Top quark transverse momentum and rapidity distributions

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- **Higher-order two-loop corrections**
- **NNLO corrections from NNLL resummation**
- **Top p_T distributions in pair production**
- **Top rapidity distributions in pair production**
- **Top p_T in single-top production**

Higher-order corrections

QCD corrections significant for top pair and single top production

Soft-gluon corrections are important

Soft terms: $\left[\frac{\ln^k(s_4/m_t^2)}{s_4}\right]_+$ **with** $k \leq 2n-1$, s_4 **distance from threshold**

Resum these soft corrections - factorization and RGE

Complete results at NNLL–two-loop soft anomalous dimensions

Approximate NNLO cross section from expansion of resummed cross section

Calculation is for partonic threshold at the double differential cross section level using the standard moment-space resummation in pQCD

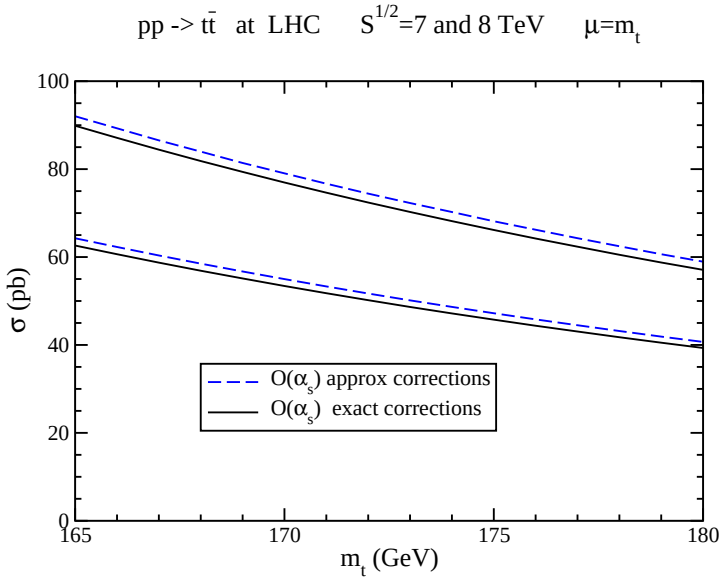
Latest results for differential distributions:

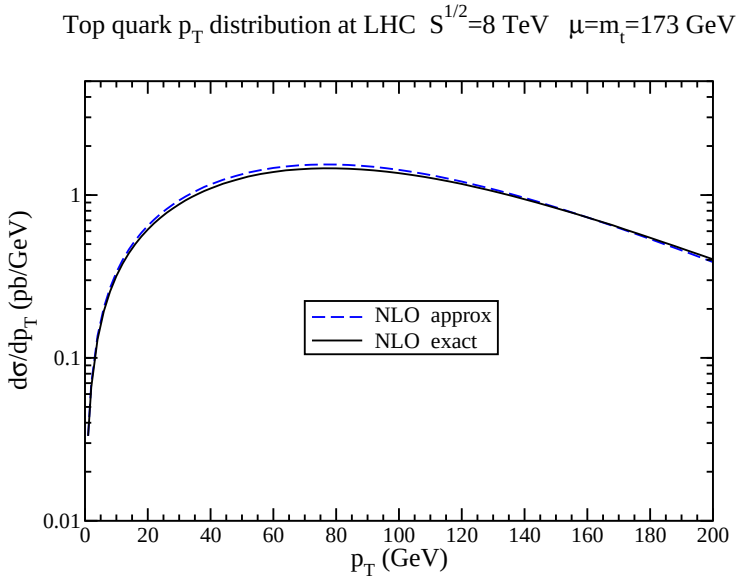
top-pair production, 1304.7775 [hep-ph], Snowmass

single-top production, 1306.3592 [hep-ph], Phys. Rev. D

Threshold approximation

Approximation works very well for LHC and Tevatron energies





excellent approximation:
$\sim$1% difference between NLO approximate and exact cross sections;
and also for differential distributions;
also true at NNLO for total cross sections

For best prediction for differential distributions add NNLO approximate corrections to exact NLO result

Differences between various resummation/NNLO approx approaches

Total vs differential cross section
moment-space pQCD vs SCET

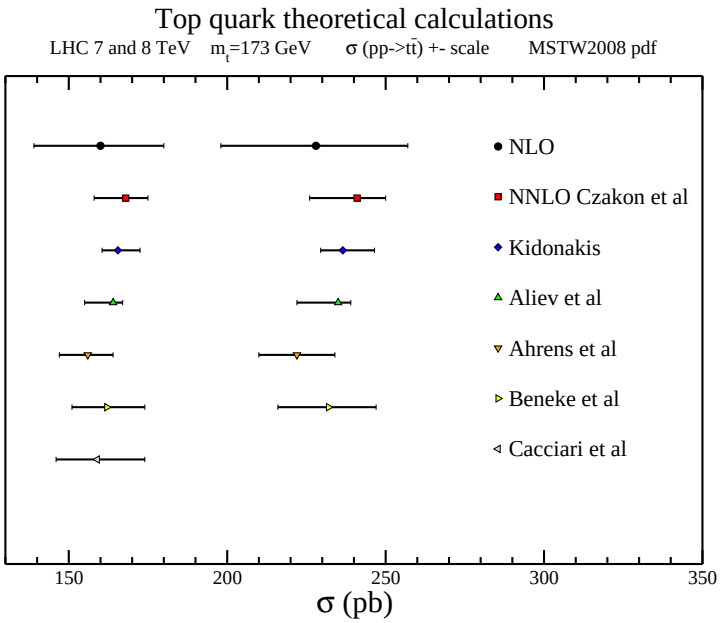
Name	Observable	Soft limit
single-particle-inclusive (1PI)	$d\sigma/dp_T dy$	$s_4 = s + t_1 + u_1 \to 0$
pair-invariant-mass (PIM)	$d\sigma/dM_{t\bar{t}}d\theta$	$(1-z) = 1 - M^2_{t\bar{t}}/s \to 0$
production threshold	σ	$\beta = \sqrt{1-4m_t^2/s} \to 0$

The more general approach is double-differential
$\to p_T$ and rapidity distributions

total-only approaches are limit/special case (absolute vs partonic threshold)

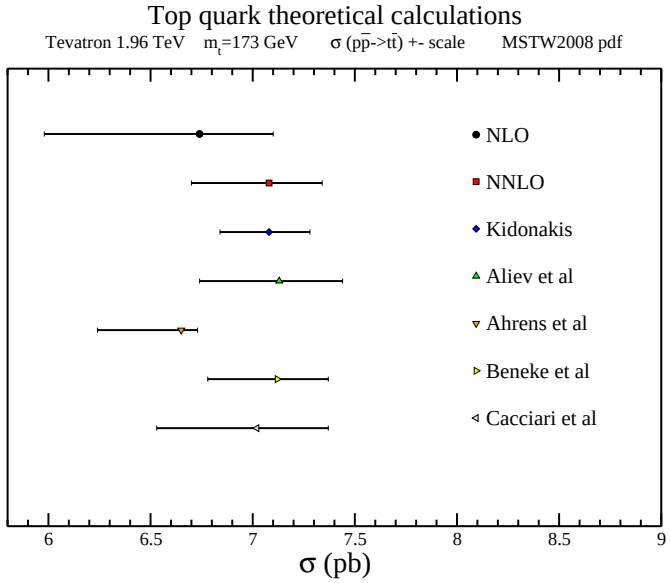
For differential calculations, further differences arise from how the relation $s + t_1 + u_1 = 0$ is used in the plus-distribution coefficients, how subleading terms are treated, damping factors, etc.

