High-precision theory for top-quark production

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- **Top-antitop pair production**
- **Single-top production**
- **Associated top production with bosons**
- **Top production via anomalous couplings**

supported by NSF

Top-antitop pair production

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

fixed-order NNLO calculations - analytical and numerical

(different approaches - many groups)

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

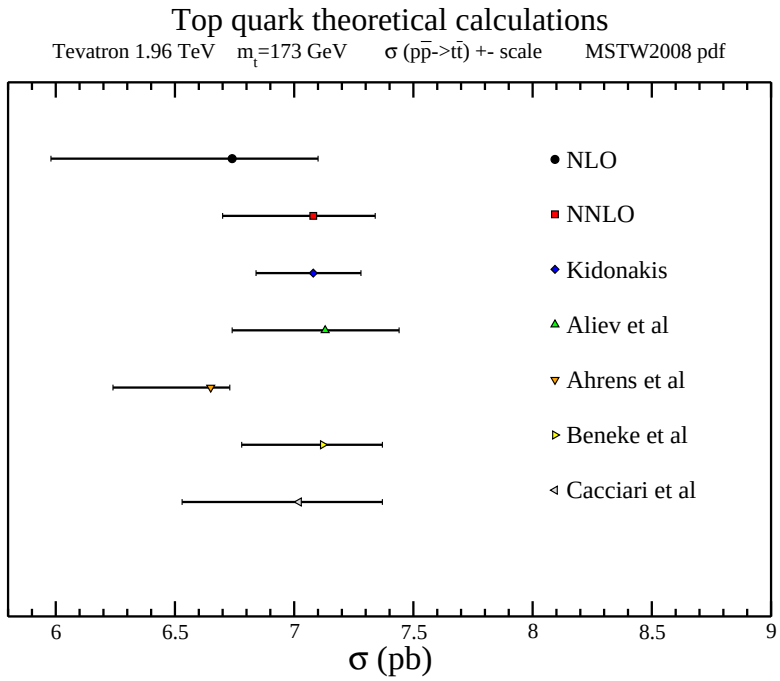
Calculate/resum these soft corrections at NNLL accuracy
– various approaches

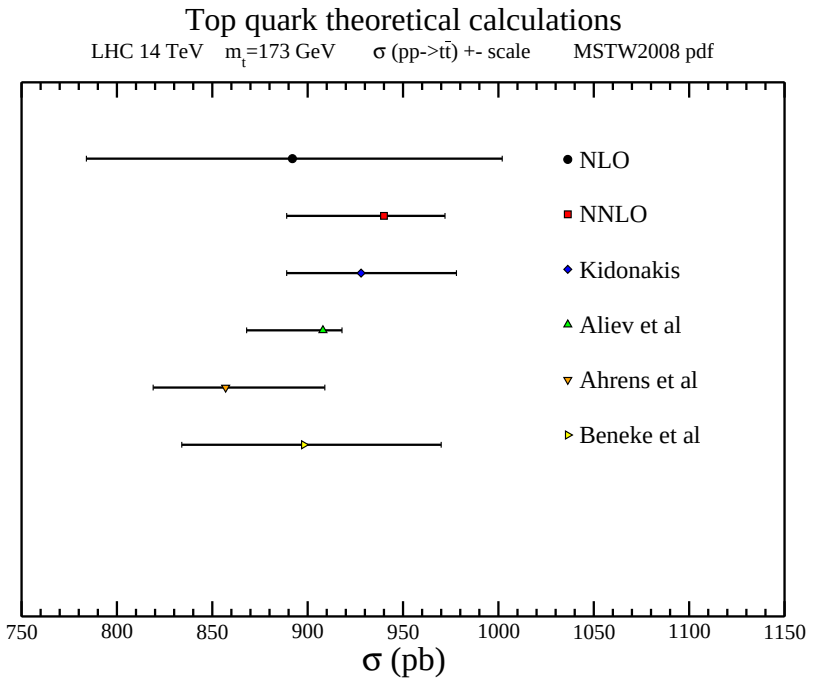
Approximate N^{3}LO (aN^{3}LO) predictions for cross sections are derived by adding third-order soft corrections to fixed-order results

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

Comparison of various approx NNLO predictions

all with the same choice of parameters





Kidonakis, PRD 82, 114030 (2010) differential-pQCD

Aliev *et al*, CPC 182, 1034 (2011) total-pQCD

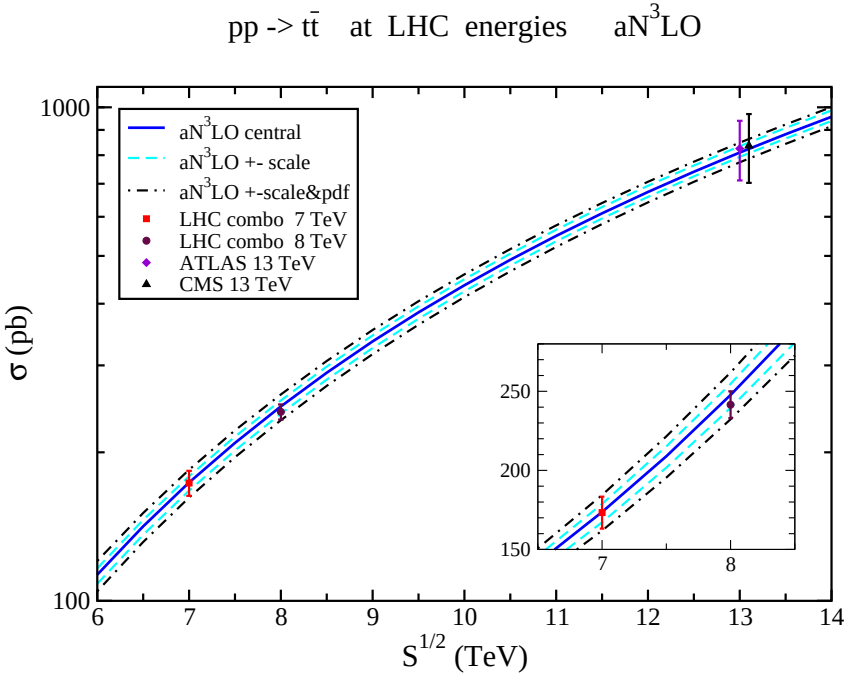
Ahrens *et al*, PLB 703, 135 (2011) differential-SCET

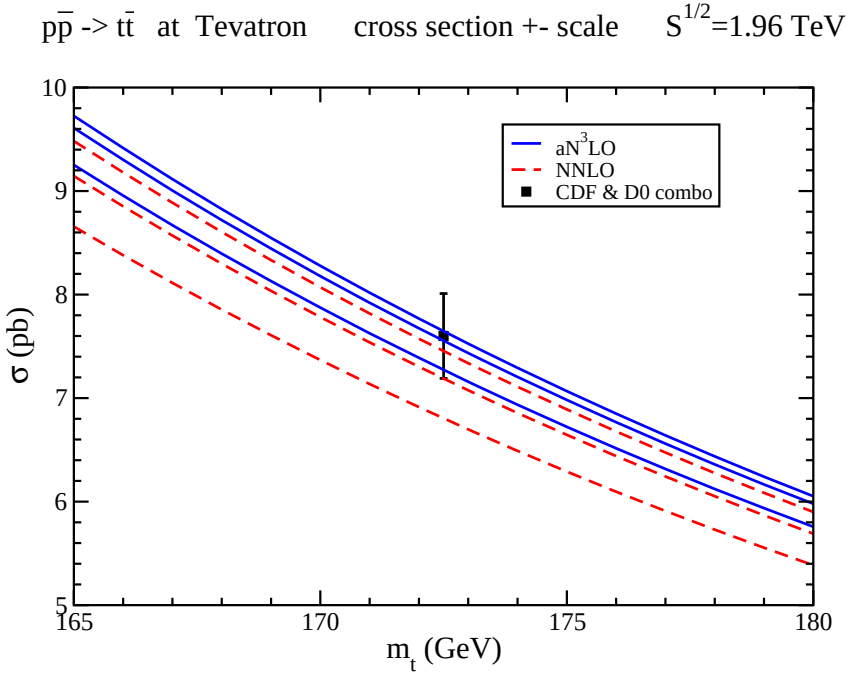
Beneke *et al*, NPB 855, 695 (2012) total-SCET

Cacciari *et al*, PLB 710, 612 (2012) total-pQCD

differences in accuracies of approximations

Top-pair cross sections at the LHC and the Tevatron





aN^{3}LO total $t\bar{t}$ cross sections with $m_t = 173.3$ GeV

LHC 13 TeV: $810^{+24\,+30}_{-16\,-32}$ **pb**

LHC 14 TeV: $957^{+28\,+34}_{-19\,-36}$ **pb**

NK, Phys. Rev. D 90, 014006 (2014) [arXiv:1405.7046 [hep-ph]]

