NNLO corrections in decay for top pair and single top

CMS top quark workshop
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Outline of talk

- Why should we care about top-quark decays?
- Narrow-width approximation
- Results (for experimentally relevant fiducial regions)
  - top pair
  - single top (t-channel)

Why should we care about top decays?

- top-quark physical final states are measured in fiducial regions
  - best precision theoretical predictions are for inclusive stable tops
  - to obtain inclusive measurements, must extrapolate from measured fiducial cross sections (performed using Monte Carlo)
  - controlling the systematics associated with 'top-parton' reconstruction/extrapolation requires control of decay dynamics
- physical final states provide a very rich spectrum of observables with which to probe top physics
  - many impactful applications to be made: m_t-measurement, spin-correlations, W-helicity fractions, PDF-extractions, ...

At the level of top-quark final states (leptons, $\not{E}_T$, (b)jets), measurements can be compared to theory predictions without the need to extrapolate data to 'top partons'

Including the top decay (at fixed order)

Two mainstream ways of calculating, when including the top decay:

- Narrow-width approximation (NWA), $\Gamma_t \to 0$ limit $\qquad p(t)^2 = m_t^2$
  - production / decay of onshell tops completely factorize
  - for large class of observables NWA is an excellent approx (error $\sim \mathcal{O}(\Gamma_t/m_t)$)
- Offshell $\qquad p(t)^2 \neq m_t^2$
  - both 'resonant' and 'non-resonant/background' diagrams contribute to physical final state
  - finite-width effects vital, i.e. $\mathcal{O}(1)$ in certain regions of phase space, e.g. edge of M_{bl} distribution!

The narrow width approximation

Look at general structure for top pair production, with leptonic W decays:

$$d\sigma = d\sigma_{t\bar{t}} \times \frac{d\Gamma_{t\to bl^+\nu_l}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}\to\bar{b}l^-\bar{\nu}_l}}{\Gamma_t}$$

Each piece has an expansion in α_s

$$d\sigma_{t\bar{t}} = \alpha_s^2 \sum_{n=0}^{\infty} \left(\frac{\alpha_s}{2\pi}\right)^n d\sigma_{t\bar{t}}^{(n)}, \qquad d\Gamma_{t(\bar{t})} = \sum_{n=0}^{\infty} \left(\frac{\alpha_s}{2\pi}\right)^n d\Gamma_{t(\bar{t})}^{(n)}$$

$$\Gamma_t = \sum_{n=0}^{\infty} \left(\frac{\alpha_s}{2\pi}\right)^n \Gamma_t^{(n)}$$

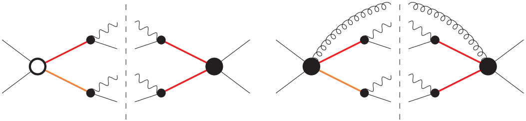
Using these expansion, expand $d\sigma$ up to a fixed order in α_s:

NLO up to $\mathcal{O}(\alpha_s^3)$, NNLO up to $\mathcal{O}(\alpha_s^4)$

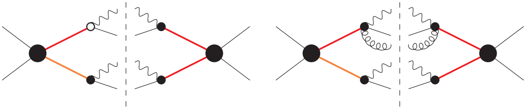
Note: exactly the same framework used for single top, just slightly simpler, with one less top to worry about.

The narrow width approximation: NLO

NLO production $\sim \sigma_{t\bar{t}}^{(1)} \times d\Gamma_t^{(0)} \times d\Gamma_{\bar{t}}^{(0)}$

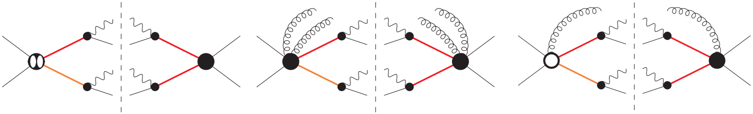


NLO decay $\sim \sigma_{t\bar{t}}^{(0)} \times d\Gamma_t^{(1)} \times d\Gamma_{\bar{t}}^{(0)}$

