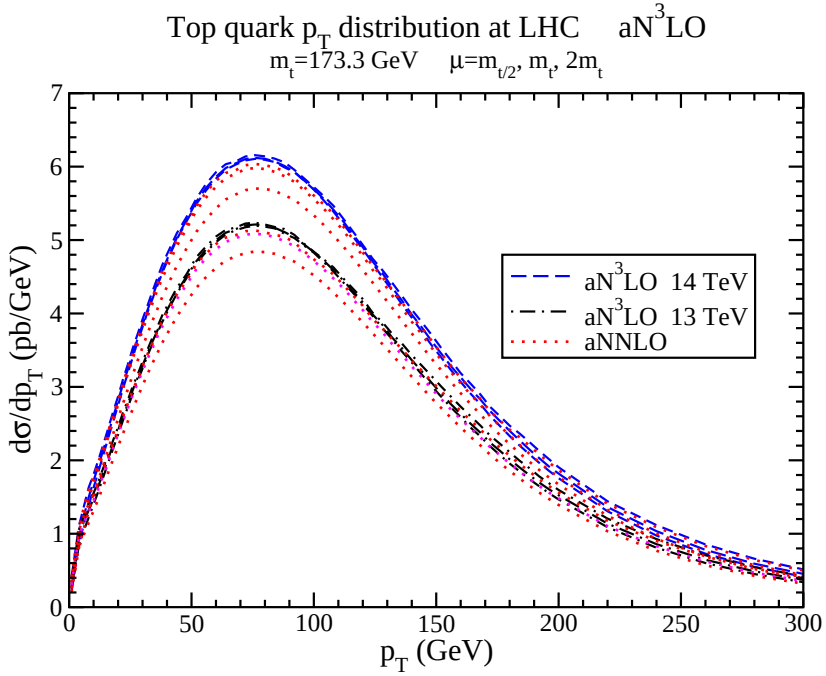
Higher-order corrections are sizable for total cross sections and also for differential distributions

NNLO is not enough

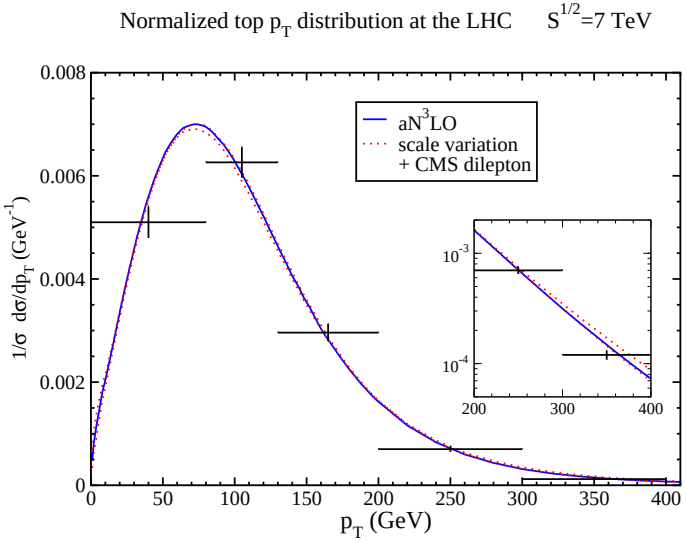
aN^{3}LO needed for precision physics

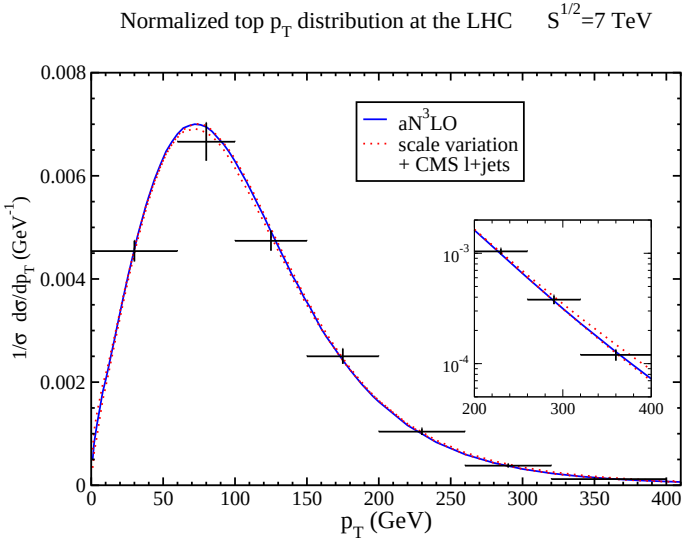
Top quark p_T distribution at the LHC

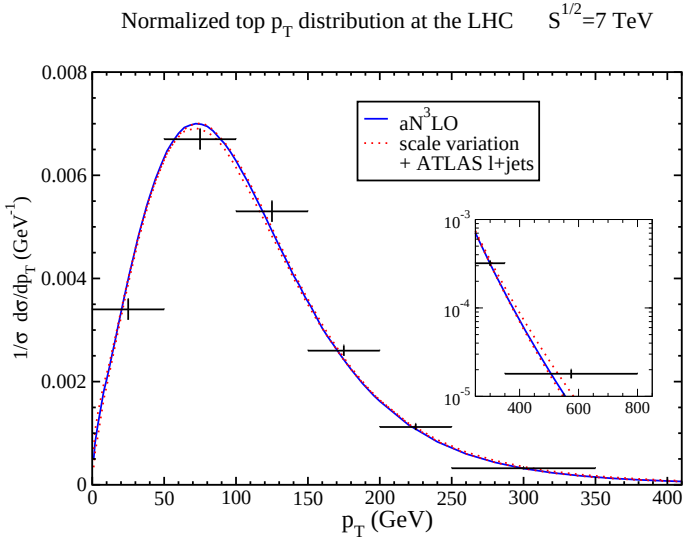




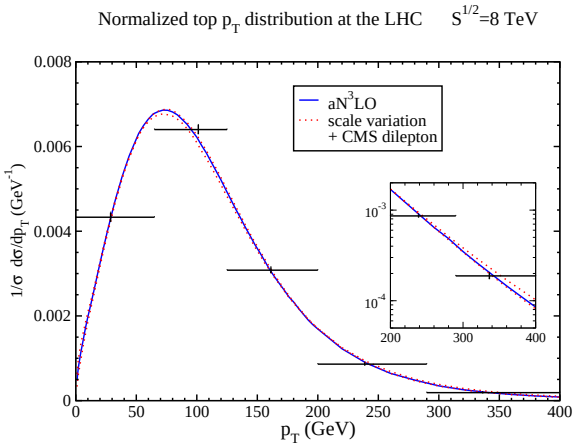
Normalized top quark p_T distribution at 7 TeV LHC