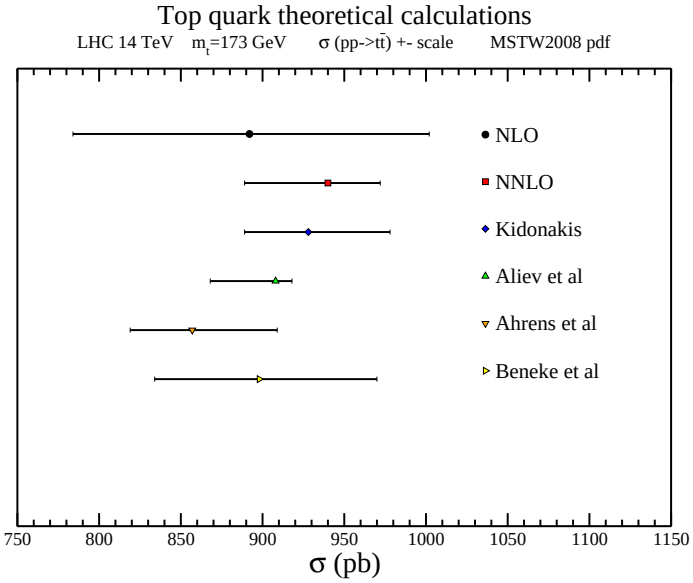
see N. Kidonakis and B.D. Pecjak, Eur. Phys. J C 72, 2084 (2012)
for details and review



Comparison of various NNLO approx approaches
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





Varying degree of success of the various approaches

The Kidonakis PRD 82 result is very close to the exact NNLO:
both the central values and the scale uncertainty are nearly the same
true for all collider energies and top quark masses

This was expected from comparison to NLO, and comparison of 1PI and PIM results at NNLO in 2003

(PRD 68, N. Kidonakis & R. Vogt; see also discussion in PRD78 and PRD82)

less than 1% difference between NLO approximate and exact cross sections at both NLO and NNLO

In near future add approximate NNNLO

(see N. Kidonakis PRD 73,034001 (2006) for early NNNLO results)

This is the only calculation for partonic threshold at the double differential cross section level using the standard moment-space resummation in pQCD

stability of the theoretical NNLO approx result over the past decade

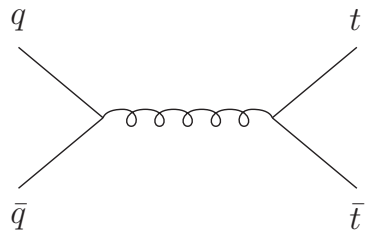
the reliability of the NNLO approximate result and near-identical value to exact NNLO is very important for several reasons

- **provides confidence of application to other processes (single-top, W, etc)**
- **used as background for many analyses (Higgs, etc)**
- **means that we have near-exact NNLO p_T and rapidity distributions**

Top-pair partonic processes at LO

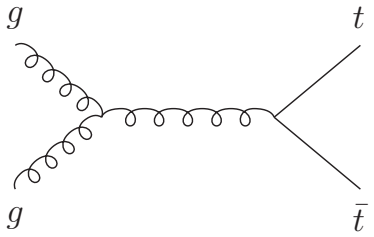
- $q\bar{q} \to t\bar{t}$

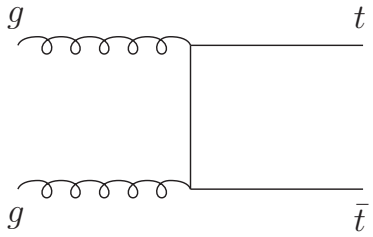
dominant at Tevatron

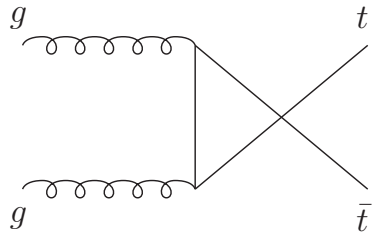


- $gg \to t\bar{t}$

dominant at LHC

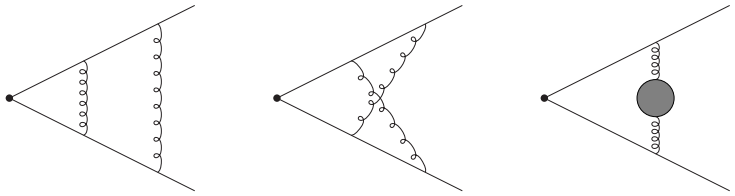




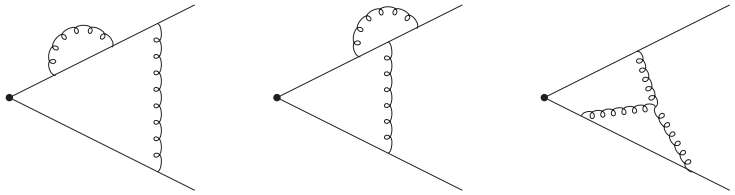


Typical two-loop eikonal diagrams

Vertex correction graphs

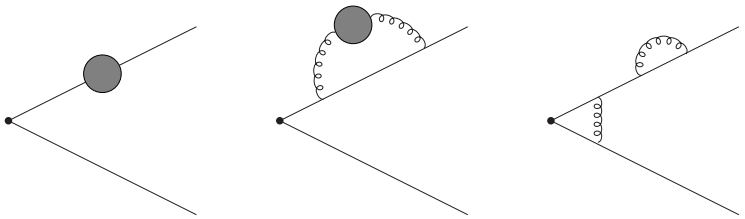


(a) (b) (c)



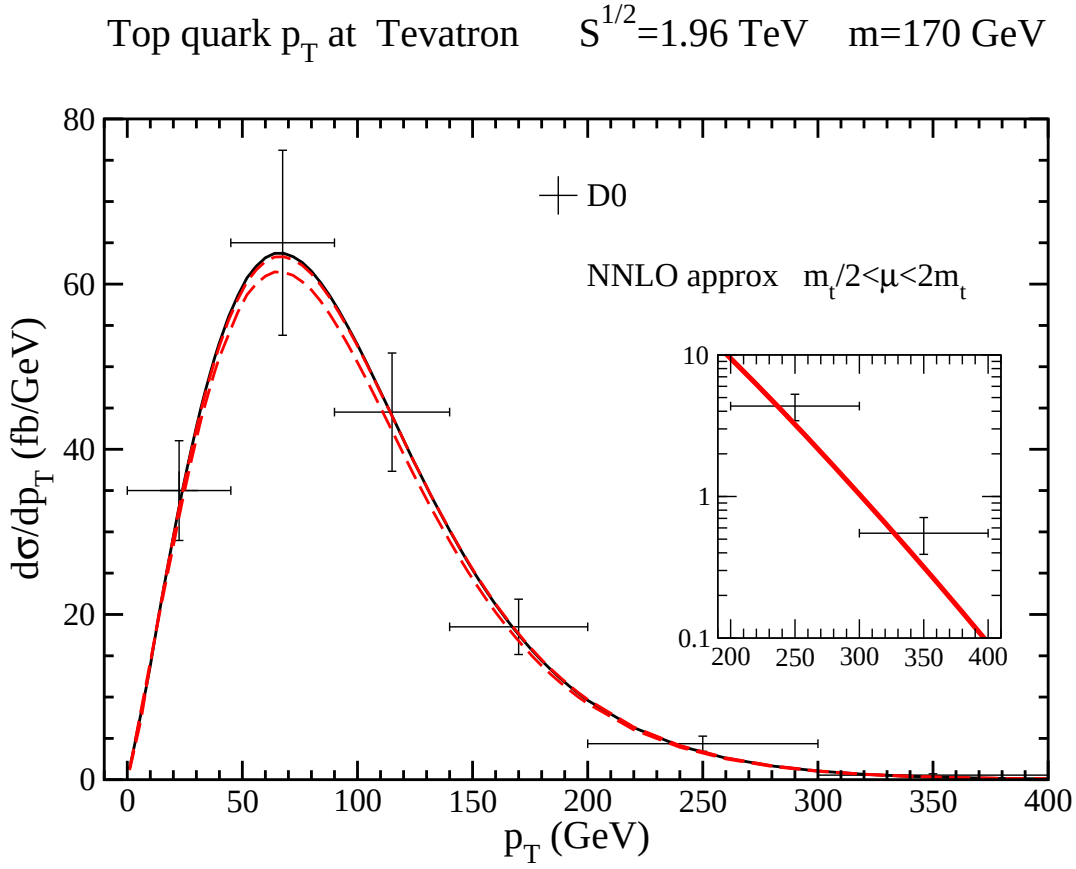
(d) (e) (f)