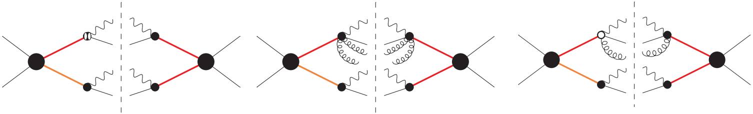


The narrow width approximation: NNLO

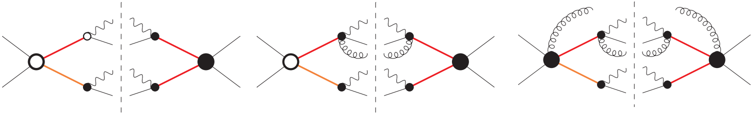
NNLO production $\sim \sigma_{t\bar{t}}^{(2)} \times d\Gamma_t^{(0)} \times d\Gamma_{\bar{t}}^{(0)}$



NNLO decay $\sim \sigma_{t\bar{t}}^{(0)} \times d\Gamma_t^{(2)} \times d\Gamma_{\bar{t}}^{(0)}$



NLO-production x NLO-decay $\sim \sigma_{t\bar{t}}^{(1)} \times d\Gamma_t^{(1)} \times d\Gamma_{\bar{t}}^{(0)}$



(also: NLO-$t$decay x NLO-$\bar{t}$decay)

NWA beyond NLO: single top and $t\bar{t}$

- $t\bar{t}$ production and decay [Gao,AP '17]
  - NNLO-decay and NLO-prod x NLO-dec included exactly
  - NNLO-prod included approximately (soft-gluon approx.)
- t-channel single top production and decay [Berger,Gao,Yuan,Zhu '16, Berger,Gao,Zhu '17]
  - NNLO-decay and NLO-prod x NLO-dec included exactly
  - NNLO-prod exact up to terms $\sim \mathcal{O}(1/N_c^2)$

Codes to produce results are parton-level Monte Carlos (like for e.g. `MCFM`), which produce results at LO, NLO and NNLO ($\widehat{\text{N}}$NLO).

So far, only (direct) leptonic decays of W-bosons included.

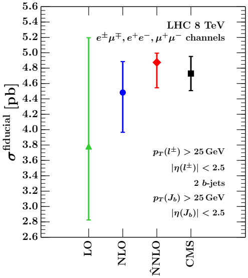
Predictions for any IR-safe observable constructed from final state leptons and (b)jets, in fiducial regions, can be made.

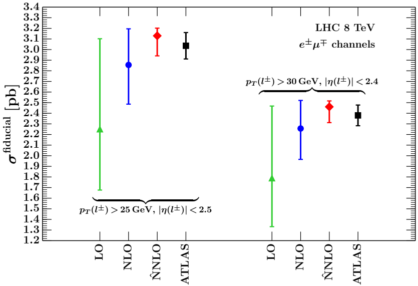
Fiducial cross sections

$t\bar{t}$ in di-lepton channel

Two different fiducial volumes investigated:

- CMS (8 TeV): require 2 $b$jets, $p_T(J_b) > 25$ GeV, $|\eta(J_b)| < 2.5$, $p_T(l^{\pm}) > 25$ GeV, $|\eta(l^{\pm})| < 2.5$
- ATLAS (8 TeV): $p_T(l^{\pm}) > 25(30)$ GeV, $|\eta(l^{\pm})| < 2.5(2.4)$





- corrections beyond NLO important

✓ significant improvement in agreement of theory with measurements

Fiducial cross sections

$t\bar{t}$ in di-lepton channel: decay corrections vary with cuts

Look at breakdown of higher-order corrections in decay (as % of fid xs):

ATLAS:

- $\delta^{(1)}_{\rm dec} = -0.25\%$
- $\delta^{(2)}_{\rm dec} = -0.10\%$
- $\delta^{(2)}_{\rm prodxdec} = +0.05\%$

CMS:

- $\delta^{(1)}_{\rm dec} = -7.4\%$ $\in$ NLO
- $\delta^{(2)}_{\rm dec} = -2.9\%$ $\in$ NNLO
- $\delta^{(2)}_{\rm prodxdec} = +1.6\%$ $\in$ NNLO

(Note: $\delta^{(1)}_{\rm prod} \sim +20\%$, $\delta^{(2)}_{\rm prod} \sim +10\%$)