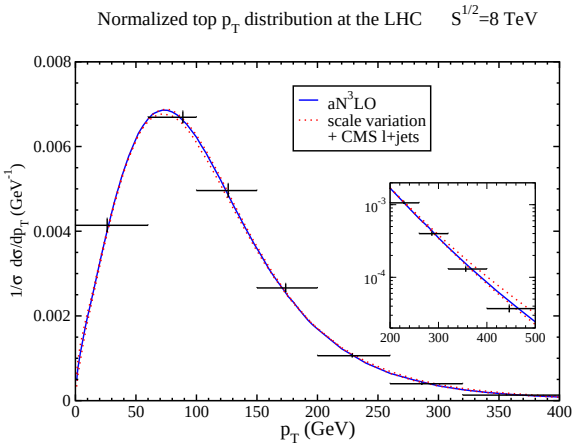


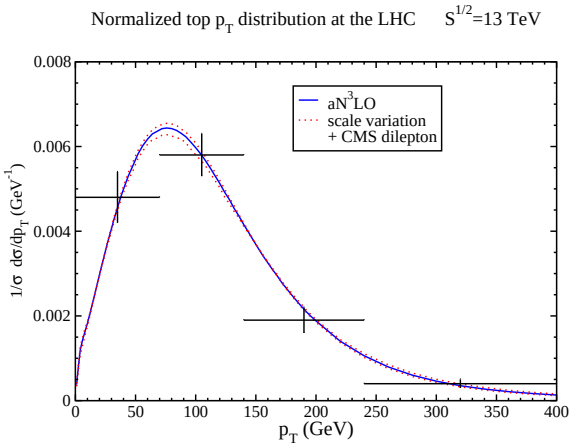




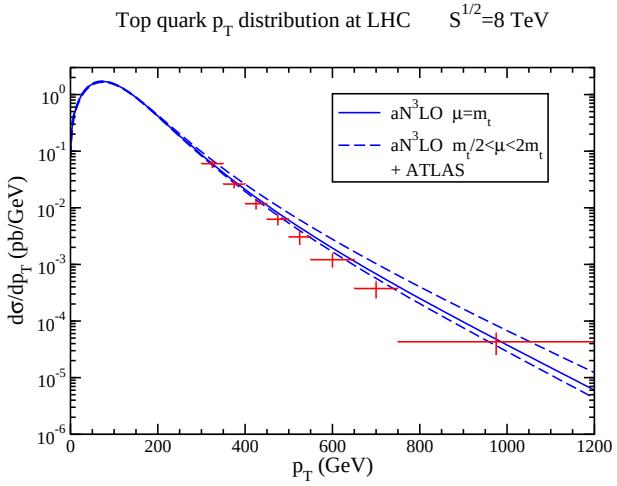
Normalized top quark p_T distribution at 8 and 13 TeV LHC

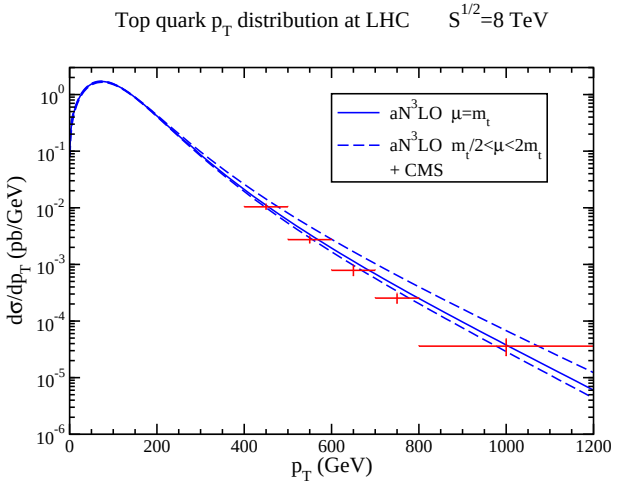




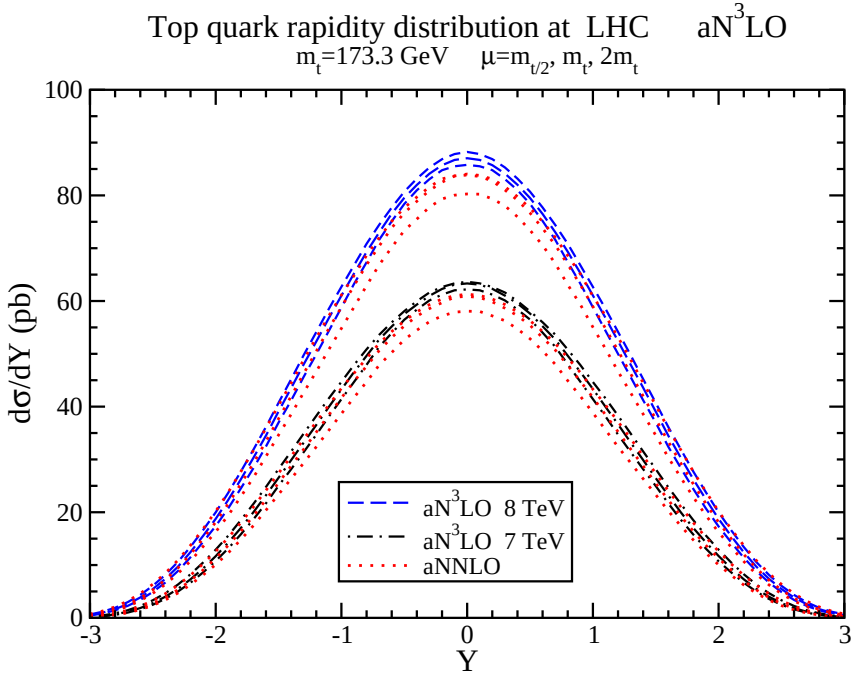


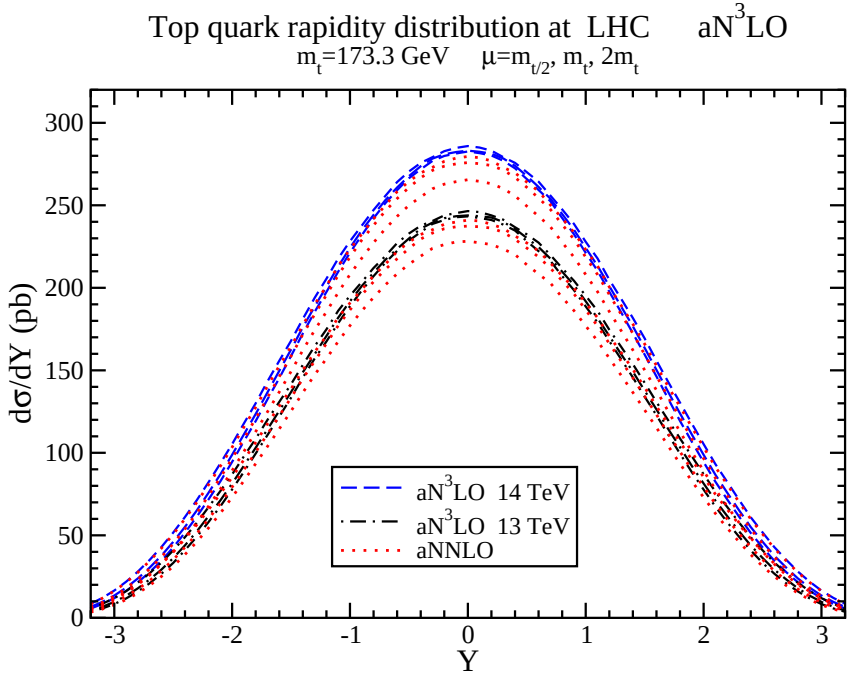
Boosted top quark p_T distribution at 8 TeV LHC