Heavy-quark self-energy graphs



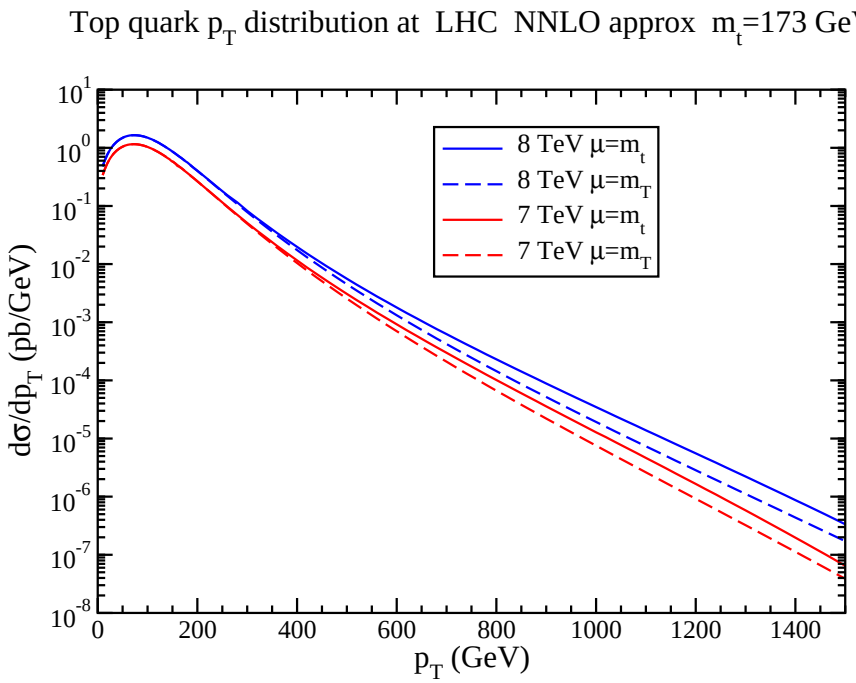
(a) (b) (c)

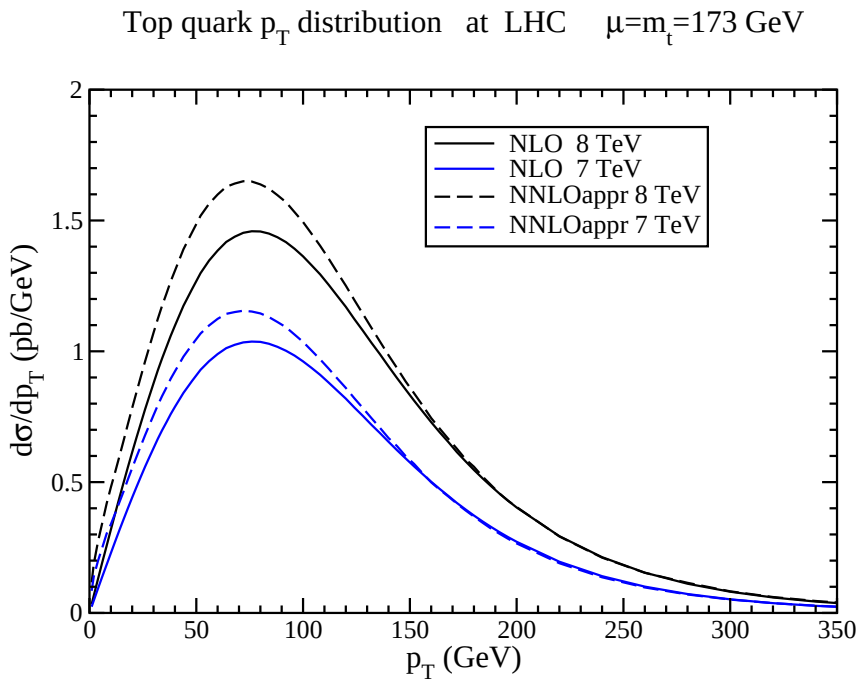
Top quark p_T distribution at Tevatron



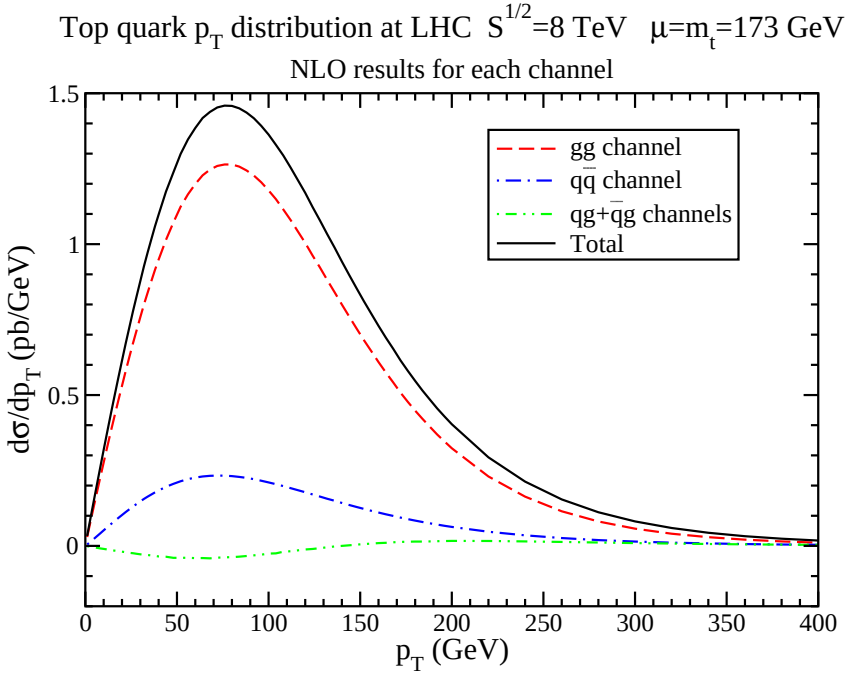
Excellent agreement of NNLO approx results with D0 data