What we learn:

- including higher-orders in decay generally reduces fid. cross section
- size/impact of corrections in decay depend on cuts on final states

  (for good theory/data agreement in both ATLAS and CMS fiducial volumes, must include corrections in production & decay)
- NNLO-decay + NLO-prod x NLO-decay corrections, are small (large cancellation in sum)

Fiducial cross sections

t-channel single top

Berger,Gao,Yuan,Zhu '16
Berger,Gao,Zhu '17

Fiducial volume (for decay to one family of leptons)

- anti-k_T jets, $D = 0.5$, $p_{T,\mathrm{jet}} > 40$ GeV, $|\eta_{\mathrm{jet}}| < 5$
- require exactly 2 jets, with one of them b-tagged ($|\eta_{b\mathrm{jet}}| < 2.4$)
- charged lepton: $p_{T,l} > 30$ GeV, $|\eta_l| < 2.4$

LHC 13 TeV

fiducial [pb]		LO	NLO	NNLO
t quark	total	$4.07^{+7.6\%}_{-9.8\%}$	$2.95^{+4.1\%}_{-2.2\%}$	$2.70^{+1.2\%}_{-0.7\%}$
	corr. in pro.		-0.79	-0.24
	corr. in dec.		-0.33	-0.13

- $\delta^{(1)}_{\mathrm{dec}} = -12.2\% \in$ NLO
- $\delta^{(2)}_{\mathrm{dec}} = -4.8\% \in$ NNLO
- $\delta^{(2)}_{\mathrm{prodxdec}} = +4.4\% \in$ NNLO

(Note: $\delta^{(1)}_{\mathrm{prod}} \sim -30\%$, $\delta^{(2)}_{\mathrm{prod}} \sim +9\%$)

- corrections in decay important for description of fiducial volume
- sum NNLO-decay + NLO-prod x NLO-decay corrections small

Fiducial cross sections

Effects of decay corrections on acceptances

To obtain the fully inclusive cross section, one has to extrapolate from the fiducial cross section based on acceptances estimated from MC.

As a simple exercise: defining 'parton-level' acceptance naively as

$$\text{acceptance} = \sigma^{\text{fiducial}}/\sigma^{\text{inclusive}}$$

and computing with prod+decay or prod-only corrections:

NLO NNLO

$t\bar{t}$ (CMS volume):

$$\text{acceptance (prod+decay)} = \{0.0202, 0.0199\}$$

$\sim 8\%$ different $\downarrow$

$$\text{acceptance (prod only)} = \{0.0219, 0.0216\}$$

t-ch. single top:

$$\text{acceptance (prod+decay)} = \{0.0214, 0.0201\}$$

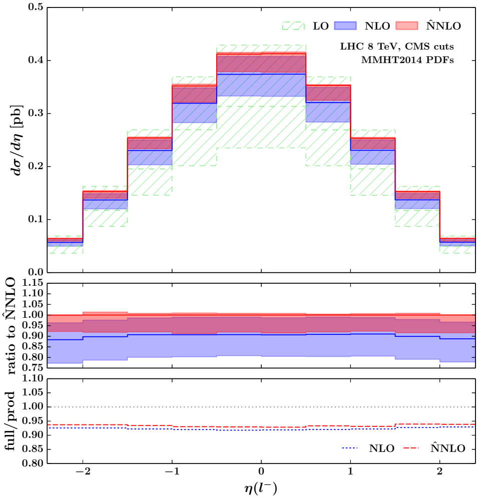
$\sim 12\%$ different $\downarrow$

$$\text{acceptance (prod only)} = \{0.0238, 0.0226\}$$

- when it comes to acceptance, corrections in decay can be important

Distributions in fiducial regions

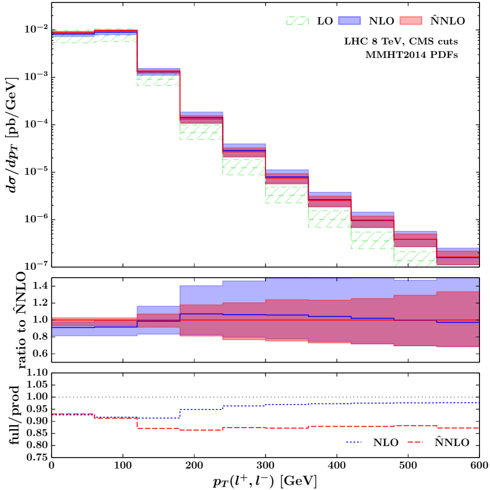
$t\bar{t}$: pseudo-rapidity of charged lepton, $\eta(l)$