Relative size of perturbative corrections

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

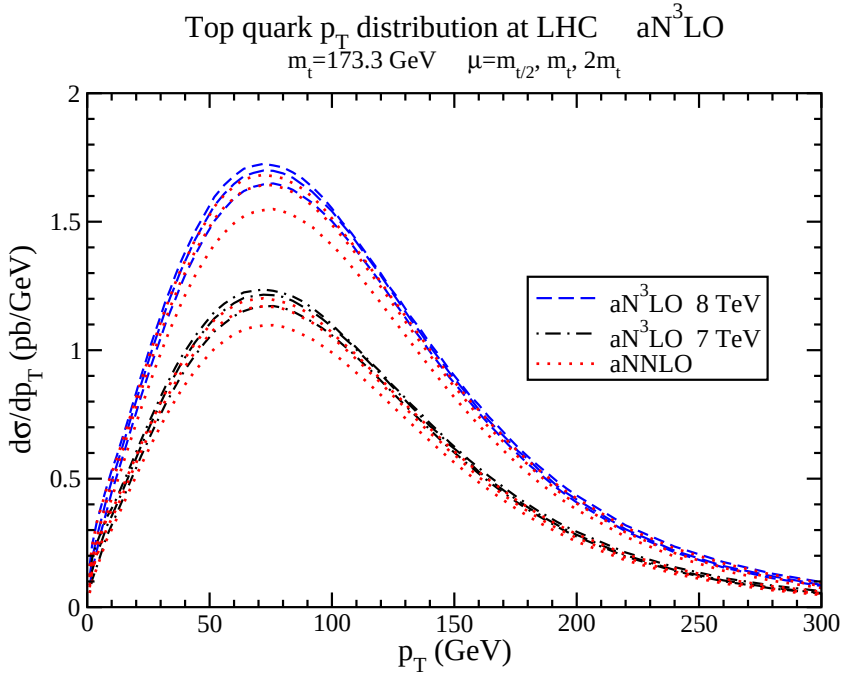
Fractional contributions to the perturbative series for the $t\bar{t}$ cross section					
corrections	Tevatron 1.96 TeV	LHC 7 TeV	LHC 8 TeV	LHC 13 TeV	LHC 14 TeV
$\sigma^{(1)}/\sigma^{(0)}$	0.236	0.470	0.476	0.493	0.496
$\sigma^{(2)}/\sigma^{(0)}$	0.106	0.178	0.177	0.172	0.170
$\sigma^{(\rm a3)}/\sigma^{(0)}$	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

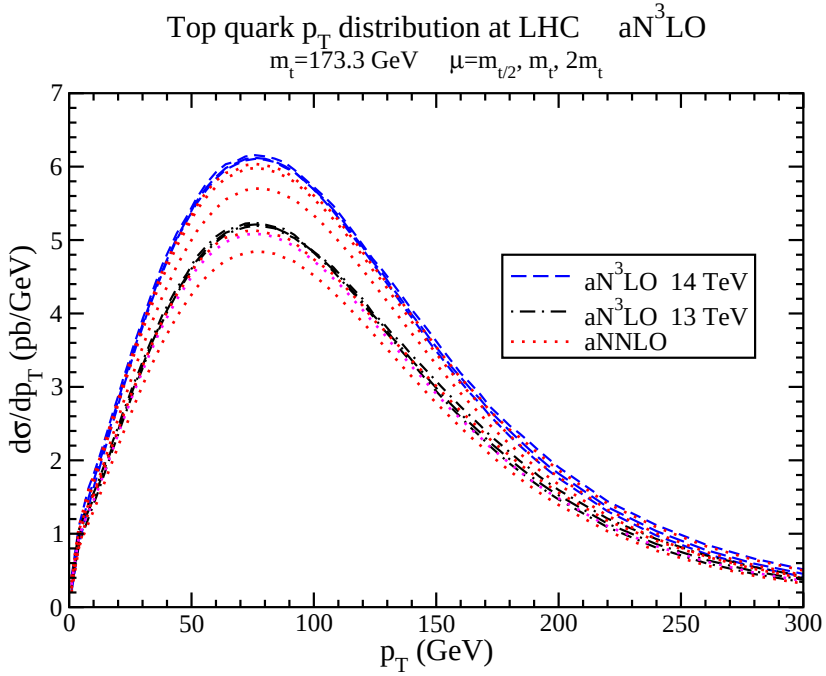
Higher-order corrections are sizable for total cross sections and also for differential distributions

NNLO is not enough

aN^{3}LO needed for precision physics

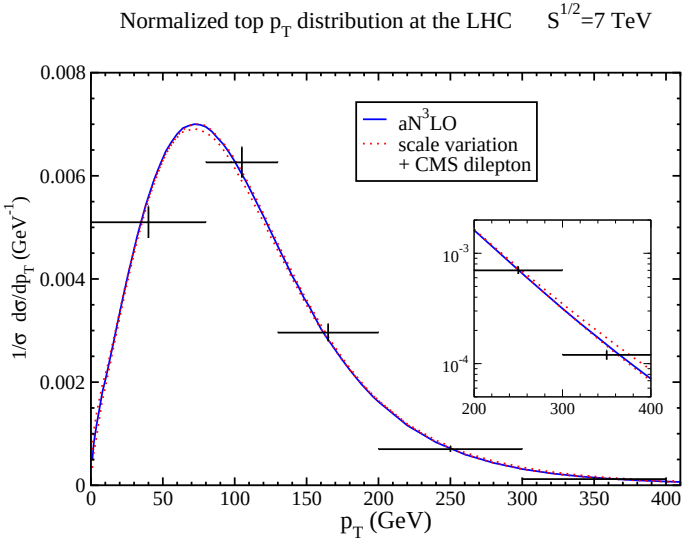
Top quark p_T distribution at the LHC

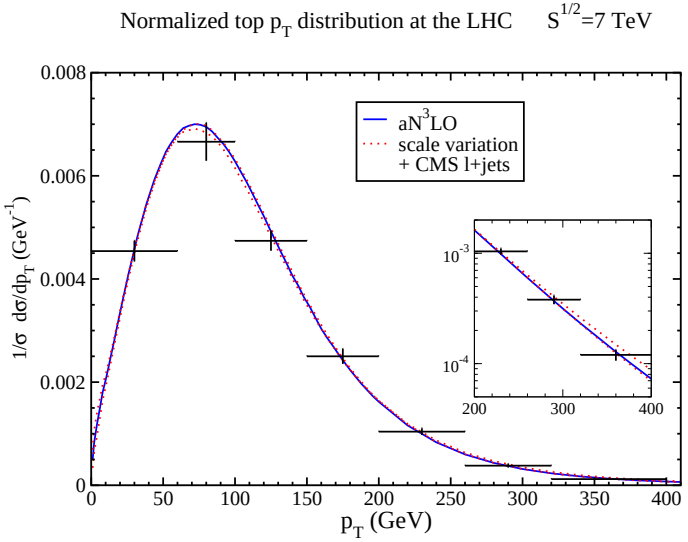


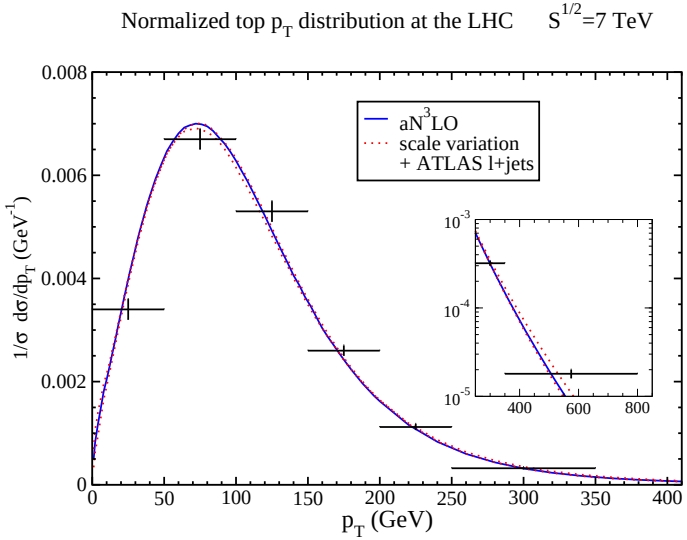


NK, Phys. Rev. D 91, 031501 (2015) [arXiv:1411.2633 [hep-ph]]

