NNLO single-top-quark production and decay: Discrepancies resolved, PDFs challenged

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C T E Q

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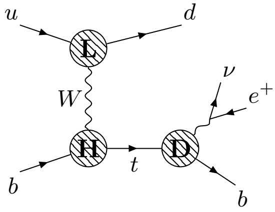
Based on publications:
T. Neumann, ZS, JHEP 06(2019)022 [1903.11023]
J. Campbell, T. Neumann, ZS, JHEP 02(2021)040 [2012.01574]
ZS, EPJ 172(2018)03008 [1711.04018], & J. Campell, T. Neumann, ZS [21xx.yyyyy]

Structure of t-channel single-top



Previously calculated at NNLO in on-shell scheme at fixed scale m_t by:

Brucherseifer, Caola, Melnikov PLB 736, 58 (14)

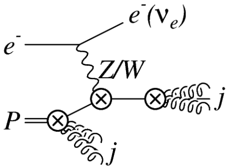
Berger, Gao, Yuan, Zhu PRD 94, 071501 (16)

- Inclusive results disagreed by 100% of the NNLO correction. (Differentially even more.)
- We wanted to see stability of sub-leading jet predictions at NNLO.
  (Leading jets: stable by NLO; sub-leading jets: large change at NNLO in fiducial region.)
- Needed double-deep-inelastic scattering (DDIS) scales to check PDFs.
  (All PDFs are inconsistent between LO and NLO ZS 1711.04018 — and NNLO. new)

PDFs and scales — a subtlety

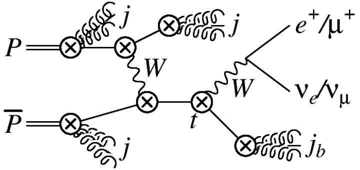
We factorize real observables (e.g., F_2, F_3) into $\overline{MS}$ PDFs (f's) and matrix elements

$$\sigma_{\text{obs.}} = \int f_1(x_1,\mu_1) f_2(x_2,\mu_2) \otimes \overline{|M|^2} \otimes d\text{P.S.} \otimes D_i(p_i)\ldots D_n(p_n)$$



DIS is measured at 1 scale:

$$\mu^2 = Q^2$$



Double-DIS (DDIS) probes 2 scales:

$$\mu_l^2 = Q^2,\ \mu_h^2 = Q^2 + m_t^2$$

Fits can be done at LO, NLO or NNLO to extract PDFs, but... the most important *mathematical* constraint is that a *calculation* must give the the same answer for these *inclusive* observables at all orders.

$$\sigma^{LO} = \sigma^{NLO} = \sigma^{NNLO}$$

Data is data. You are just undoing the original PDF fits.

NNLO cross section results — discrepancy resolved

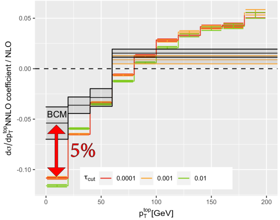
J. Campbell, T. Neumann, ZS, JHEP 02(2021)040 [2012.01574]

We calculated each term of the NNLO cross section multiple ways

Fixed m_t scale comparisons:

— We exactly reproduce the differential Berger, Gao, Yuan, Zhu results (once a small bug in their b-tagging was fixed)

— We thus disagree both inclusively and differentially with Brucherseifer, Caola, Melnikov (Fig is top p_T)



Subtleties for a consistent NNLO calculation:

— You must use the same order of PDF as the matrix element

— You have to re-expand corrections in α_s to keep the one-loop light/one-loop heavy interference at order α_s^2 or you get 10–20% mistakes.

(There are delicate analytic cancellations.)

Most kinematic variables see small predictable changes

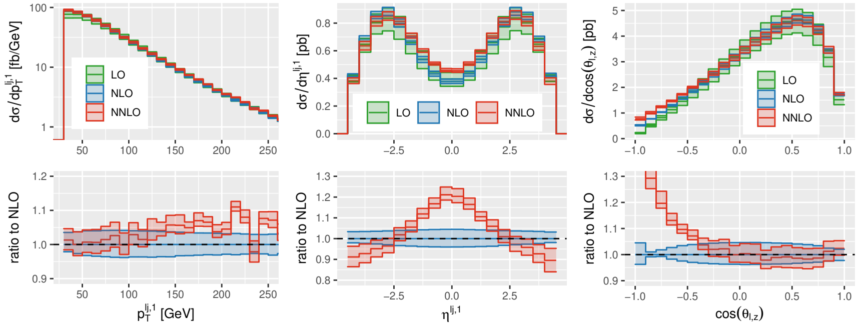
J. Campbell, T. Neumann, ZS, JHEP 02(2021)040 [2012.01574]