- decay corrections important for overall normalization (effects are of the same size as NNLO scale uncertainty)
- decay corrections do not affect shape
- NNLO-decay + NLO-prod x NLO-dec corrections small $\sim 1\%$, consistent with contribution to fiducial cross section

Distributions in fiducial regions

$t\bar{t}$: transverse momentum of (l^+, l^-)-system, $p_T(l^+, l^-)$

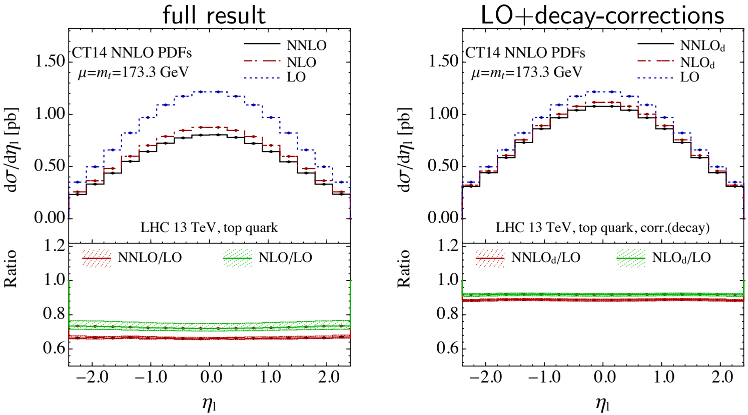


- decay corrections important for overall normalization
- decay corrections alter the shape of the distribution
- NNLO-decay
  + NLO-prod x NLO-dec corrections small in low-p_T bins, but grow in size at large p_T
- NLO and NNLO corrections in decay decay corrections soften spectrum

Distributions in fiducial regions

Berger,Gao,Yuan,Zhu '16
Berger,Gao,Zhu '17

t-ch. single top: pseudo-rapidity of charged lepton, η_l

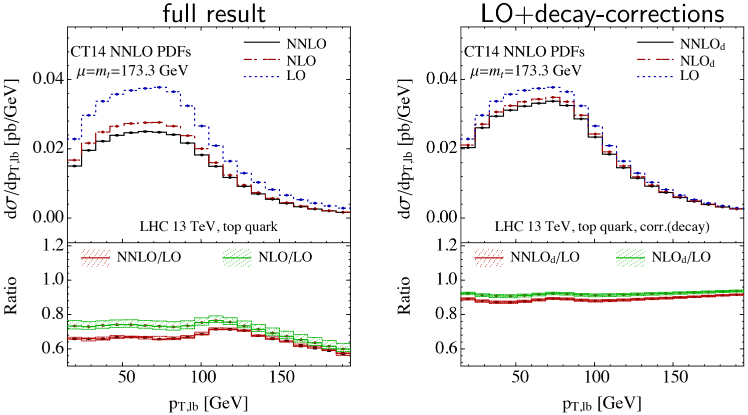


- corrections in decay important for normalization, however bring no shape changes
- pure NNLO-decay corrections $\sim -4\%$

Distributions in fiducial regions

Berger,Gao,Yuan,Zhu '16
Berger,Gao,Zhu '17

t-ch. single top: transverse momentum of $(l\ J_b)$-system, $p_{T,lb}$



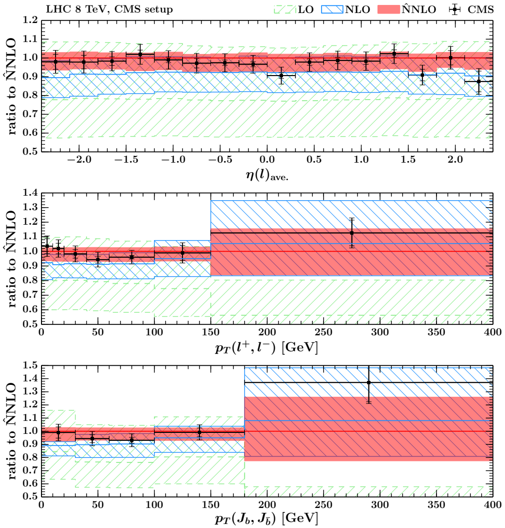
- corrections in decay important for normalization, however bring only very minor shape changes (shape driven by corrections in production)
- pure NNLO-decay corrections $\sim -4\%$