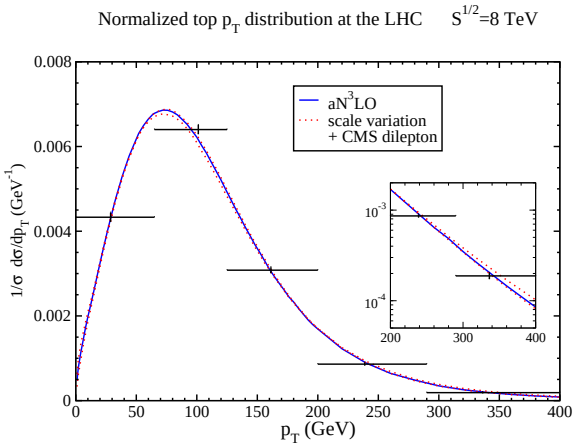
Normalized top quark p_T distribution at 7 TeV LHC

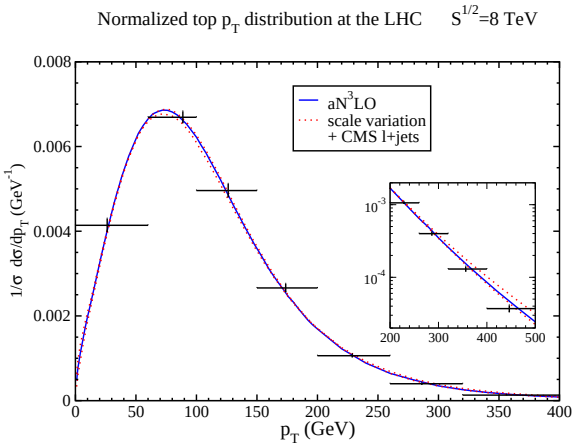


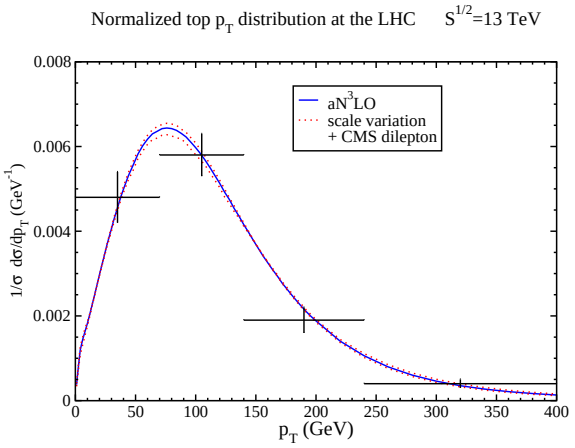




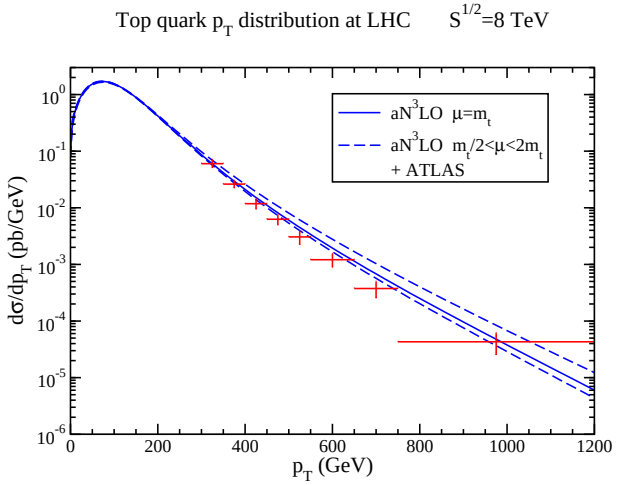
Normalized top quark p_T distribution at 8 and 13 TeV LHC

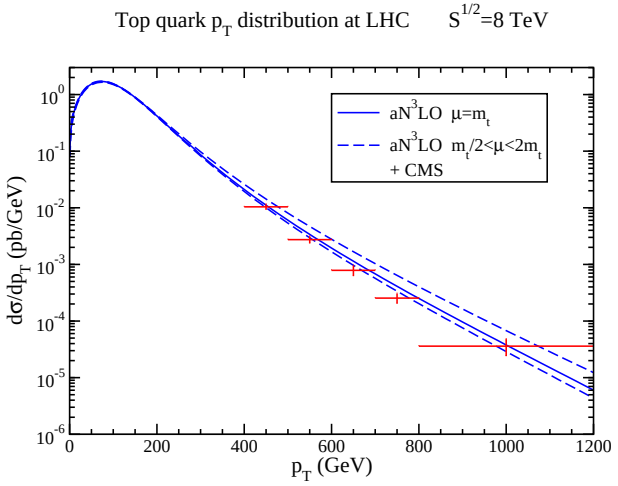




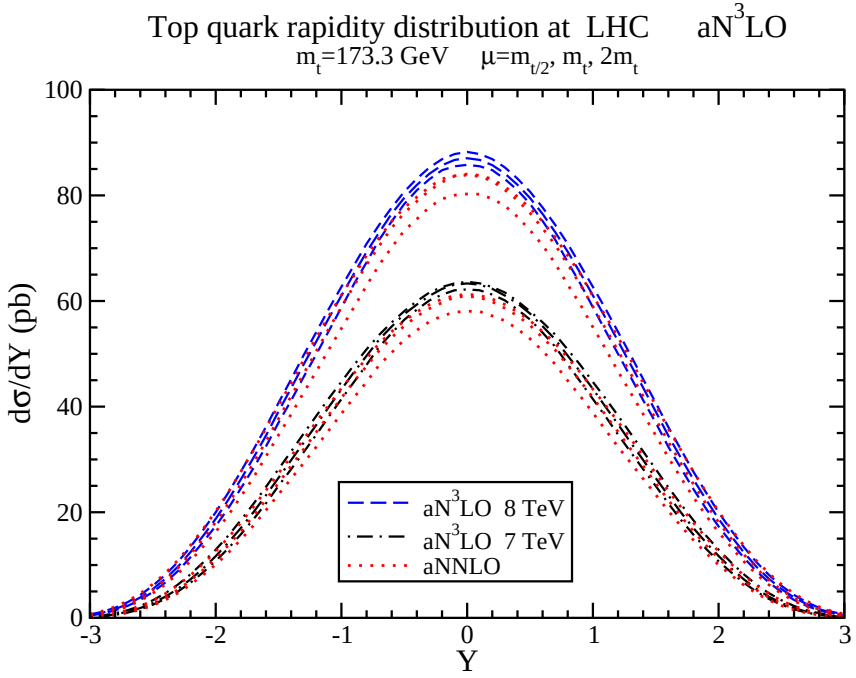


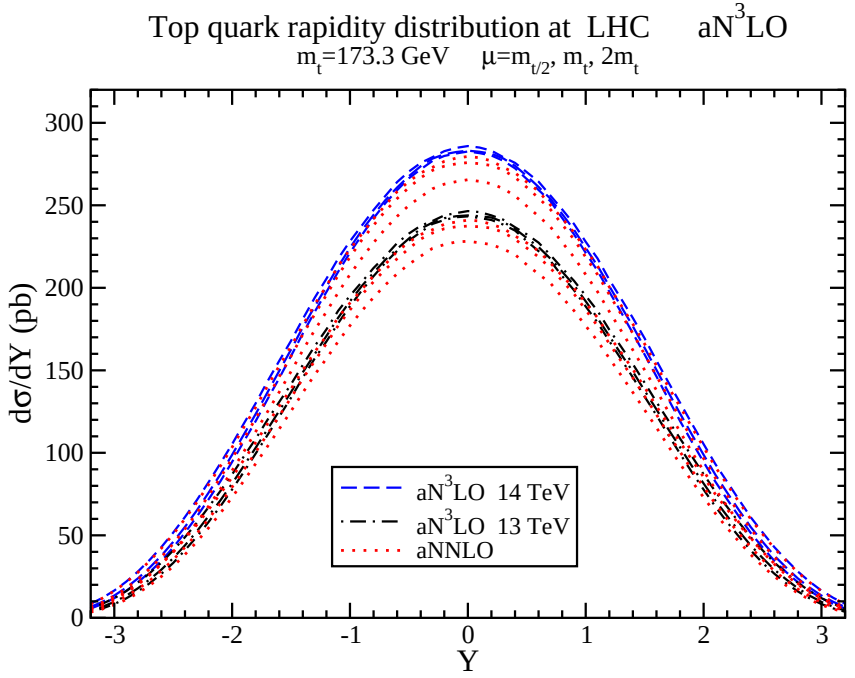
Boosted top quark p_T distribution at 8 TeV LHC