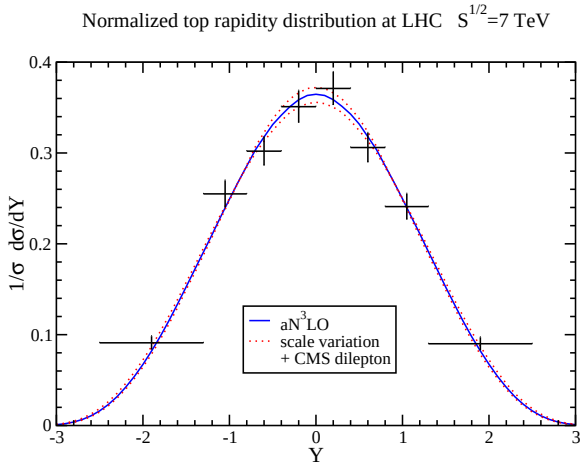


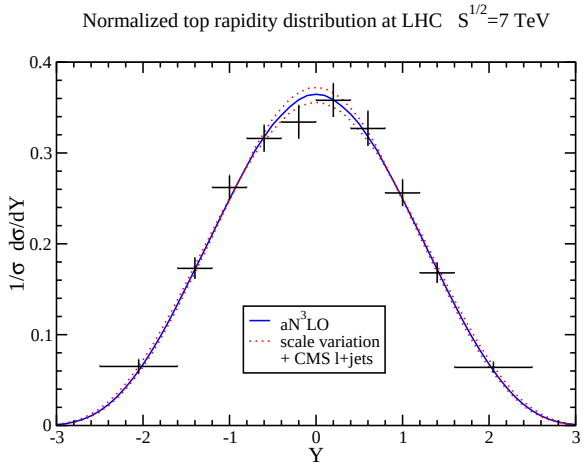
Top quark rapidity distribution at the LHC

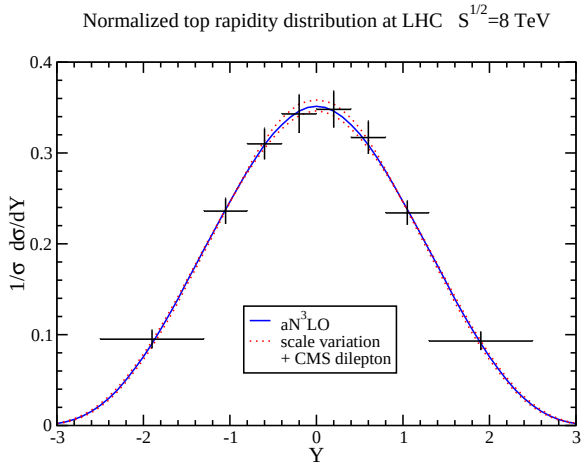


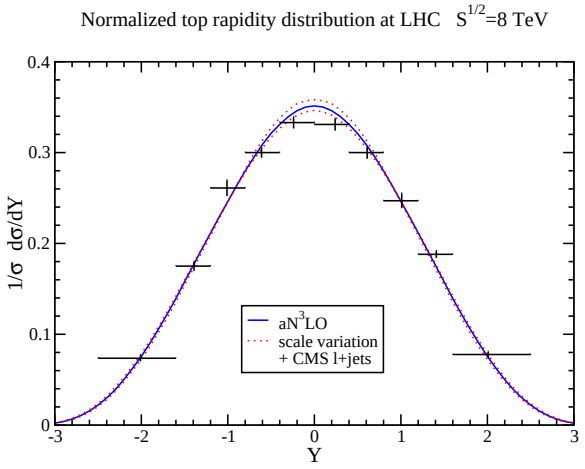


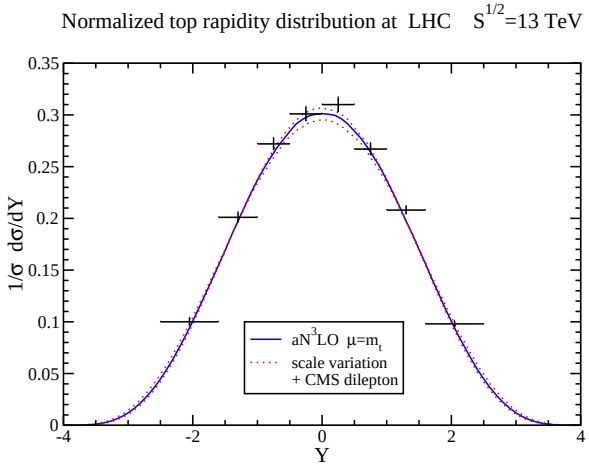
Normalized top quark rapidity distribution at the LHC