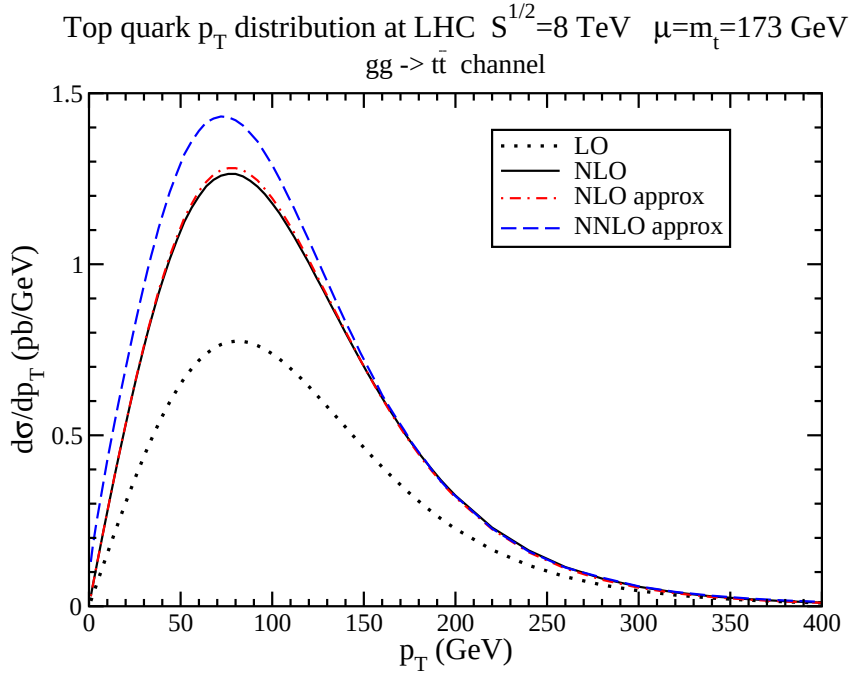
Top quark p_T distribution at the LHC



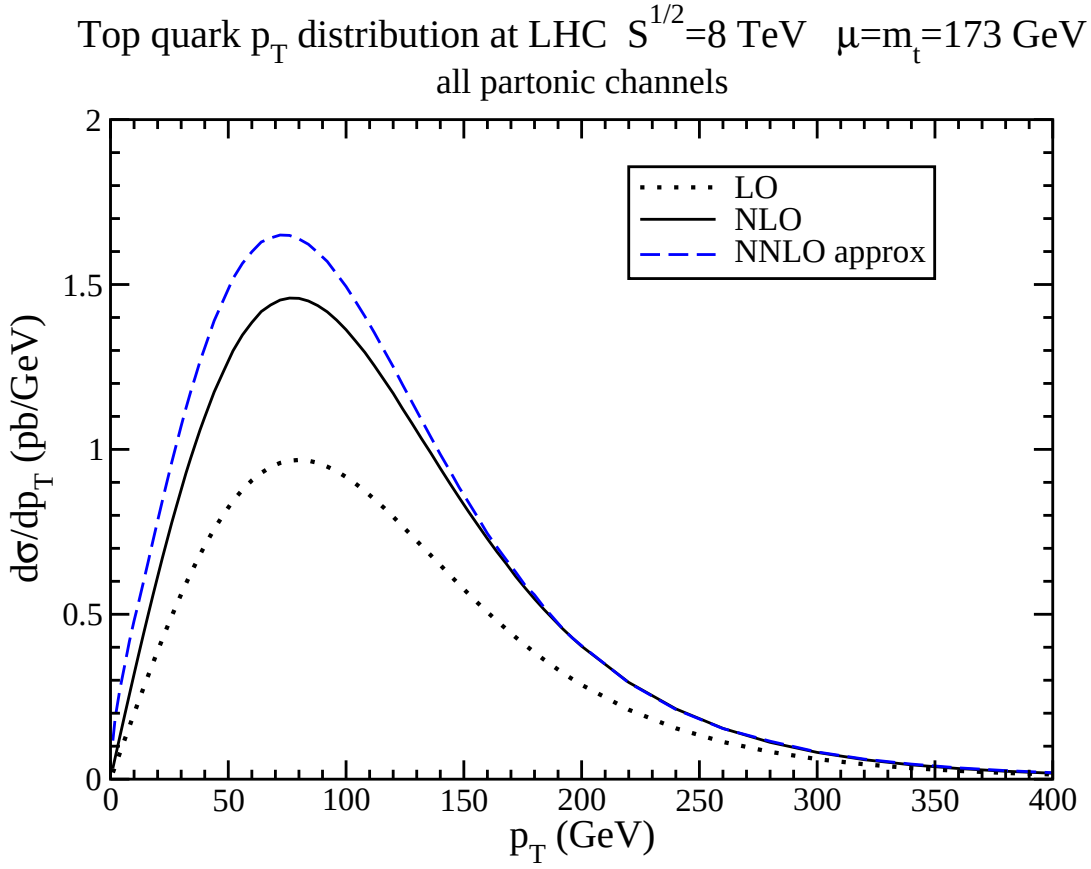


Top quark p_T distribution at the LHC

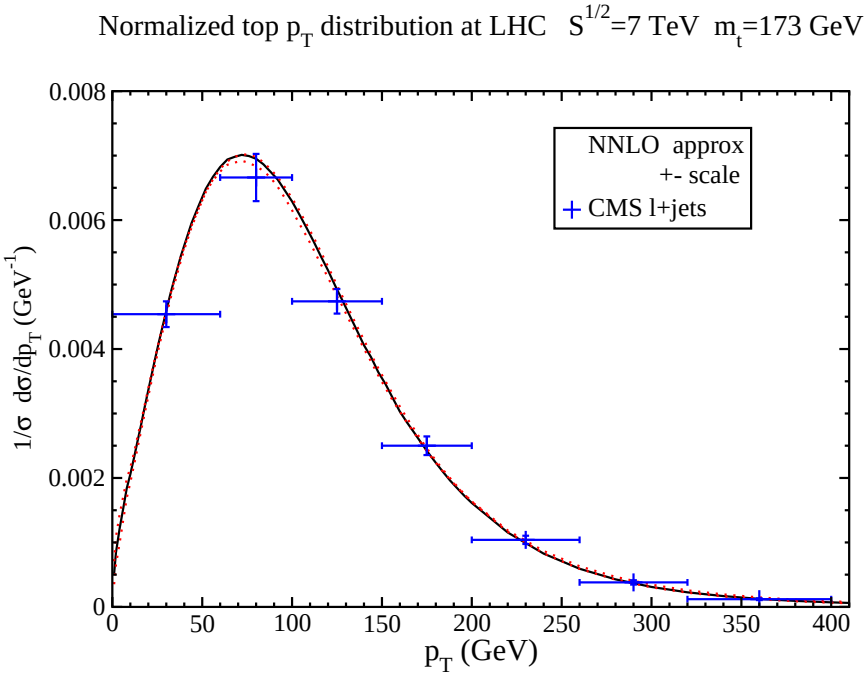


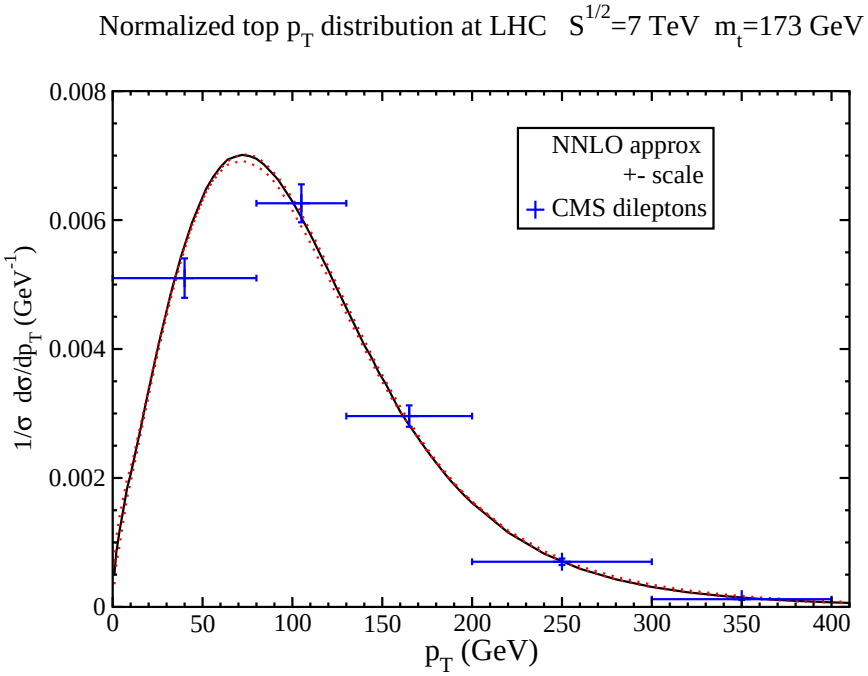


Top quark p_T distribution at the LHC