Theoretical predictions compared directly to data

- CMS 8 TeV: [1505.04480,1510.03072]

[Gao,AP '17]

$m_t = 173.3$ GeV
$\mu \in [m_t/2, 2m_t]$
MMHT2014 PDFs



- good agreement in norm. & shape with N̂NLO predictions
- look forward to exploiting these for applications, and exploring 13 TeV distributions!

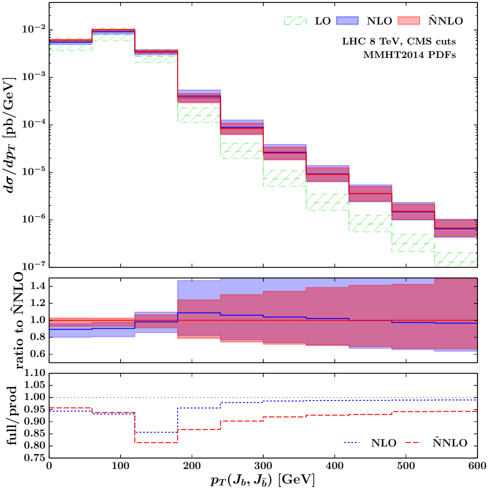
Summary

- higher order corrections in top-quark decays now included exactly up to NNLO in top-pair and t-ch. single top production
- fiducial cross sections
  - generically, decay corrections required for accurate prediction
  - corrections can be large (up to $\sim 10\%$) depending on cuts (particularly on $b$jets)
  - pure NNLO-decay corrections $\sim 1/3$ of size of NLO-decay corrections (largely cancel with NLO-prod x NLO-decay)
- distributions
  - depending on distribution, corrections in decay vary from being unimportant to crucial to the shape
  - in regions away from bulk, NNLO corrections in decay can be large, $\sim 5 - 10\%$
- $t\bar{t}$: exact NNLO-prod with decays: ongoing work in `Stripper` (Czakon,Heymes,Lim,Mitov,AP,Poncelet), aim for results @ TOP2018

Thank you for the invitation to talk to CMS!!

Distributions in fiducial regions

$t\bar{t}$: transverse momentum of $(J_b, J_{\bar{b}})$-system, $p_T(J_b, J_{\bar{b}})$

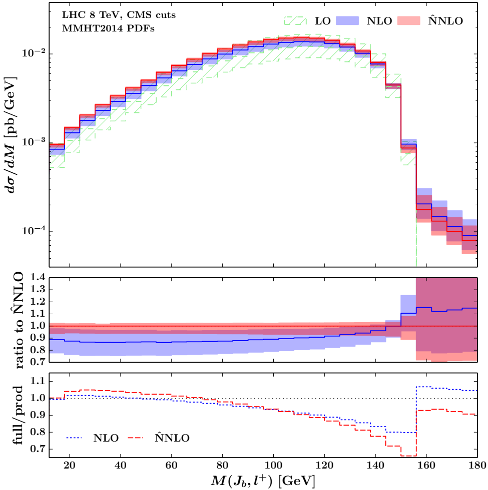


- corrections in decay important for overall normalization and shape
- NNLO corrections in decay small in low-p_T bins, larger at mid-to-large p_T
- NLO and NNLO decay corrections soften spectrum

Distributions in fiducial regions

Gao,AP '17

$t\bar{t}$: invariant mass of (l, J_b)-system, $M(l^+, J_b)$



- corrections in decay significantly alter shape of distribution, over whole range
- NNLO corrections in decay result in important differences in shape (and are very sizeable approaching the edge of the distribution!)