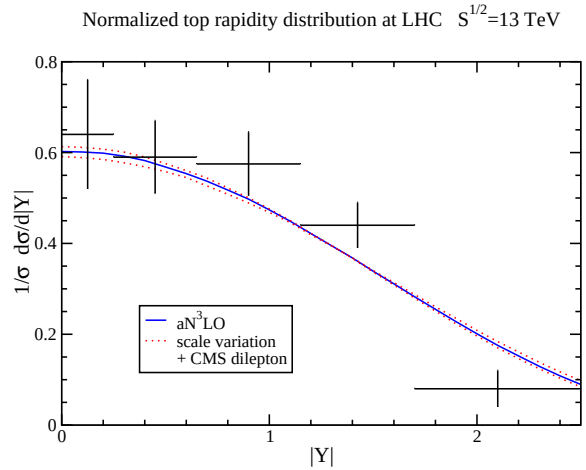




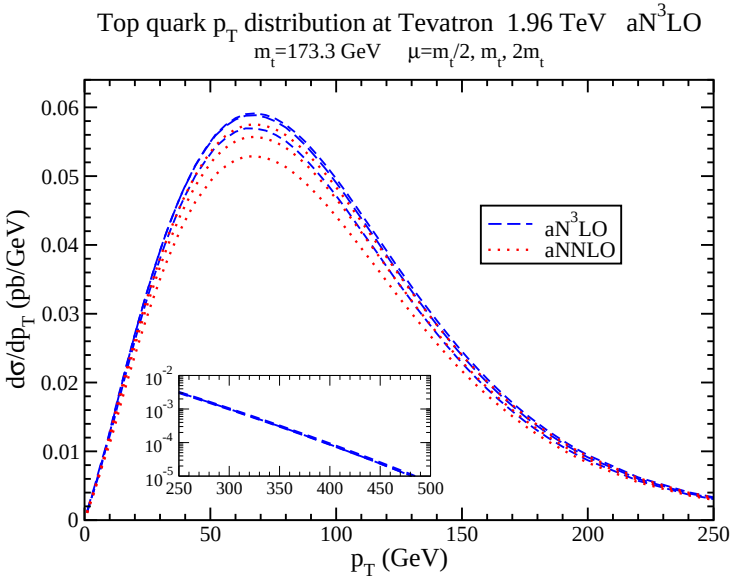


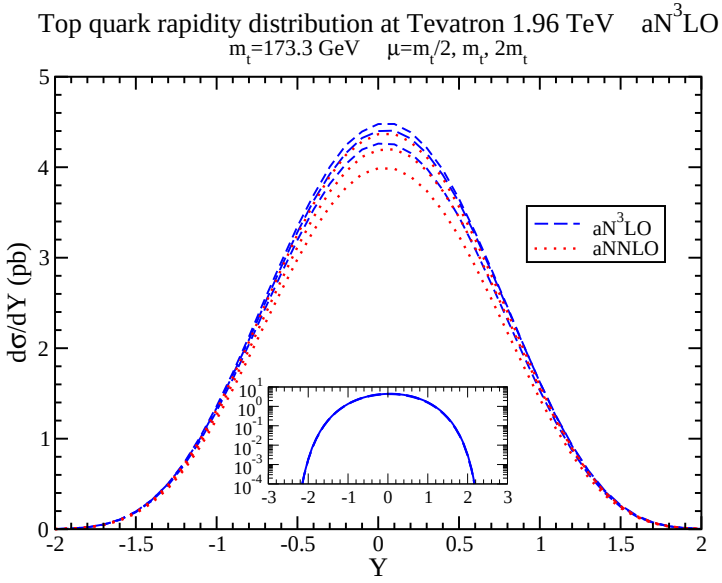


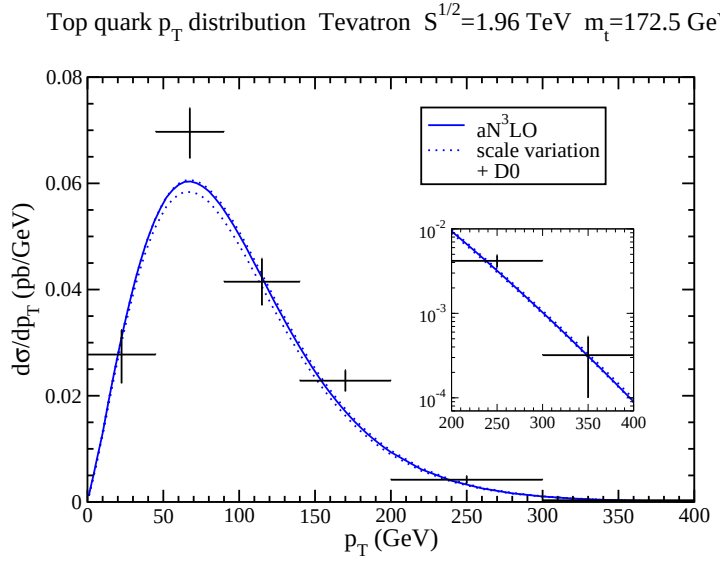


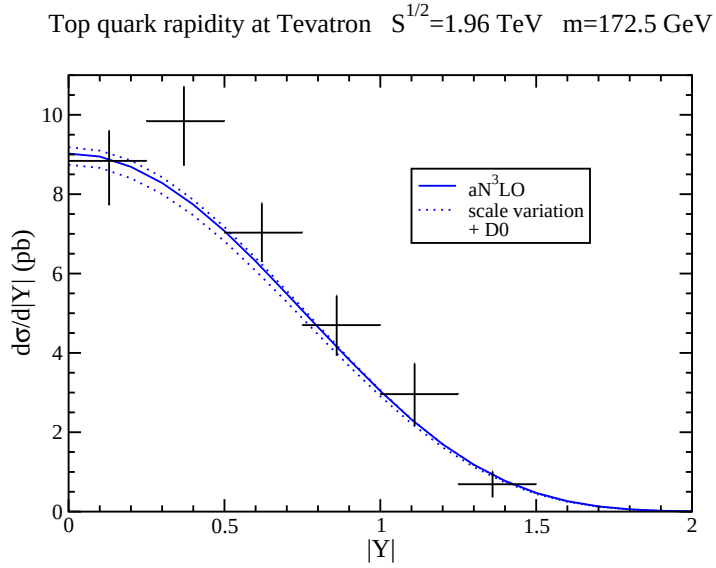


Top quark p_T and rapidity distributions at the Tevatron









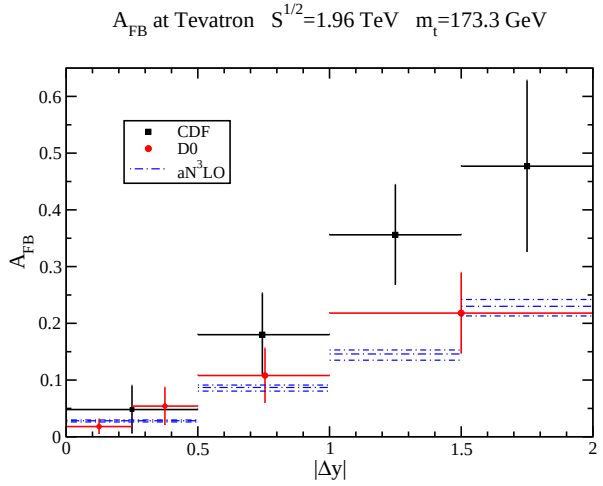
Top forward-backward asymmetry at the Tevatron

$$A_{\rm FB} = \frac{\sigma(y_t > 0) - \sigma(y_t < 0)}{\sigma(y_t > 0) + \sigma(y_t < 0)} \equiv \frac{\Delta\sigma}{\sigma}$$

large corrections: **aN^{3}LO/NNLO ratio is 1.05**

Top-quark asymmetry at the Tevatron		
aN^{3}LO A_{FB} %	$p\bar{p}$ frame	$t\bar{t}$ frame
QCD only	6.0 ± 0.1	8.7 ± 0.2
QCD+EW	6.8 ± 0.3	10.0 ± 0.6

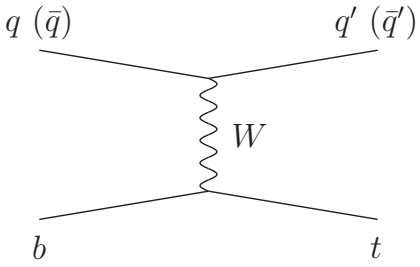
Top differential $A_{\rm FB}$: $A_{\rm FB}^{\rm bin} = \frac{\sigma^+_{\rm bin}(\Delta y) - \sigma^-_{\rm bin}(\Delta y)}{\sigma^+_{\rm bin}(\Delta y) + \sigma^-_{\rm bin}(\Delta y)}$ with $\Delta y = y_t - y_{\bar{t}}$