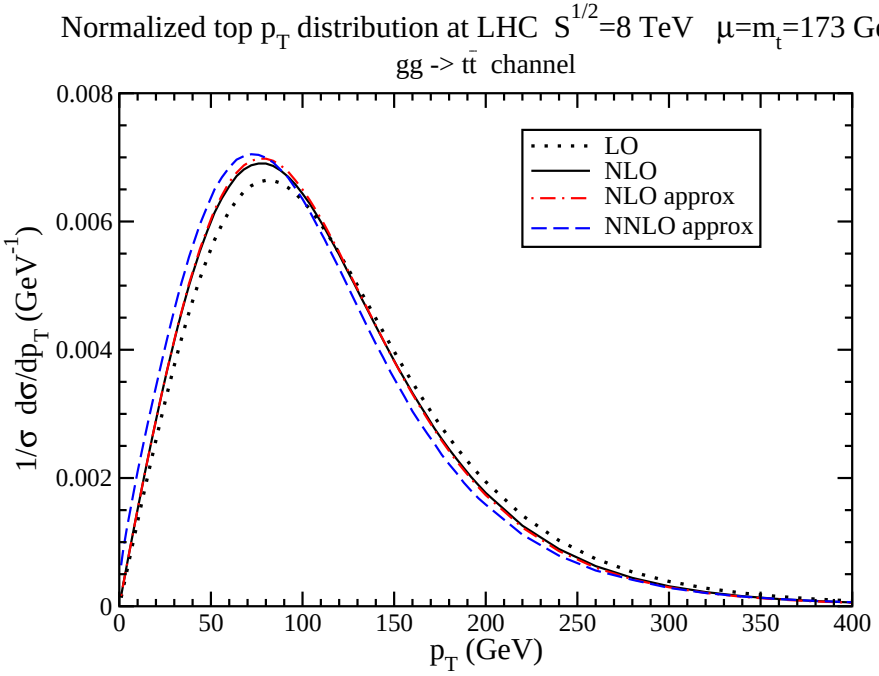
Normalized top quark p_T distribution at the LHC

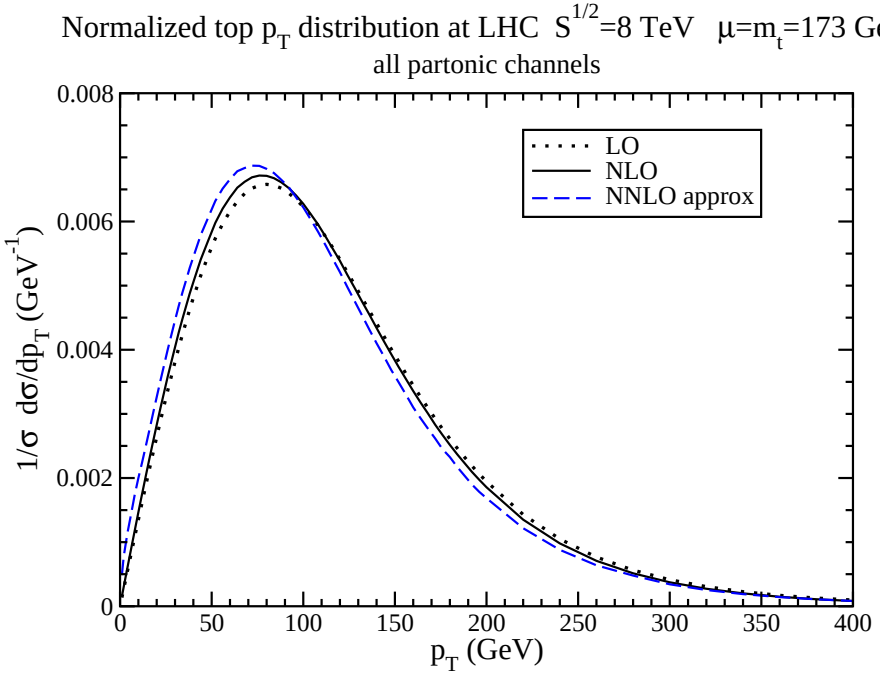




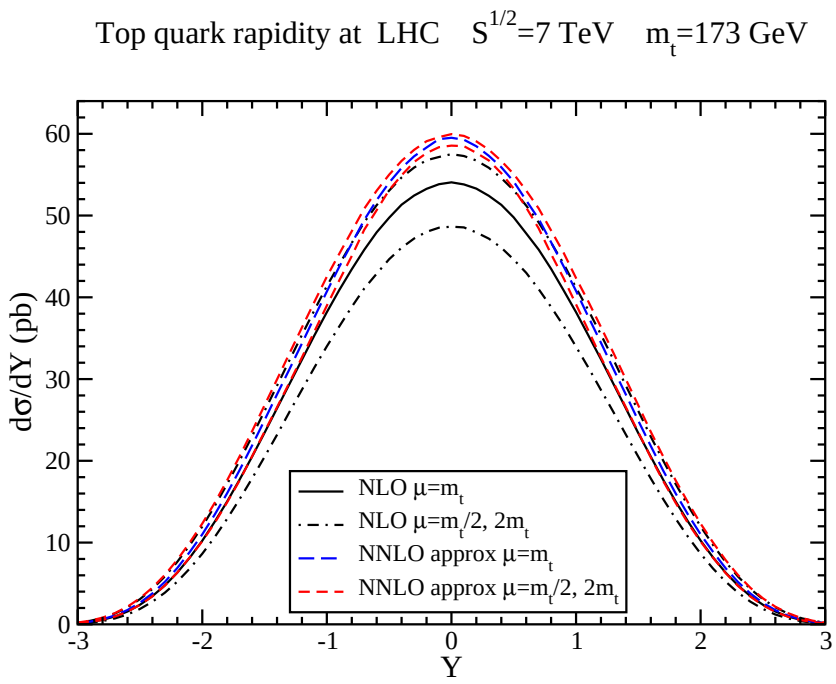
Excellent agreement with CMS data at 7 TeV; also at 8 TeV

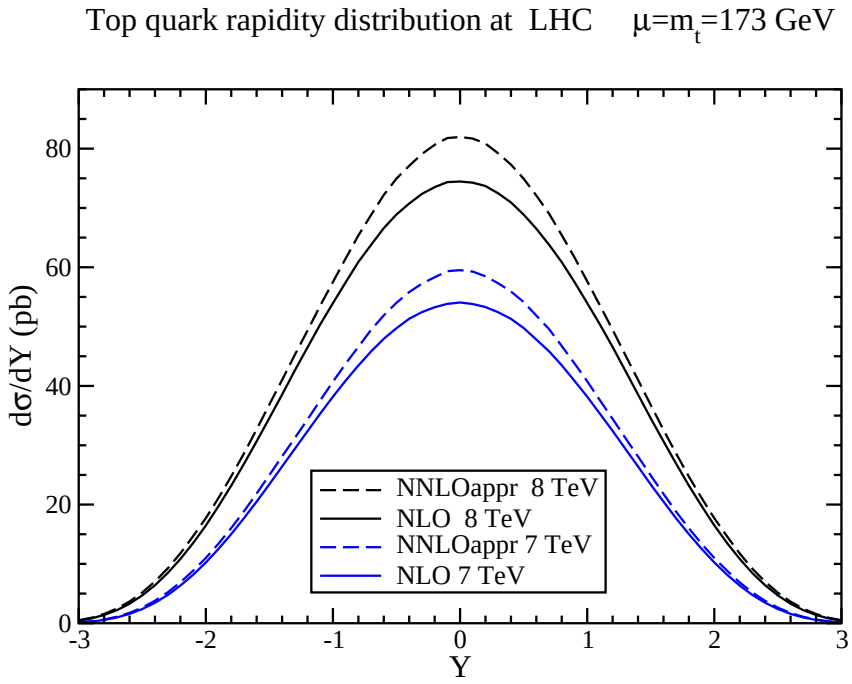
Normalized top quark p_T distribution at the LHC