The paper explores NNLO vs NLO stability for multiple kinematic distributions and angular correlations w/ bin-by-bin uncertainties

— The p_T of the lepton and most jets get harder by 15–20% above 100 GeV at NNLO

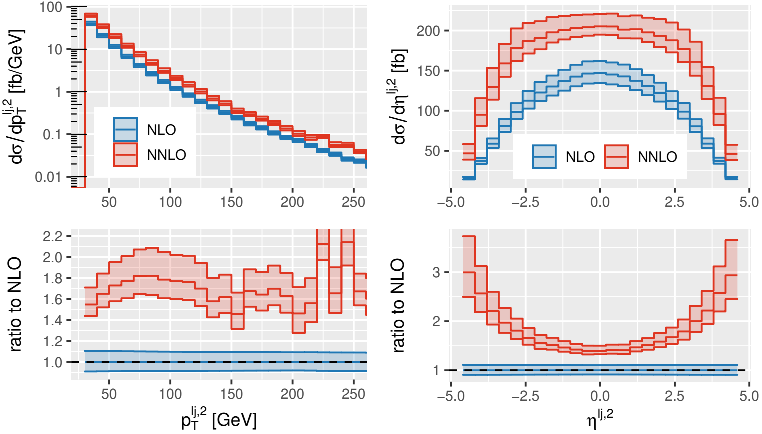
— Most pseudorapidities η become more central due to the boosts

— Angular correlations remain stable from LO to NLO to NNLO (tiny absolute change)



2nd leading jet sees large fiducial changes at NNLO

An important observation for experiment is that the sub-leading jet acceptance increases by more than 60%! (LO is $t + j_1$, here I mean the first radiated jet j_2) — separates S vs. B



The change is large because the NLO calculation predicts j_2 at LO.
The NNLO prediction is NLO in j_2 (and LO in j_3) — showering cannot capture this effect

Are modern PDFs consistent with themselves or each other?

Checked LO and NLO in ZS [1711.04018]

Important: D-DIS scales used ($\mu_l = Q^2$, $\mu_h = Q^2 + m_t^2$); $m_t = 172.5$ GeV

LO means (LO ME, $\alpha_s(M_Z) = 0.130$, LO PDFs)

NLO means (NLO ME, $\alpha_s(M_Z) = 0.118$, NLO PDFs)

Tevatron (1.96 TeV) $t + \bar{t}$ inclusive cross section $(2.25^{+0.29}_{-0.31}$ *PRL*115(15)152003)

PDF	LO (pb)	NLO (pb)	
CTEQ4L/4M	2.26	2.41	(6% not great, known α_s bug)
CTEQ5L/5M1	2.08	2.07	$< 0.5\%$ (bug fixed)
CTEQ6L1/6M	2.07	2.086	$< 0.5\%$
CTEQ6L1/6M	1.83	2.086	Scales set to m_t, 12% as expected

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CTEQ14llo/nlo	2.39	2.00	(20% deviation between orders!)
HERAPDF1.5lo/nlo	1.965	1.798	(9.3% deviation!) Should be exactly 0
HERAPDF2lo/nlo	1.910	1.762	(8.4% deviation!)
NNPDF30lo/nlo	2.33	2.21	(5.4% deviation!)

Total PDF uncertainty is $+4.3 - 5.3\%$ at NLO (NNPDF claims $\pm 1.3\%$!!!)

LO is not equal to NLO any more! We do *not* get back to data at different orders!

Further, no one agrees at NLO with each other to within 10% ($> 2\sigma$)!

Preliminary results at NNLO still disagree

J. Campell, T. Neumann, ZS [21xx.yyyyy]

Tevatron (1.96 TeV) $t + \bar{t}$ inclusive cross section

PDF	LO (pb)	NLO (pb)	NNLO (pb)	
MSTW2008	2.36	2.07	2.01	NNLO−NLO is −3% not 0, but better?
HERA20	1.91	1.76	2.02	14% NNLO vs. NLO
CT14(or CT18)	2.39	2.00	2.09	5% NNLO vs NLO
NNPDF30	2.33	2.21	2.19	0.3%! looking consistent (close to 2.25)
NNPDF31	1.98	1.928	1.944	1% BUT 3.0⇒3.1 disagree by 13%!!!

The story is complex, but the conclusions are the same.