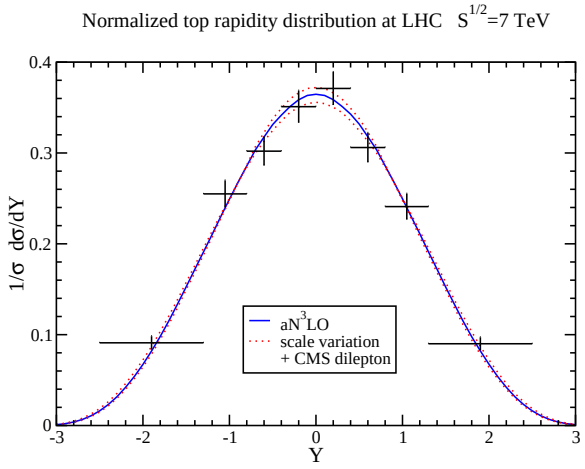
Top quark rapidity distribution at the LHC

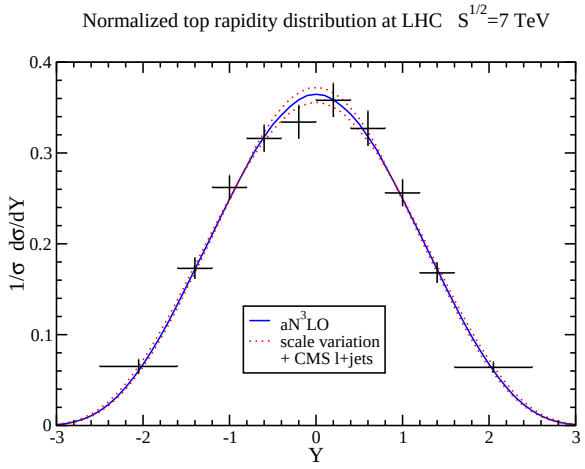


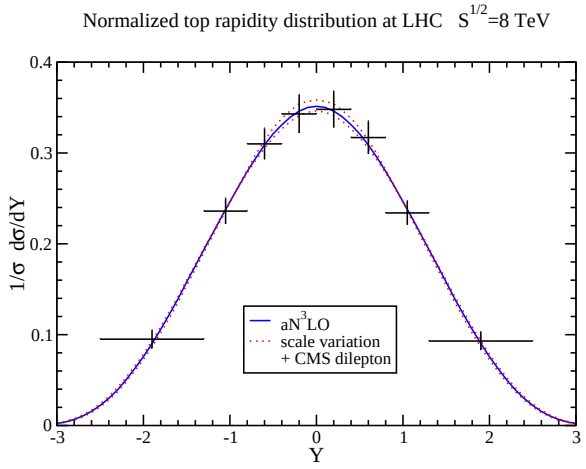


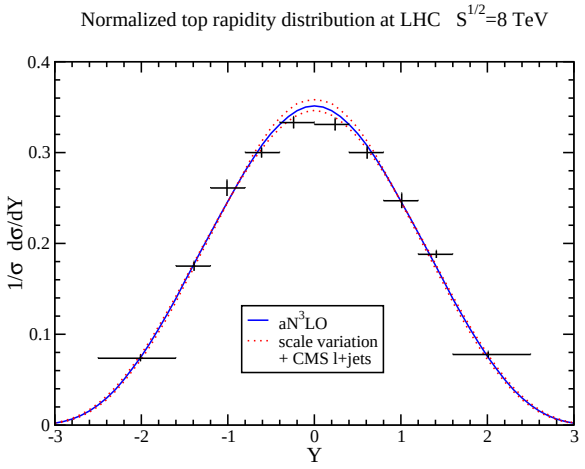
NK, Phys. Rev. D 91, 031501 (2015) [arXiv:1411.2633 [hep-ph]]

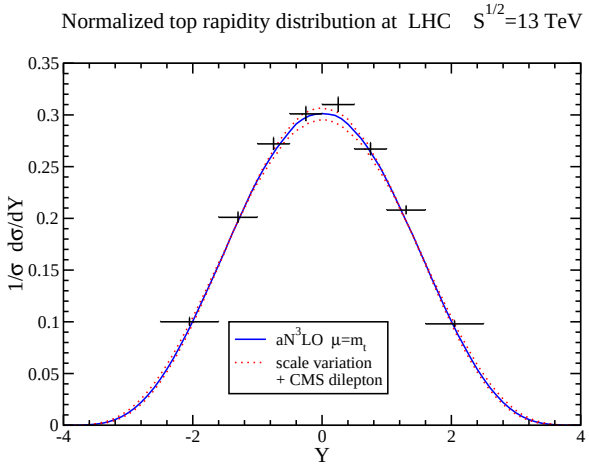
Normalized top quark rapidity distribution at the LHC