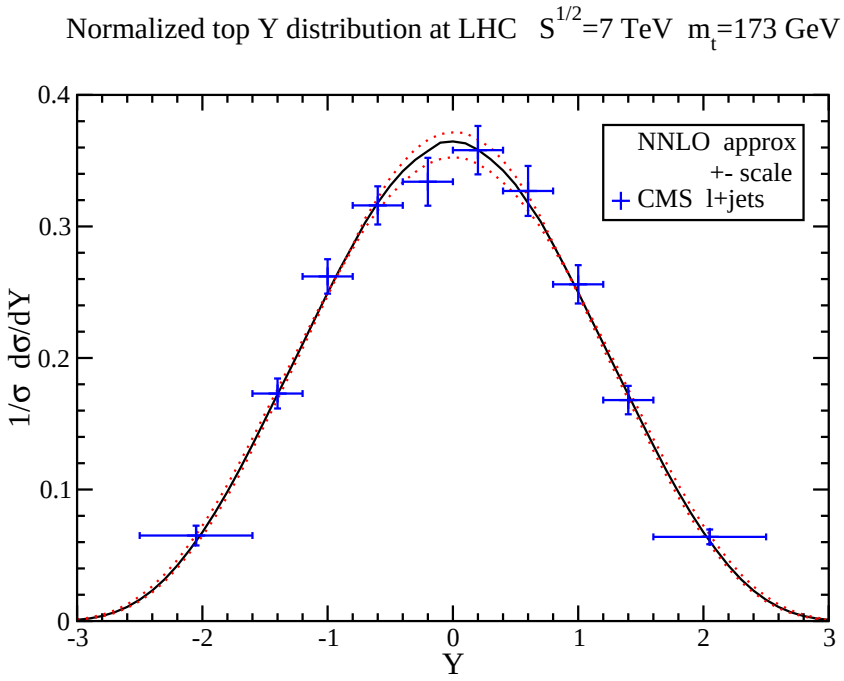


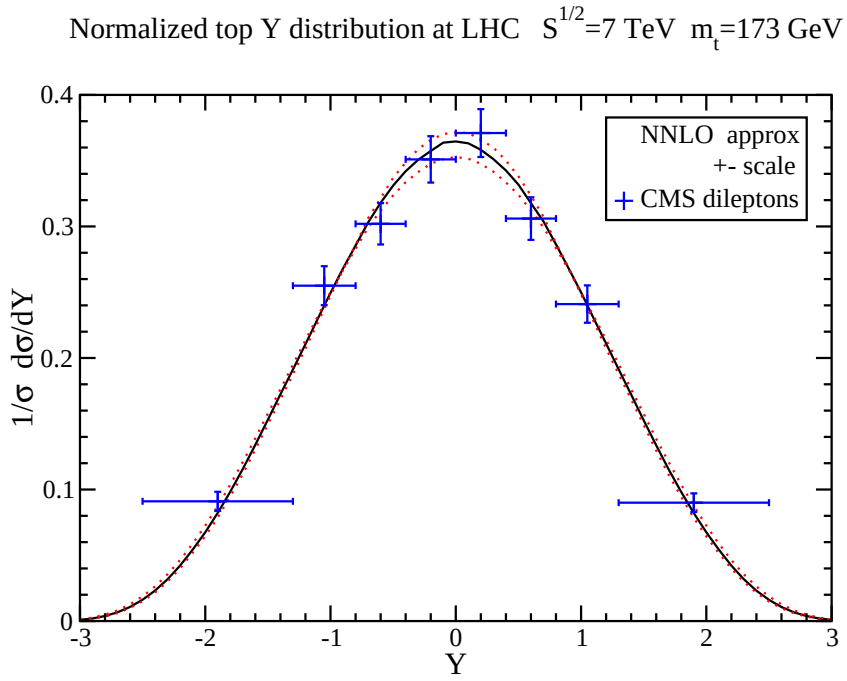
Top quark rapidity distribution at LHC





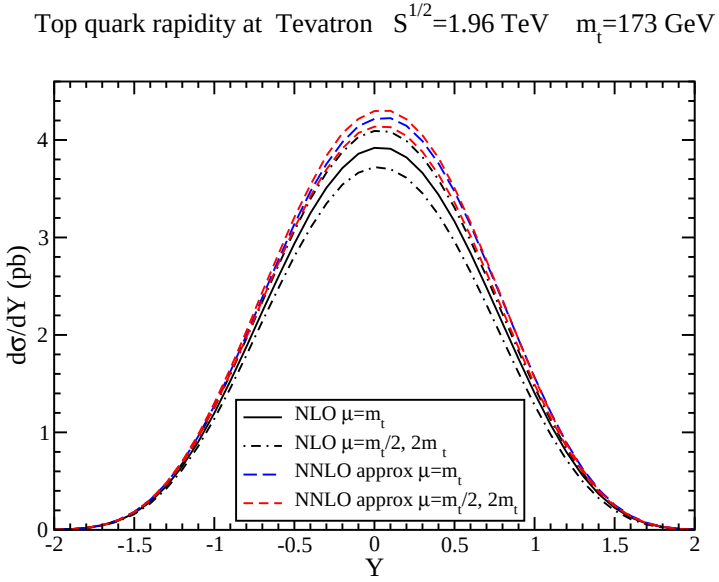
Normalized top quark rapidity distribution at LHC





Excellent agreement with CMS data at 7 TeV; also at 8 TeV

Top quark rapidity distribution at Tevatron



Top Forward-backward asymmetry

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

Asymmetry significant at the Tevatron

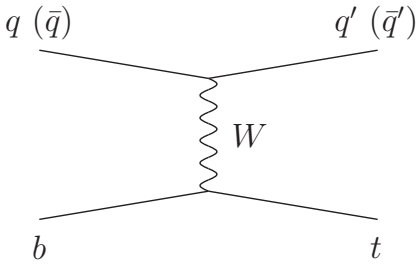
Theoretical result at Tevatron: $A_{\rm FB} = 0.052^{+0.000}_{-0.006}$

smaller than observed values

Single-top partonic processes at LO

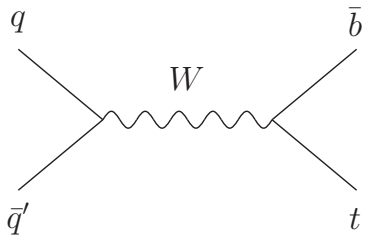
- **t channel: $qb \to q't$ and $\bar{q}b \to \bar{q}'t$**