Single-top partonic processes at LO

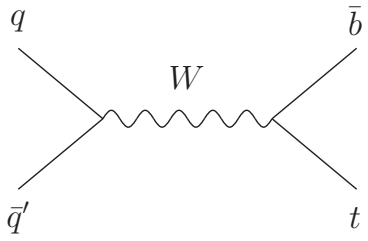
- **t channel: $qb \to q't$ and $\bar{q}b \to \bar{q}'t$**

dominant at Tevatron and LHC



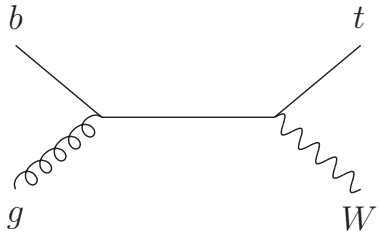
- **s channel: $q\bar{q}' \to \bar{b}t$**

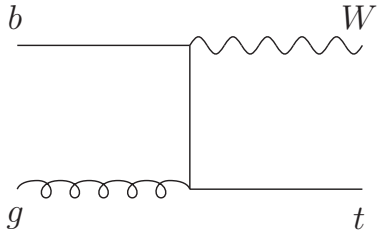
small at Tevatron and LHC



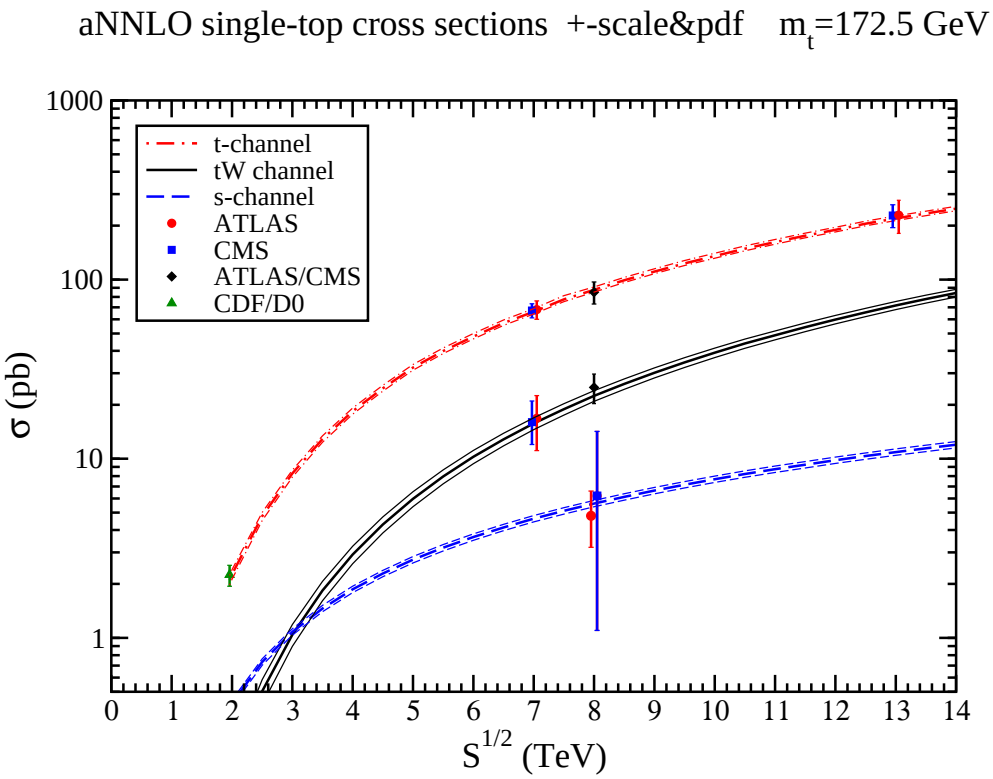
- **associated tW production: $bg \to tW^-$**

very small at Tevatron, significant at LHC





Single-top cross sections



Excellent agreement of theory with data for all three channels

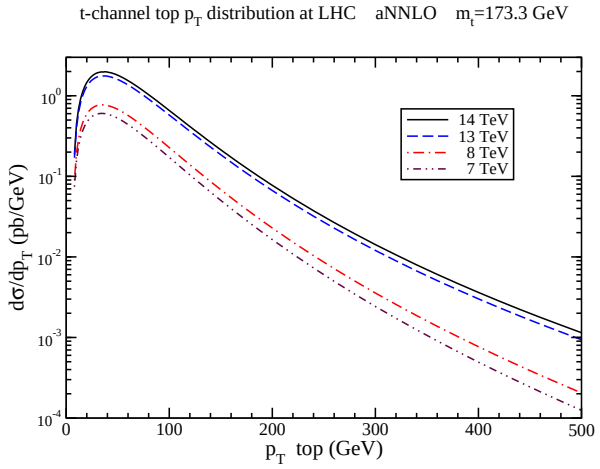
Single top t-channel production at aNNLO

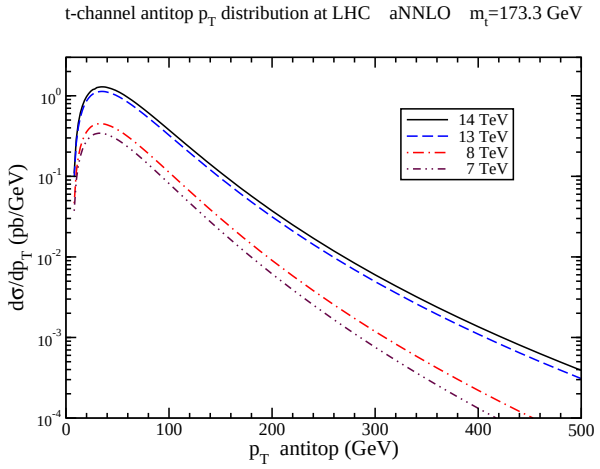
MMHT2014 NNLO pdf

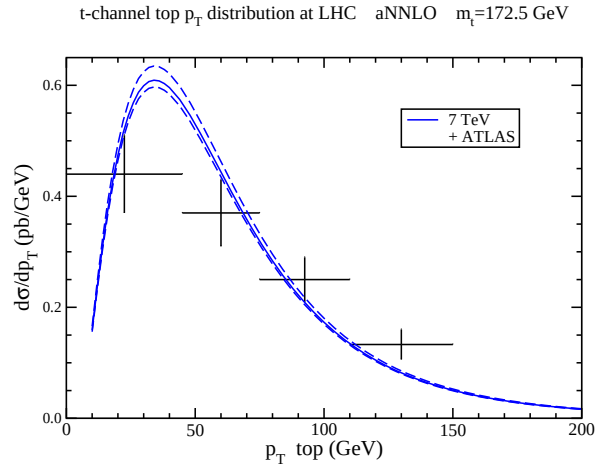
$m_t = 173.3$ **GeV**

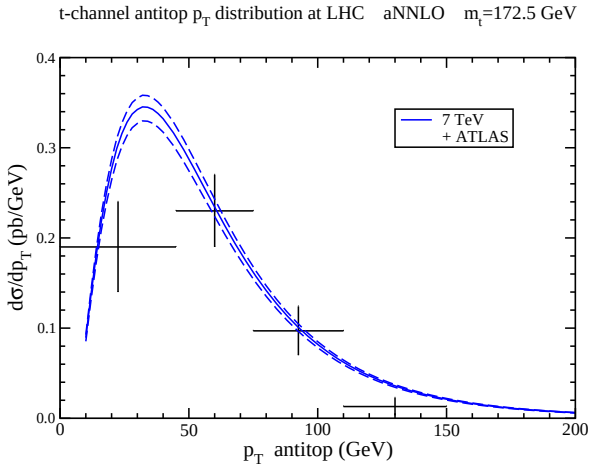
$\pm$ **scale** $\pm$ **pdf errors**

LHC	t	$\bar{t}$	Total (pb)
13 TeV	$138^{+3}_{-1} \pm 2$	$83^{+2}_{-1} \pm 1$	$221^{+5}_{-2} \pm 3$
14 TeV	$157^{+4}_{-1} \pm 2$	$95^{+2}_{-1} \pm 1$	$252^{+6}_{-2} \pm 3$