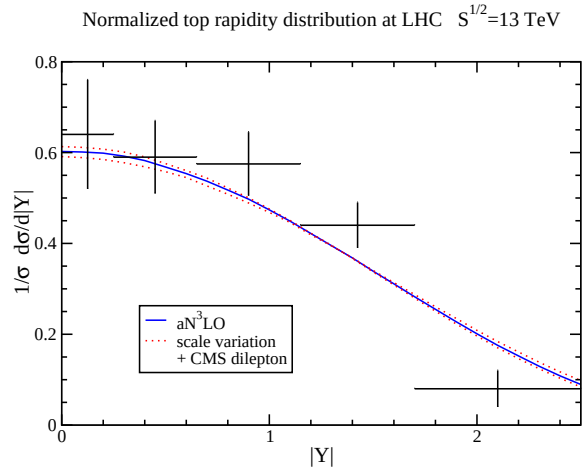




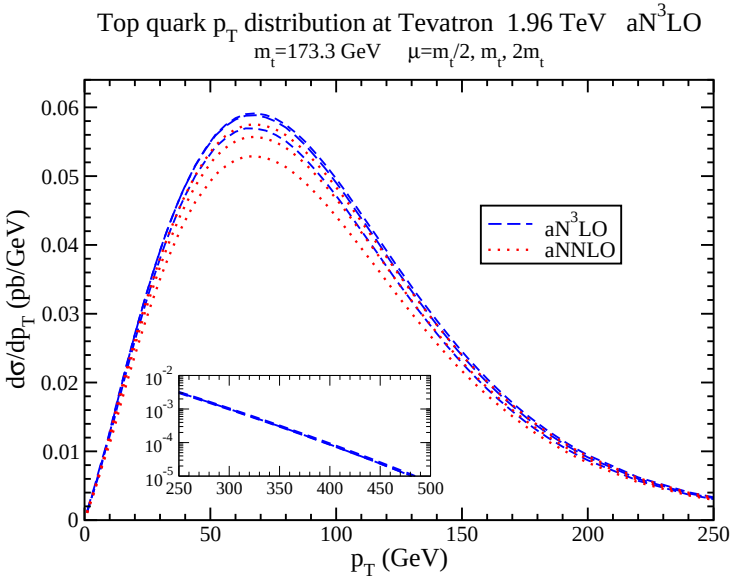


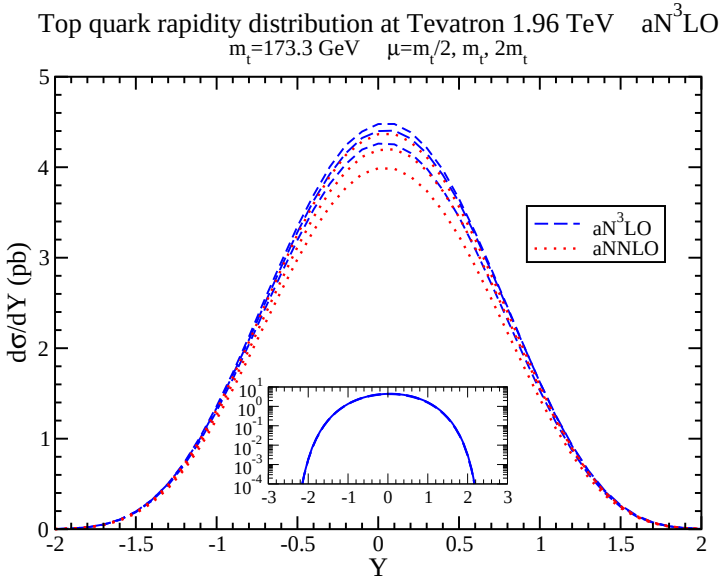


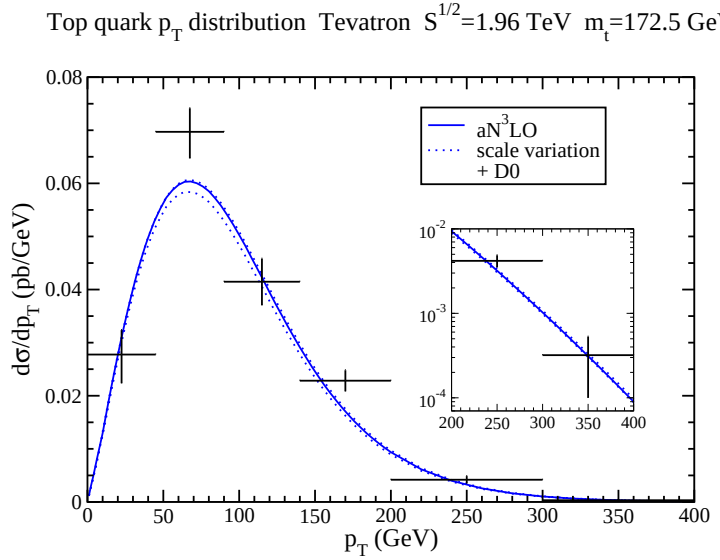


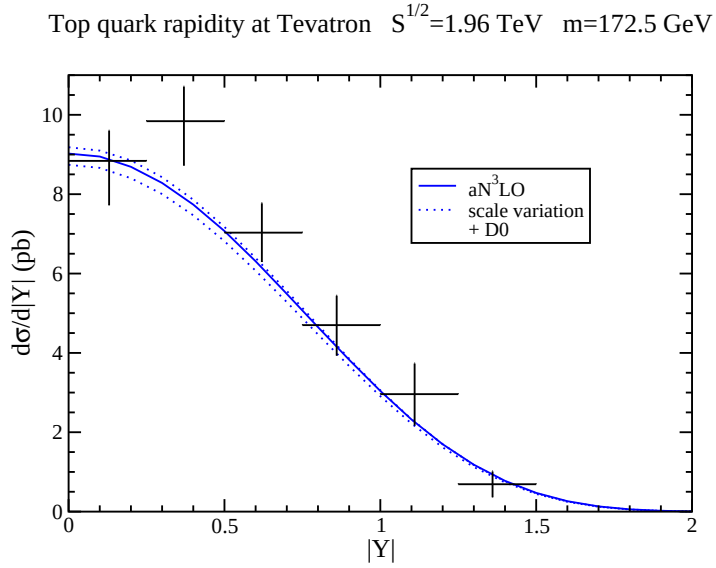


Top quark p_T and rapidity distributions at the Tevatron









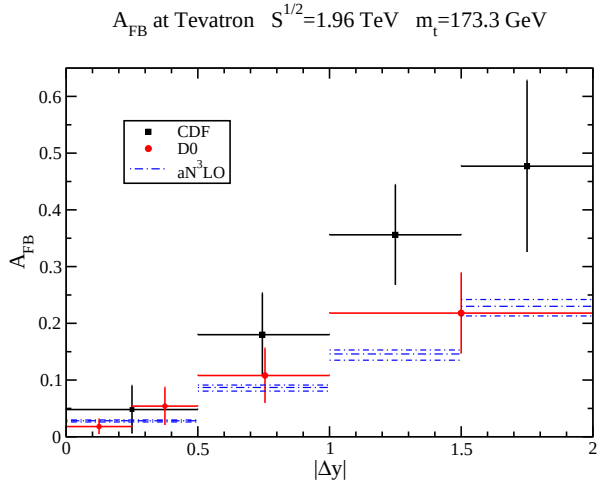
Top forward-backward asymmetry at the Tevatron

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

large corrections: **aN^{3}LO/NNLO ratio is 1.05** **NK, Phys. Rev. D 91, 071502 (2015) [arXiv:1501.01581]**

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

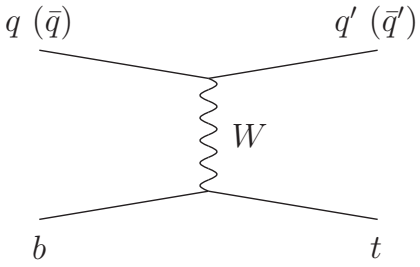
Top differential $A_{\rm FB}$: $A_{\rm FB}^{\rm bin} = \frac{\sigma^+_{\rm bin}(\Delta y) - \sigma^-_{\rm bin}(\Delta y)}{\sigma^+_{\rm bin}(\Delta y) + \sigma^-_{\rm bin}(\Delta y)}$ with $\Delta y = y_t - y_{\bar{t}}$



Single-top partonic processes at LO

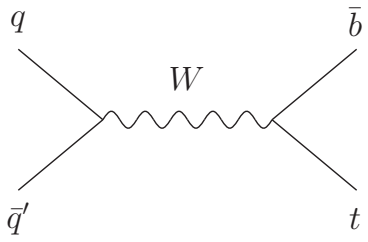
- **t channel: $qb \to q't$ and $\bar{q}b \to \bar{q}'t$**

dominant at Tevatron and LHC



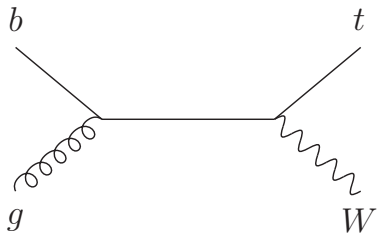
- **s channel: $q\bar{q}' \to \bar{b}t$**

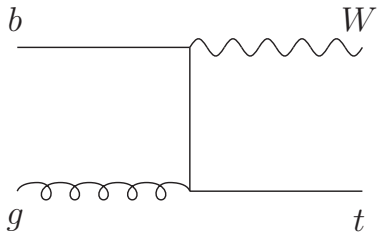
small at Tevatron and LHC



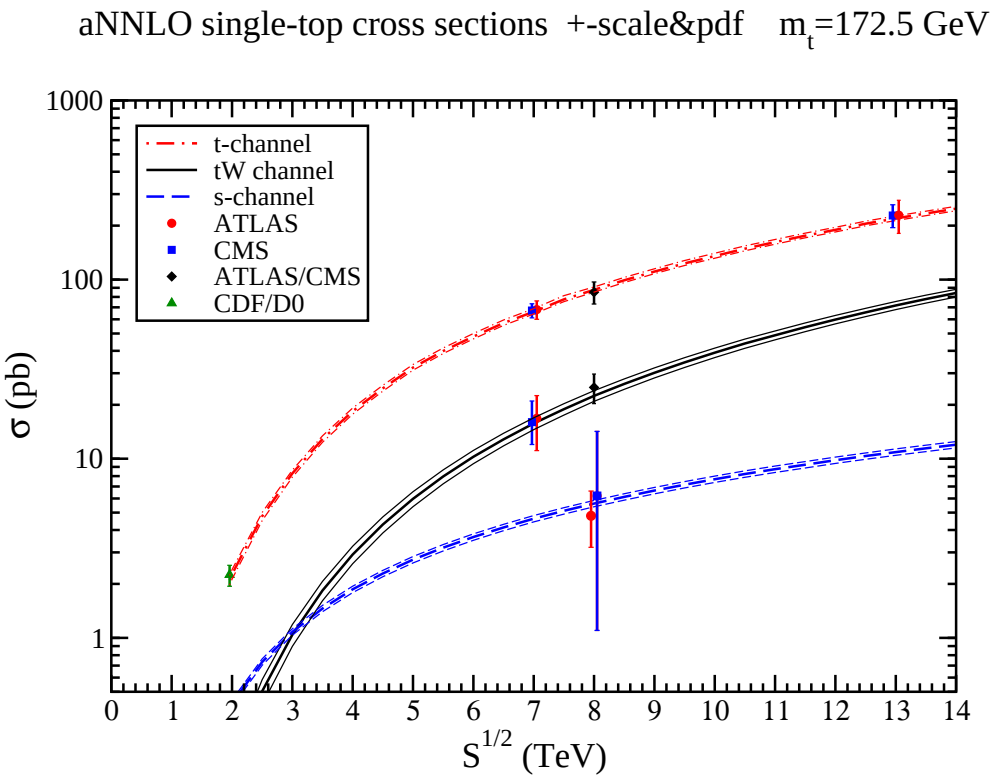
- **associated tW production: $bg \to tW^-$**

very small at Tevatron, significant at LHC





Single-top cross sections



Excellent agreement of theory with data for all three channels

NK, PRD 81, 054028 (2010); PRD 82, 054018 (2010); PRD 83, 091503(R) (2011)

Single top t-channel production at aNNLO

$m_t = 173.3$ **GeV**

LHC	t	$\bar{t}$	Total (pb)
13 TeV	$136^{+3}_{-1} \pm 3$	$82^{+2}_{-1} \pm 2$	$218^{+5}_{-2} \pm 5$
14 TeV	$154^{+4}_{-1} \pm 3$	$94^{+2\,+2}_{-1\,-3}$	$248^{+6\,+5}_{-2\,-6}$