dominant at Tevatron and LHC



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

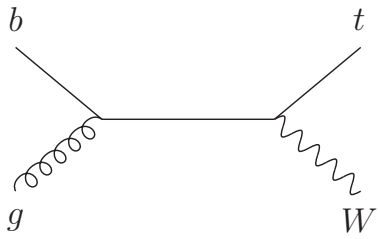
small at Tevatron and LHC

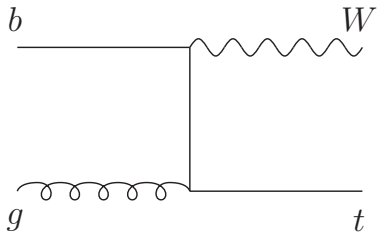


- **associated tW production: $bg \to tW^-$**

very small at Tevatron, significant at LHC

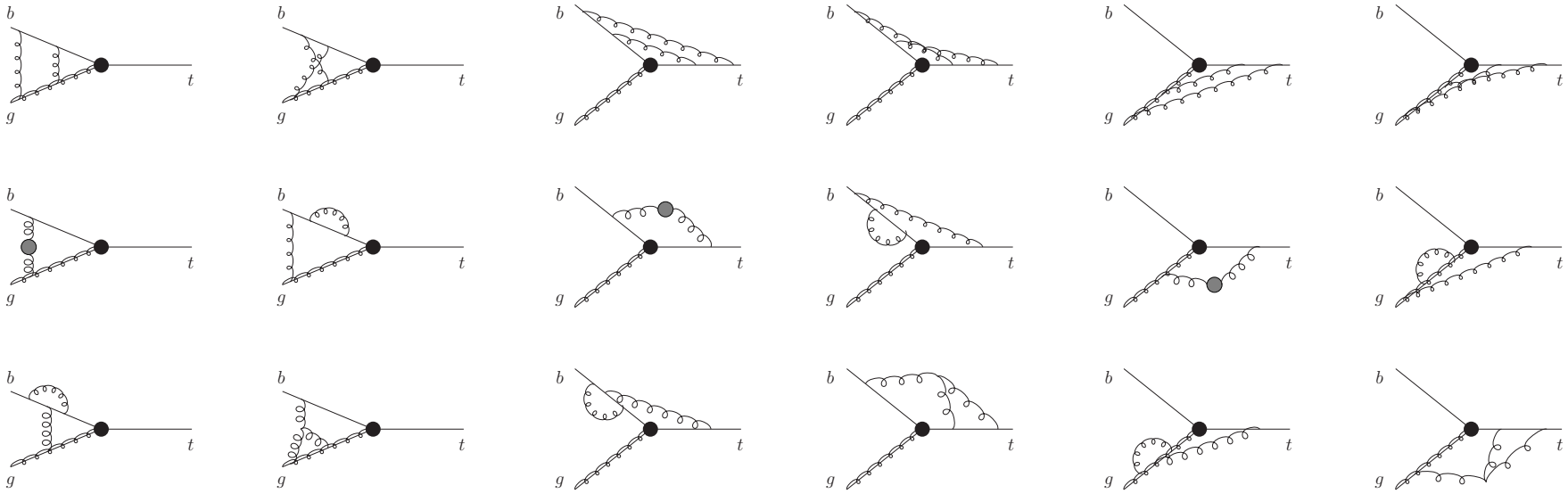
Related process: $bg \to tH^-$



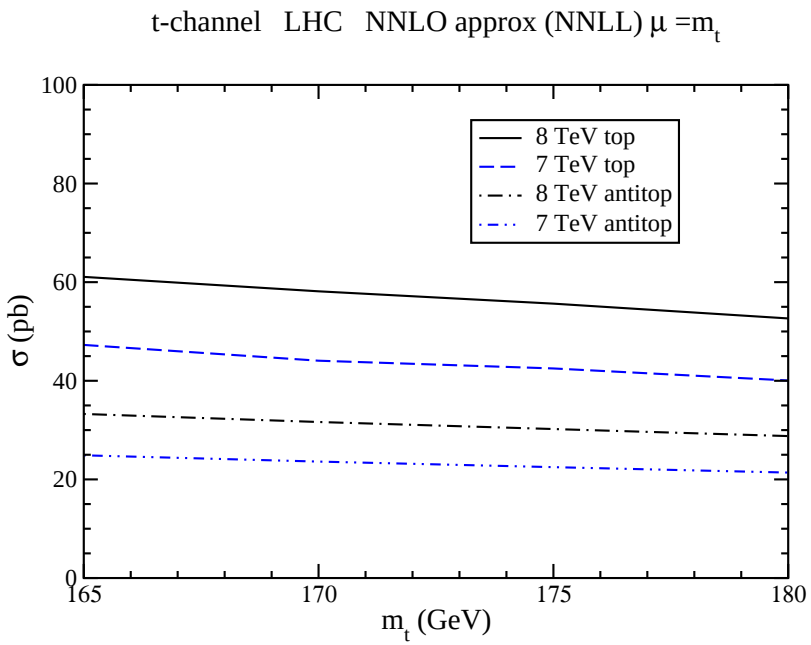


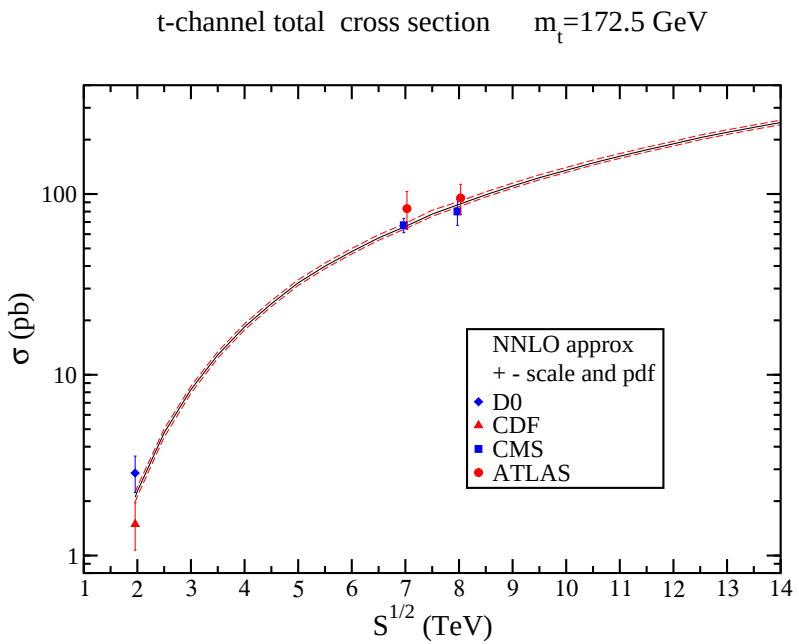
Typical two-loop eikonal diagrams for tW production

(+ extra top-quark self-energy graphs)



Single top t-channel cross sections at LHC





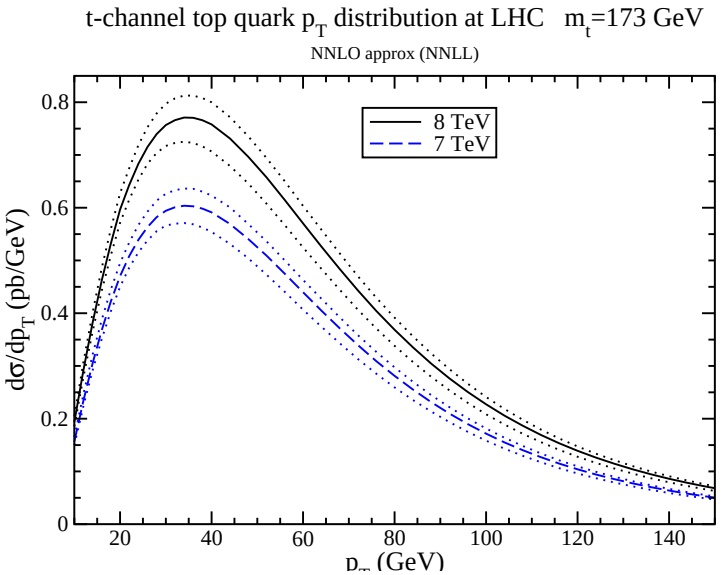
$m_t = 173$ **GeV**

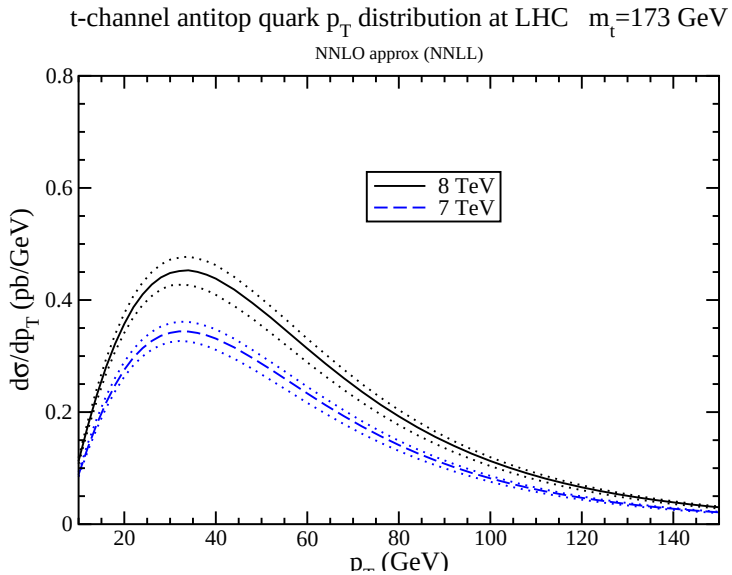
LHC	t	$\bar{t}$	Total (pb)
7 TeV	$43.0^{+1.6}_{-0.2} \pm 0.8$	$22.9 \pm 0.5^{+0.7}_{-0.9}$	$65.9^{+2.1+1.5}_{-0.7-1.7}$
8 TeV	$56.4^{+2.1}_{-0.3} \pm 1.1$	$30.7 \pm 0.7^{+0.9}_{-1.1}$	$87.2^{+2.8+2.0}_{-1.0-2.2}$
14 TeV	$154^{+4}_{-1} \pm 3$	94^{+2+2}_{-1-3}	248^{+6+5}_{-2-6}