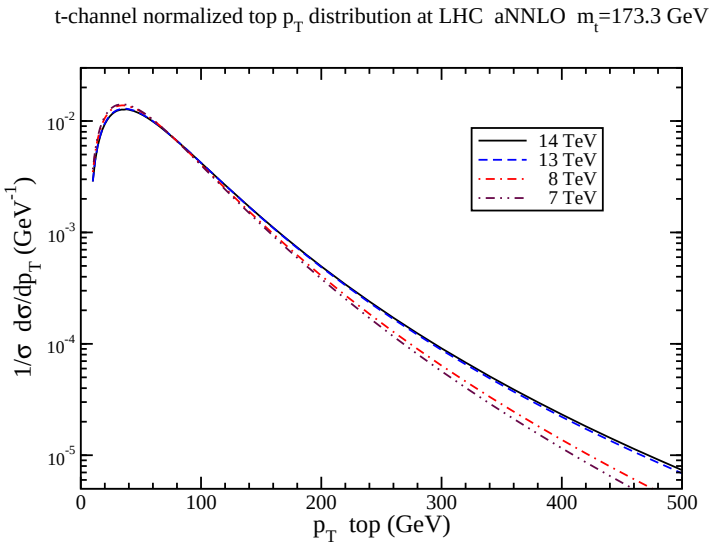


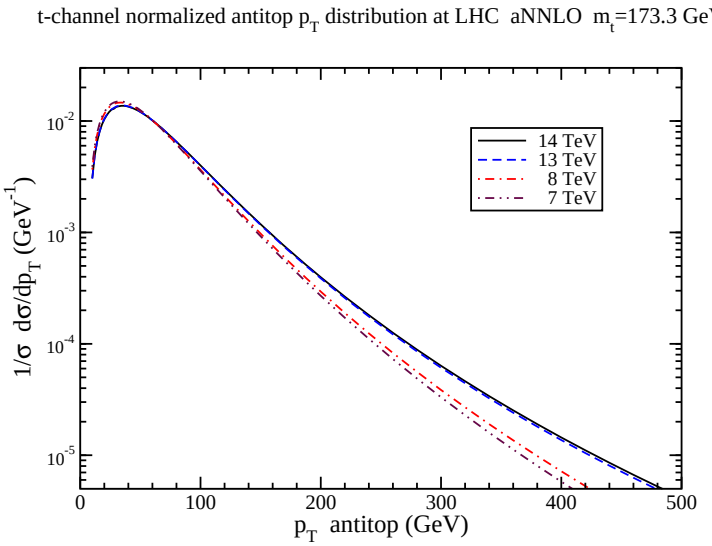


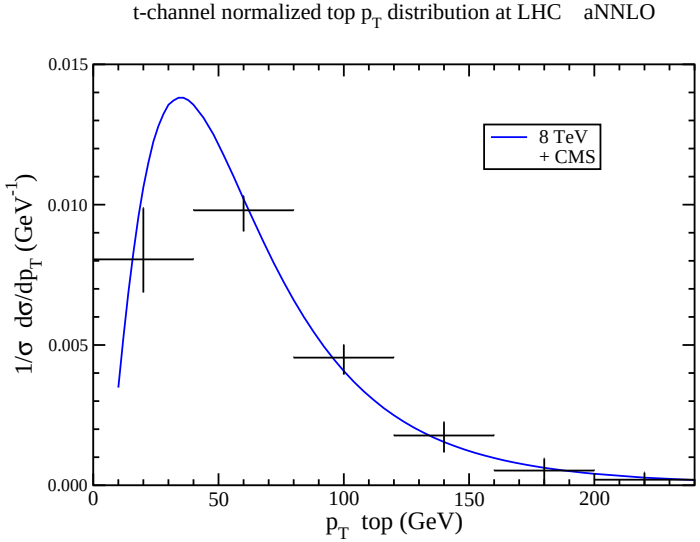


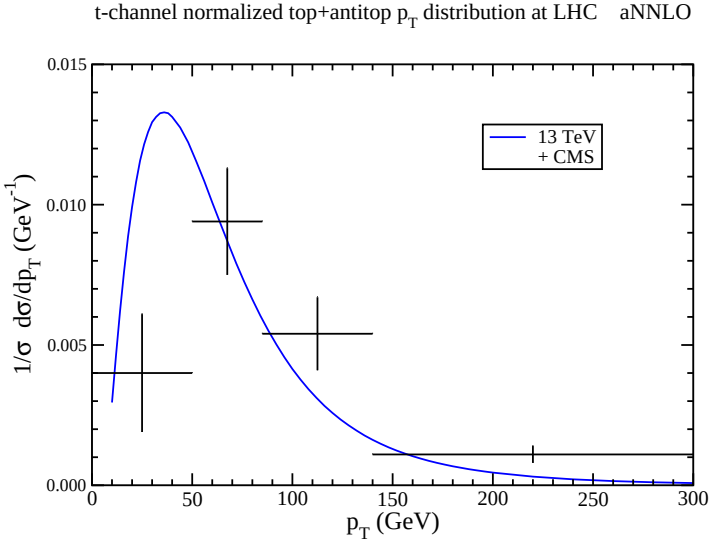


Single top t-channel aNNLO normalized p_T distributions at the LHC





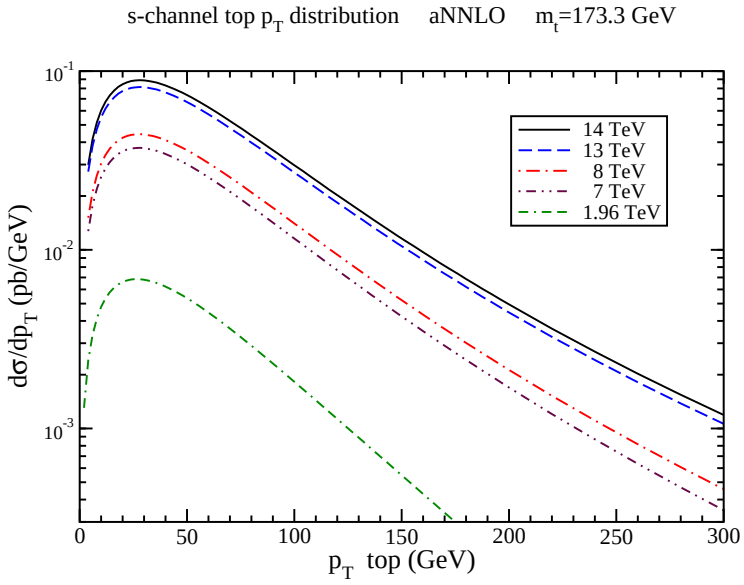


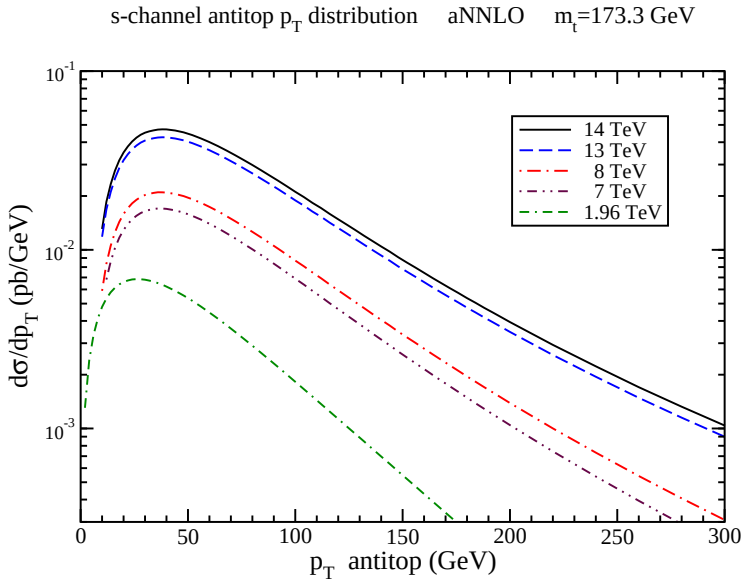


Single top s-channel production at aNNLO

LHC	t	$\bar{t}$	Total (pb)
13 TeV	$7.15 \pm 0.13^{+0.15}_{-0.17}$	$4.14 \pm 0.05 \pm 0.10$	$11.29 \pm 0.18 \pm 0.26$
14 TeV	$7.83 \pm 0.14 \pm 0.18$	$4.60 \pm 0.05 \pm 0.11$	$12.43 \pm 0.19 \pm 0.29$