$\pm$ scale $\pm$ pdf errors with MSTW2008 NNLO pdf 90% CL

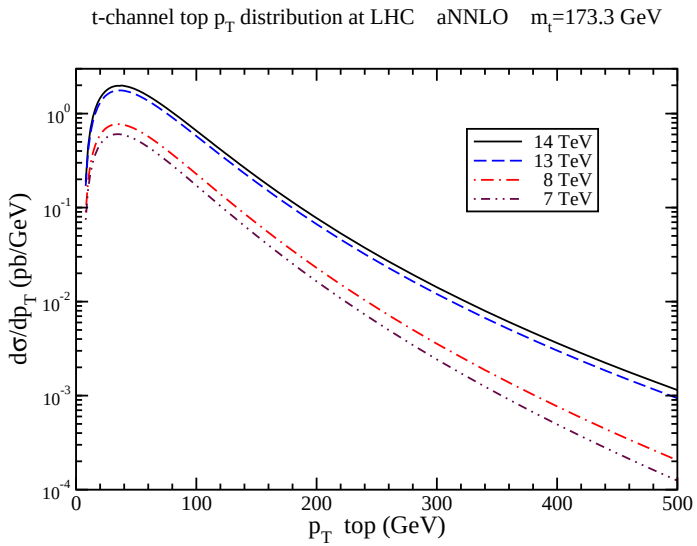
ratio $\sigma(t)/\sigma(\bar{t}) = 1.82^{+0.10}_{-0.09}$ at 8 TeV

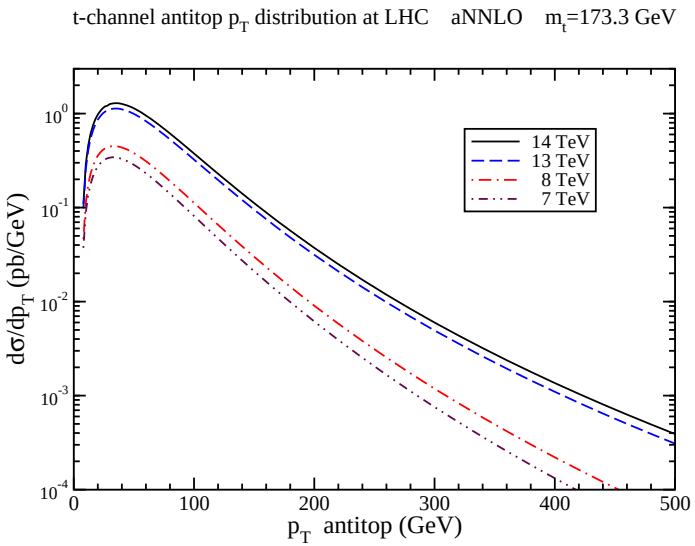
- compares well with CMS result $1.95 \pm 0.10 \pm 0.19$

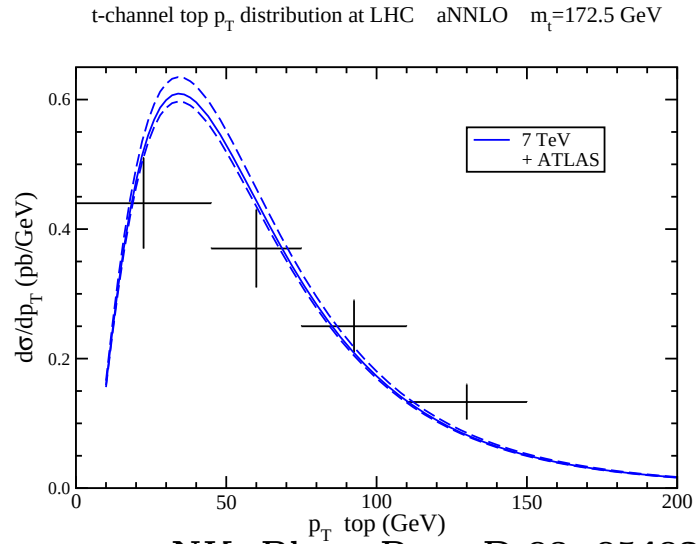
agrees with NNLO result of

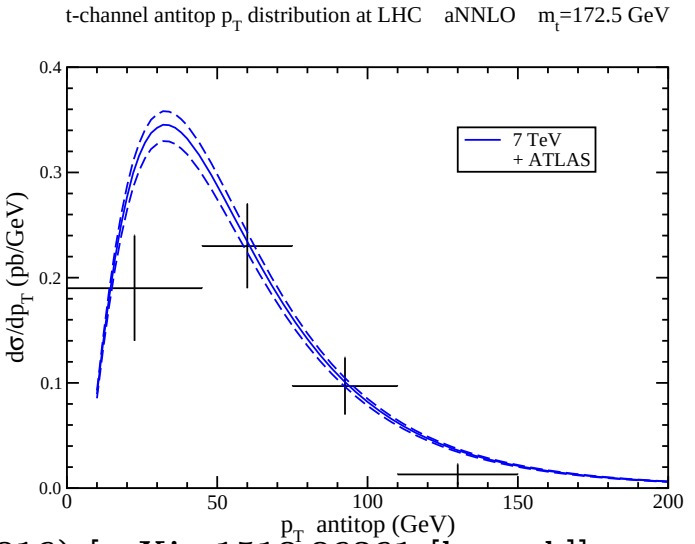
Brucherseifer, Caola, Melnikov, Phys. Lett. B 736, 58 (2014) [1404.7116 [hep-ph]]