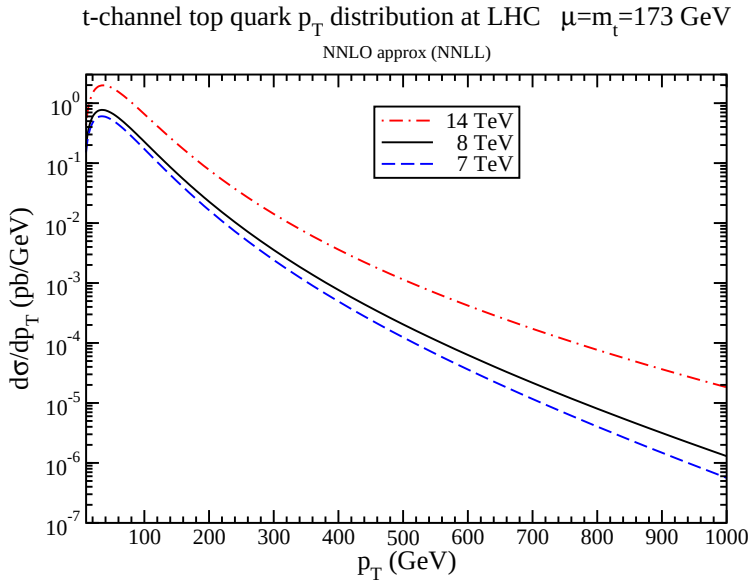
$\pm$ scale $\pm$ pdf errors with MSTW2008 NNLO pdf 90% CL

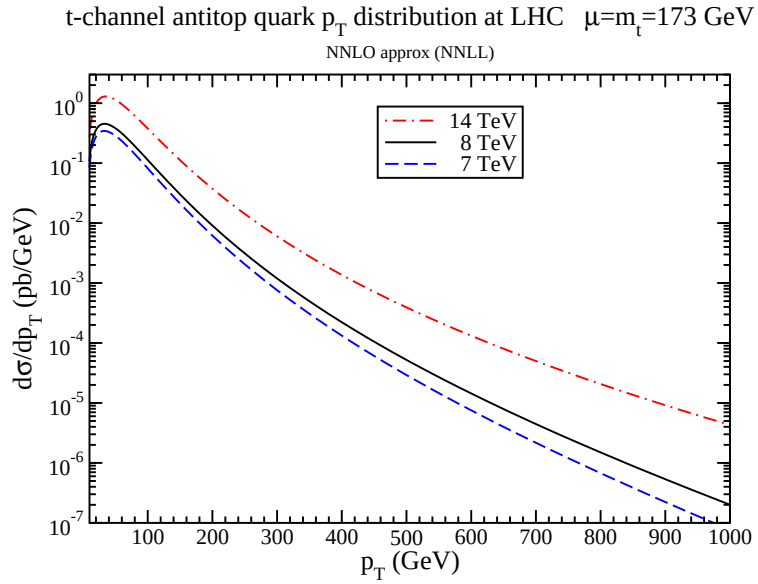
ratio $\sigma(t)/\sigma(\bar{t}) = 1.88^{+0.11}_{-0.09}$ at 7 TeV - compares well with ATLAS result $1.81^{+0.23}_{-0.22}$

t-channel top and antitop p_T distributions at LHC

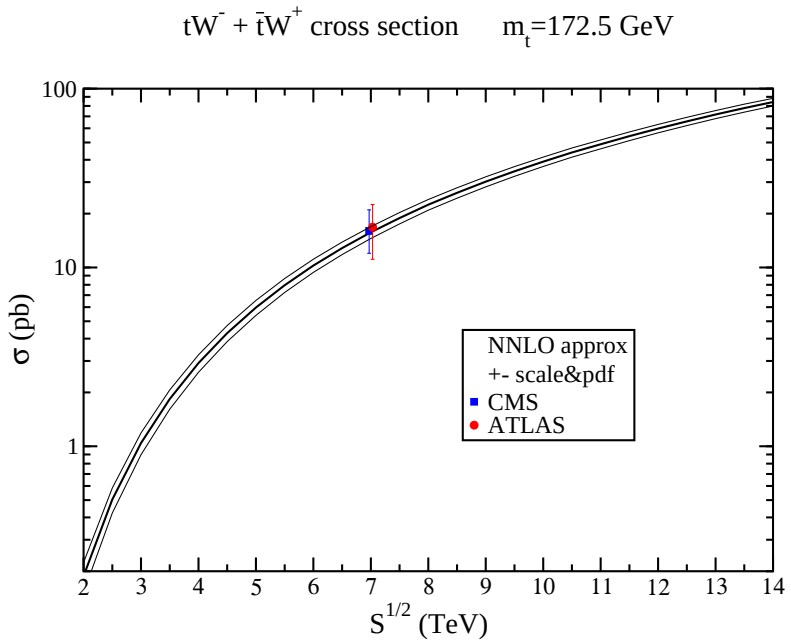


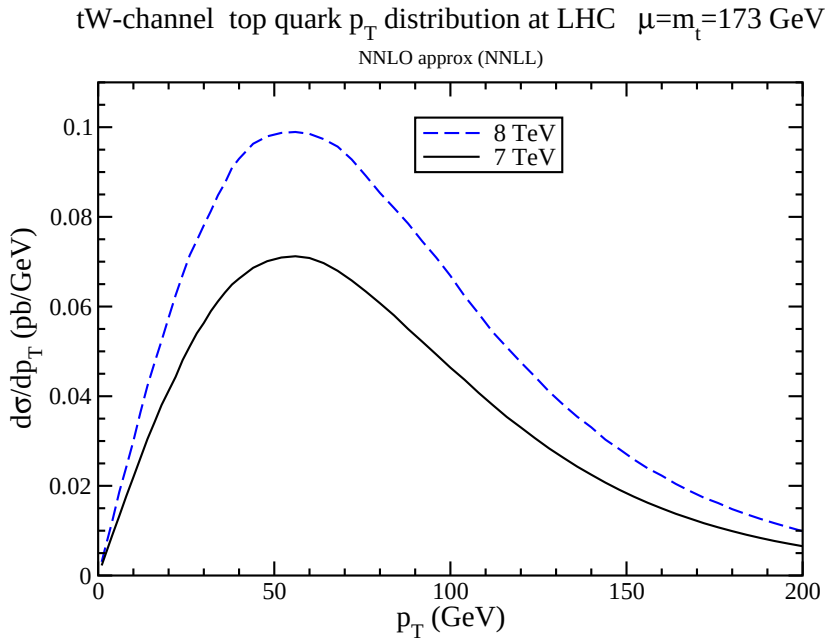






Associated tW^- production at the LHC





Cross section for $\bar{t}W^+$ production is identical to tW^-

Summary

- **NNLL resummation for top-pair and single-top production**
- **top quark p_T and rapidity distributions**
- **NNLO approx corrections are significant at the LHC and the Tevatron**
- **excellent agreement with LHC and Tevatron data**
- **future work on more differential distributions**