($m_t = 173.3$ **GeV**) $\pm$ **scale** $\pm$ **pdf errors with MMHT2014 NNLO pdf**





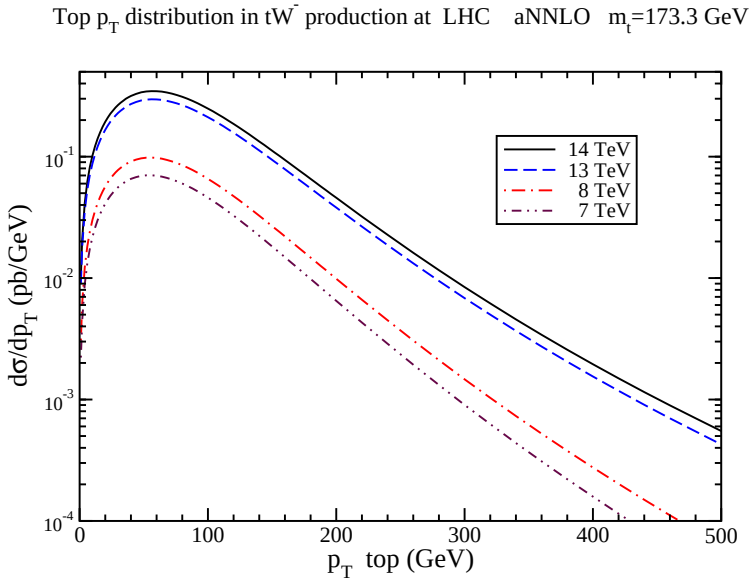
Associated tW^- production at aNNLO at the LHC

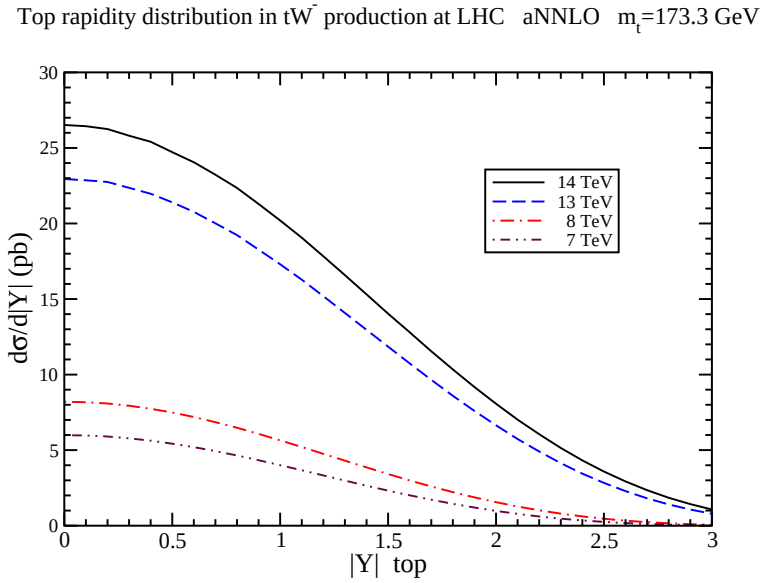
MMHT2014 NNLO pdf

$m_t = 173.3$ **GeV**

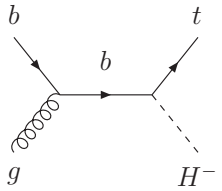
$\pm$ **scale** $\pm$ **pdf errors**

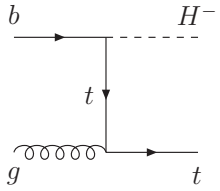
LHC	tW^-	$tW^- + \bar{t}W^+$ (pb)
13 TeV	$36.3 \pm 0.9 \pm 0.9$	$72.6 \pm 1.8 \pm 1.8$
14 TeV	$42.8 \pm 1.0 \pm 1.1$	$85.6 \pm 2.0 \pm 2.2$