Single top t-channel aNNLO p_T distributions at the LHC



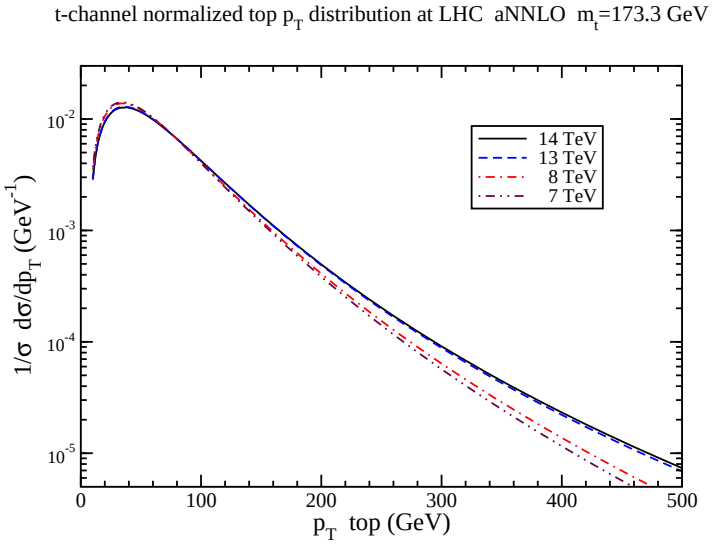


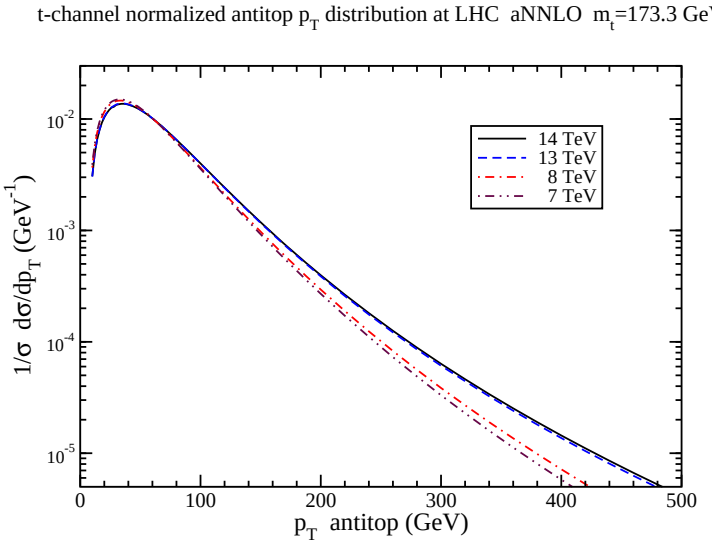


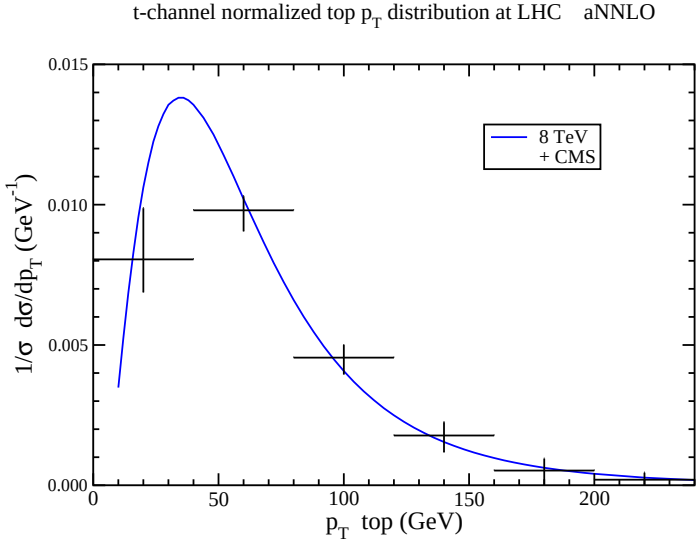


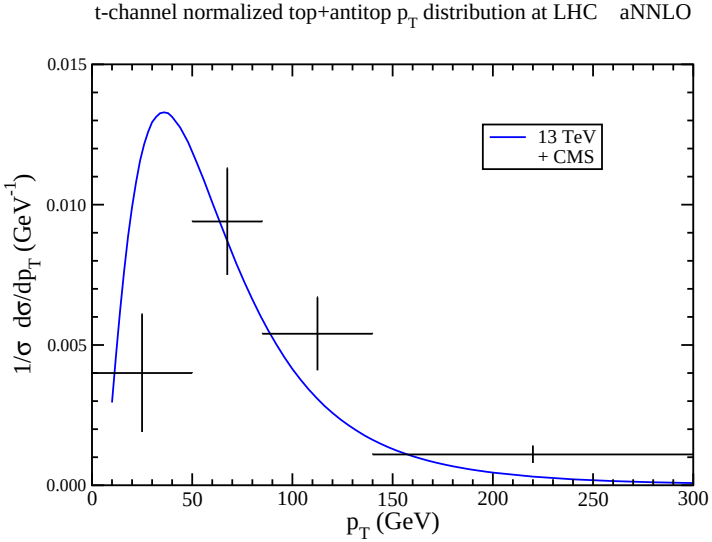
NK, Phys. Rev. D 93, 054022 (2016) [arXiv:1510.06361 [hep-ph]]

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





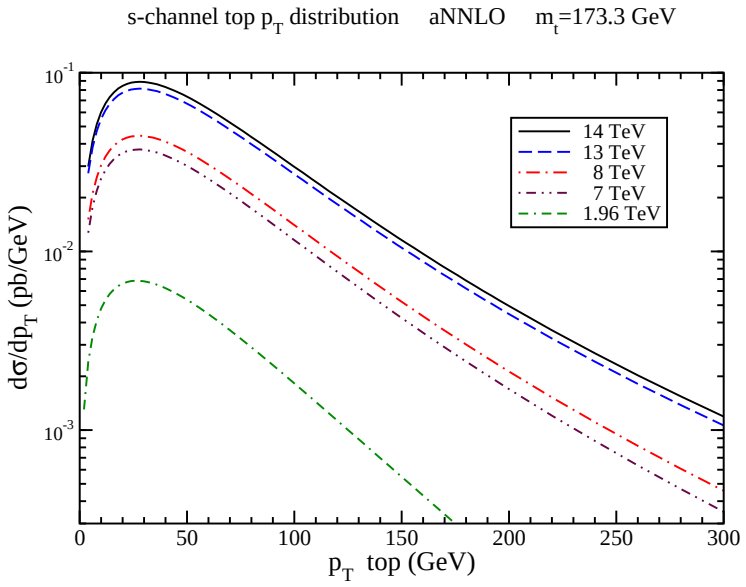


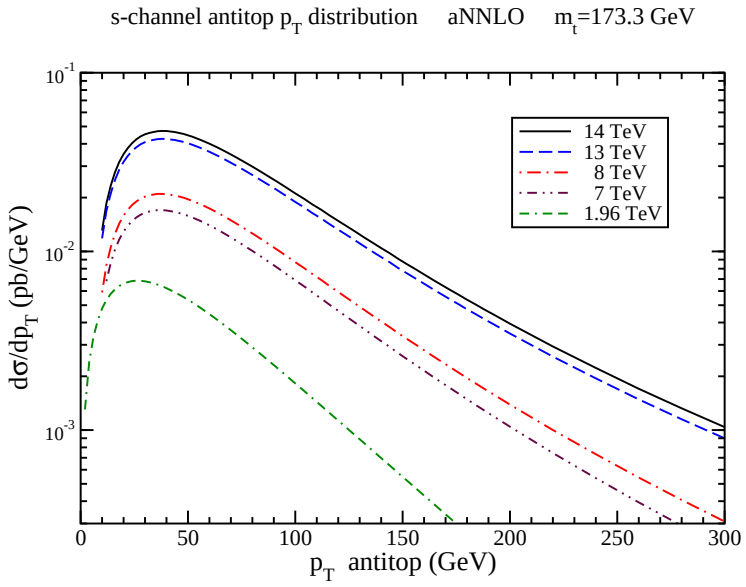


Single top s-channel production at aNNLO

LHC	t	$\bar{t}$	Total (pb)
13 TeV	$7.07 \pm 0.13^{+0.24}_{-0.22}$	$4.10 \pm 0.05^{+0.14}_{-0.16}$	$11.17 \pm 0.18 \pm 0.38$
14 TeV	$7.79 \pm 0.14^{+0.31}_{-0.24}$	$4.57 \pm 0.05^{+0.18}_{-0.17}$	$12.35 \pm 0.19^{+0.49}_{-0.41}$

($m_t = 173.3$ GeV) $\pm$ scale $\pm$ pdf errors with MSTW2008 NNLO pdf 90% CL



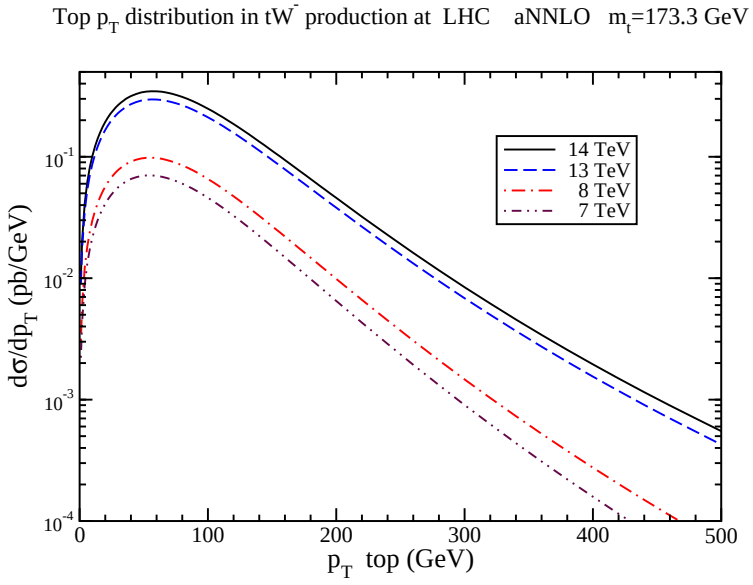


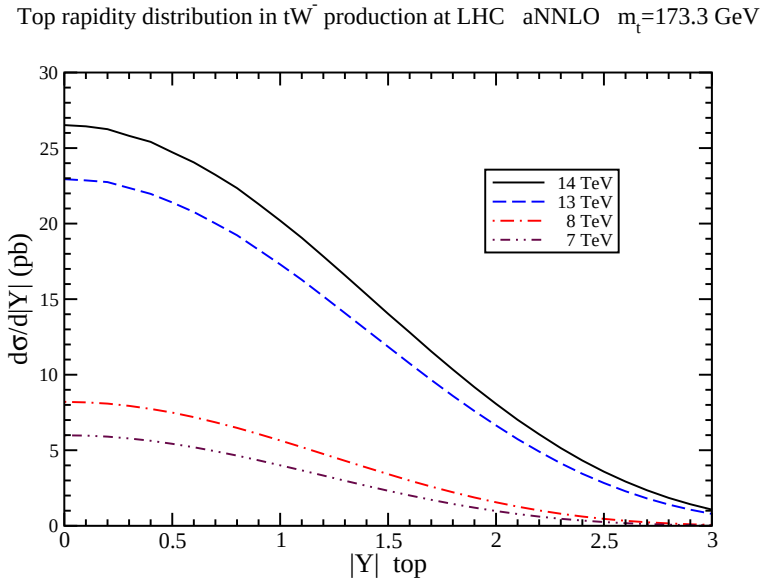
Associated tW^- production at aNNLO at the LHC

$m_t = 173.3$ **GeV**

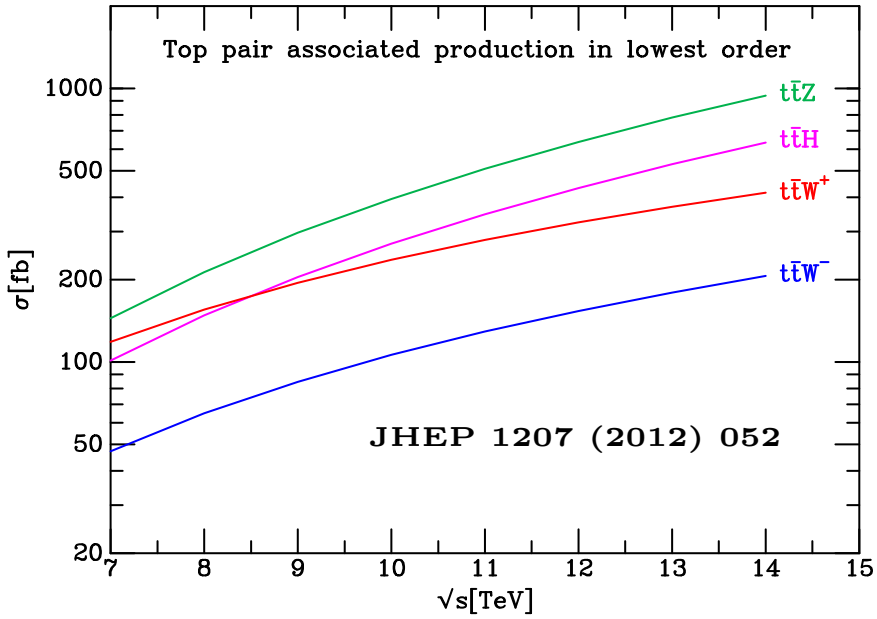
LHC	tW^-	$tW^- + \bar{t}W^+$ (pb)
13 TeV	$35.2 \pm 0.9^{+1.6}_{-1.7}$	$70.4 \pm 1.8^{+3.2}_{-3.4}$
14 TeV	$41.6 \pm 1.0^{+1.5}_{-2.3}$	$83.1 \pm 2.0^{+3.1}_{-4.6}$

$\pm$ scale $\pm$ pdf errors with MSTW2008 NNLO pdf 90% CL





Associated production of a $t\bar{t}$ pair with bosons



NLO: $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}\gamma$ **production**

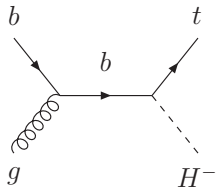
NLO+NLL: $t\bar{t}H$ **production**

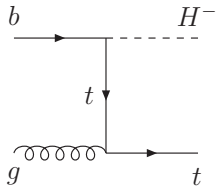
Associated production of a single top with bosons

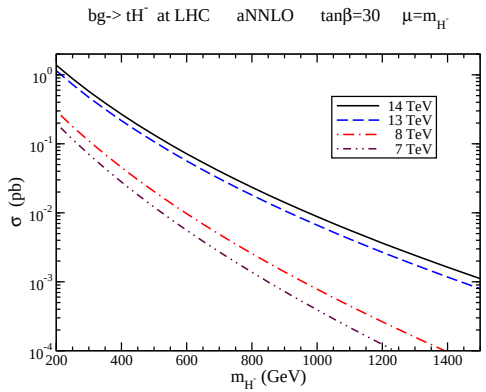
NLO: tH **and** tZ **production**

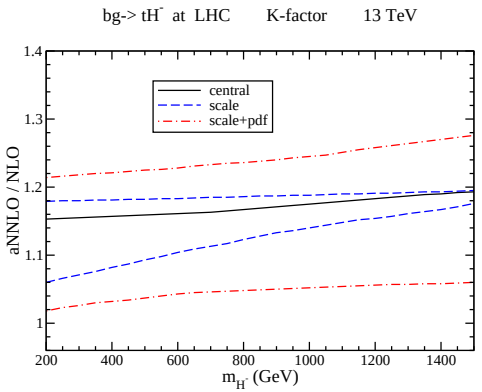
aNNLO: tH^- **production**

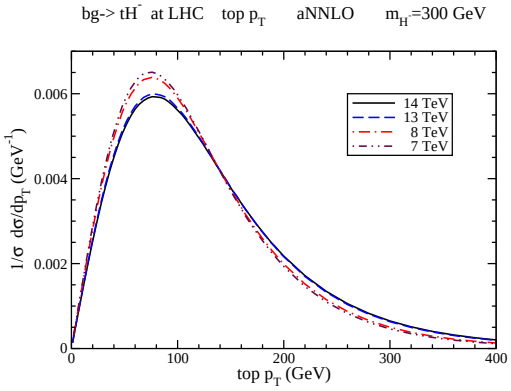
tH^- production

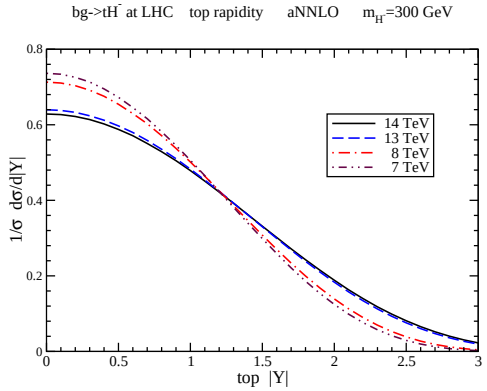












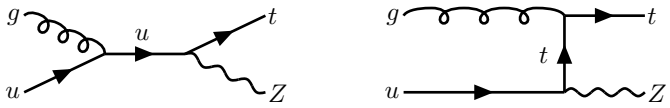
NK, arXiv:1605.00622 [hep-ph]

FCNC processes via anomalous top couplings

Single-top production via flavor-changing neutral currents
Anomalous couplings in Lagrangian, e.g.

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

$gu \to tZ$

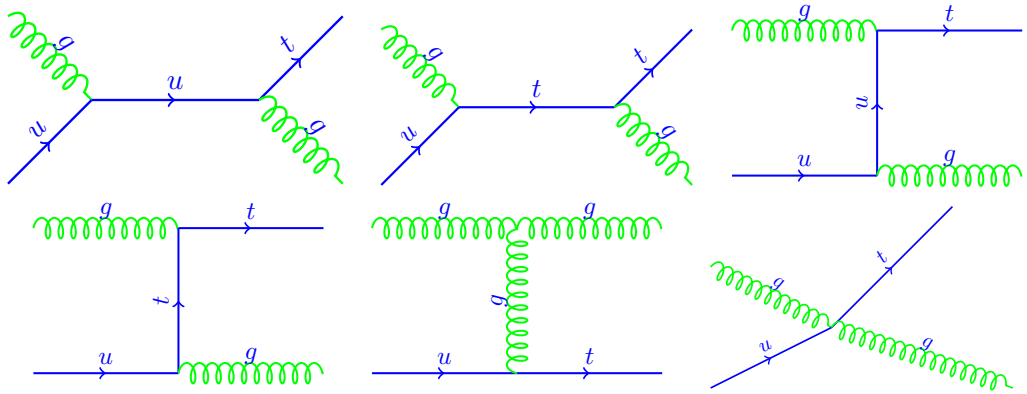


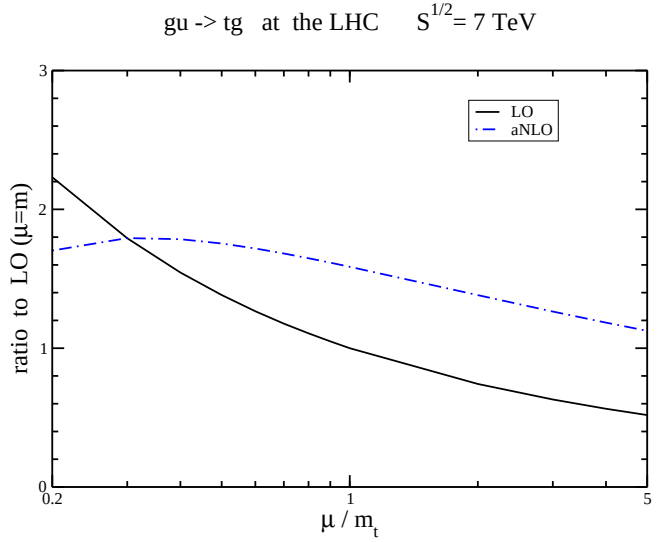
$gu \to t\gamma$

known at LO + soft-gluon corrections

the corrections beyond LO are significant

Top production via anomalous gluon couplings





NK and E. Martin, Phys. Rev. D 90, 054021 (2014) [1404.7488 [hep-ph]]

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**
- **top production in association with bosons**
- **top production via anomalous couplings**
- **high-order corrections are very significant**
- **excellent agreement with LHC and Tevatron data**
- **a lot of theoretical progress**