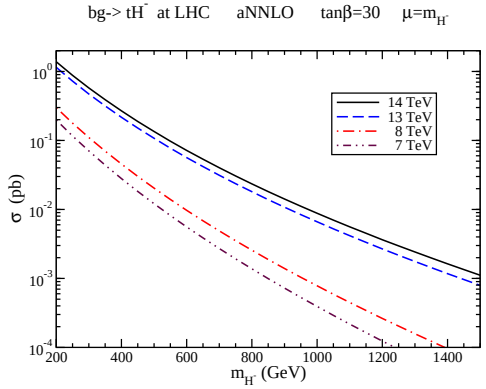


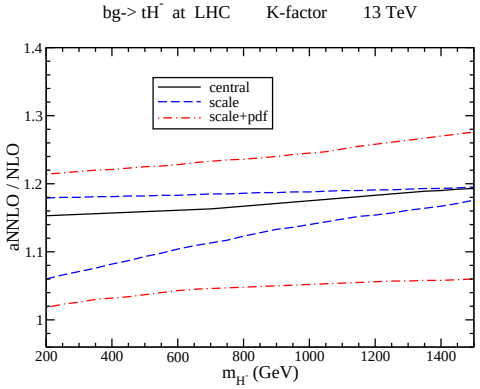


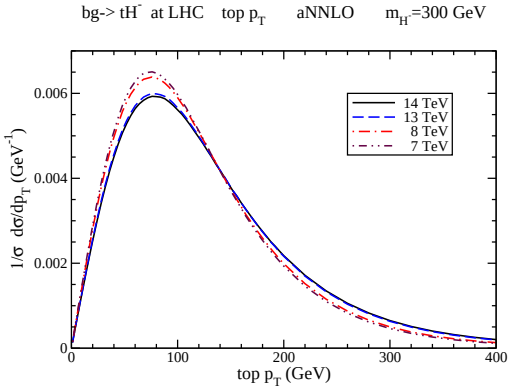
tH^- production

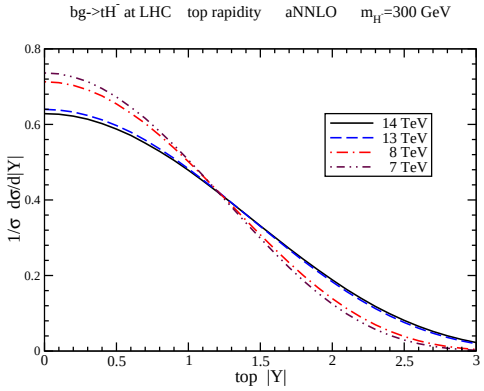




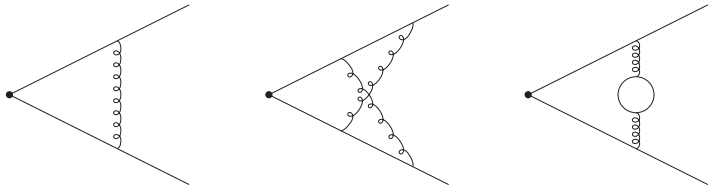








Cusp anomalous dimension



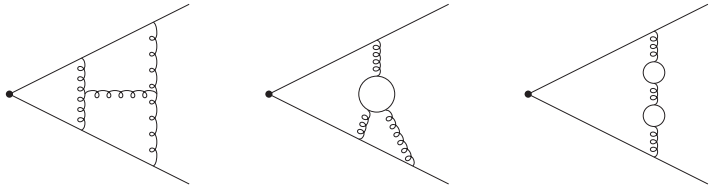
cusp angle $\theta = \cosh^{-1}(v_i \cdot v_j / \sqrt{v_i^2 v_j^2})$ **where** v_i **are velocity vectors**

$$\Gamma_{\rm cusp} = \sum_{n=1}^{\infty} \left(\frac{\alpha_s}{\pi}\right)^n \Gamma^{(n)}$$

$$\Gamma^{(1)} = C_F(\theta \coth\theta - 1)$$

$$\Gamma^{(2)} = \frac{K}{2}\Gamma^{(1)} + \frac{1}{2}C_F C_A \left\{1 + \zeta_2 + \theta^2 - \coth\theta\left[\zeta_2\theta + \theta^2 + \frac{\theta^3}{3} + {\rm Li}_2\left(1 - e^{-2\theta}\right)\right] + \coth^2\theta\left[-\zeta_3 + \zeta_2\theta + \frac{\theta^3}{3} + \theta\,{\rm Li}_2\left(e^{-2\theta}\right) + {\rm Li}_3\left(e^{-2\theta}\right)\right]\right\}$$

where $K = C_A(67/18 - \zeta_2) - 5n_f/9$



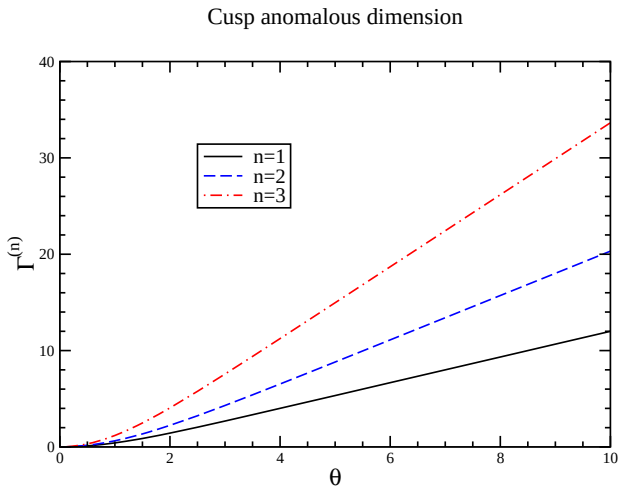
$$\Gamma^{(3)} \quad = \quad C^{(3)} + K^{'(3)}\Gamma^{(1)} + K\left[\Gamma^{(2)} - \frac{K}{2}\Gamma^{(1)}\right]$$

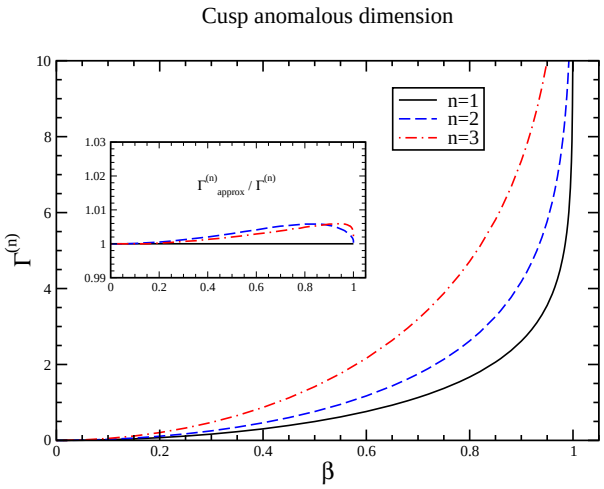
where $K^{'(n)} = K^{(n)}/C_F$

n-loop conjecture

$$\Gamma^{(n)} \quad = \quad \sum_{k=1}^{n} \frac{(n-1)!}{(k-1)!\,(n-k)!}\, K^{'(k)}\, C^{(n-k+1)}\,.$$

$$\Gamma^{(n)} \quad = \quad C^{(n)} + \sum_{k=2}^{n} \frac{(n-1)!}{(k-1)!\,(n-k)!}\, F^{(k)}\, \Gamma^{(n-k+1)}$$





Numerical approximations with $n_f = 5$

$$\Gamma^{(2)}_{\rm approx}(\beta) \quad = \quad -0.38649\,\beta^2 + 1.72704\,\Gamma^{(1)}(\beta)$$

$$\Gamma^{(3)}_{\rm approx}(\beta) \quad = \quad 0.09221\,\beta^2 + 2.80322\,\Gamma^{(1)}(\beta)$$

with $\beta = \tanh(\theta/2)$

Summary

- **cross sections and distributions for $t\bar{t}$ through aN^{3}LO**

  top quark p_T and rapidity distributions

  top quark forward-backward asymmetry

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

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

- **excellent agreement with LHC and Tevatron data**

- **cusp anomalous dimension at high orders**