— All sets claim to rule each other out at NLO and some at NNLO

— NNPDF error estimates are WAY too small (±1.3% at NLO and NNLO)
other NNLO set errors are ±4%

— Only NNPDF 3.1 *may* agree with itself, but central values shifted by 10σ from 3.0 to 3.1 using their own uncertainties

Preliminary: We are currently confirming there are missing systematic errors in standard PDF error estimates. This affects all cross sections (e.g. missing error is 3x NNPDF error estimate for NNLO Higgs production, 1.5x more conservative CTEQ errors).

Conclusions

Between T. Neumann, ZS, JHEP 06(2019)022 [1903.11023], J. Campbell, T. Neumann, ZS, JHEP 02(2021)040 [2012.01574], ZS, EPJ 172(2018)03008 [1711.04018], and J. Campell, T. Neumann, ZS [21xx.yyyyy] we are cleaning up t-channel single top-quark production

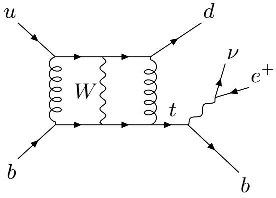
1. Off-shell, SMEFT, and NNLO codes are publicly available through MCFM including b-tagging, DDIS scales, and the ability to get PDF uncertainties
2. Some important subleading jet distributions change substantially at NNLO
3. All modern PDF sets are looking to be inconsistent with each other and with themselves
   Are we starting to see new gluon degrees of freedom or major errors in PDF fitting?
   At least it is looking like more systematic errors need to be included...

A full resolution will take new theory, LHC data and EIC data to resolve!

THANK YOU

BACKUP SLIDES

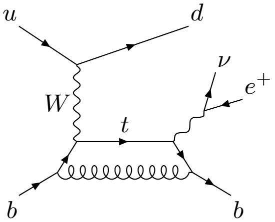
What about NNLO light/heavy interference, off-shell tops?



Simplified calc (fixed scale, mass ratios) claims numerically small
Assadsolimani, Kant, Tausk, Uwer PRD 90, 114024 (14)

We are currently redoing this w/ DDIS scales, no approximations

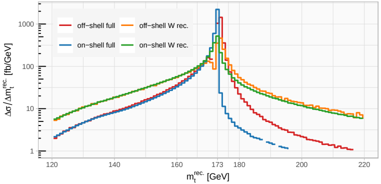
Will not affect PDF question.



We looked at off-shell tops at NLO (and SMEFT)

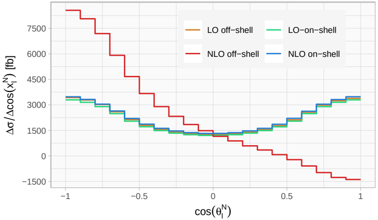
T. Neumann, ZS, JHEP 06(2019)022 [1903.11023]

— Other than top resonance, most SM kinematic variables are unaffected (SMEFT greatly affected)

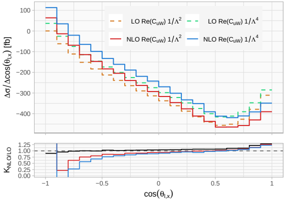


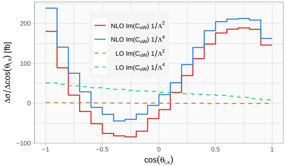
Off-shell effects are very important for 1 SM angle, all of SMEFT

- $\cos\theta_l^N$ (used by experiments) is not perturbatively stable in the SM (or SMEFT)!
  On-shell calculations may be missing large corrections.



- NLO QCD corrections to SMEFT angular observables are large!
  Example: g_R: Re C_{uW}, and Im C_{uW} (often assumed to be 0 at LO in on-shell)





WARNING: Wild musings
Are we fitting the wrong gluon degrees of freedom?

At ISMD 2016, Daniel Boer gave a very dense talk on unintegrated PDFs, the gluon Sivers effect, polarized g in unpolarized p, and more

https://nuclear.korea.ac.kr/indico/contributionDisplay.py?sessionId=18&contribId=54&confId=166

A few comments he made set my mind to wandering:

1. DIS is only sensitive to the g + direction on light-cone (DY −)
2. Jets can mix +/− directions (and generically do not factorize)
3. By fitting all gluon-initiated processes with a single functional form, are we mapping different d.o.f. correctly?

   I.e., should we fit + gluon d.o.f. w/ DIS, − w/ DY, and rest with jets?

   — We would need to change the functional form for g

   — We would definitely need data from an EIC to combine w/ LHC!
4. Should we have seen these effects numerically?

   Polarized gluons in *unpolarized* protons give 2–5% corrections to Higgs production.
   Pisano et al., 2013, 2015; Boer 2014

   Single-top (also color singlet exchange) has $\ln(m_t^2/m_b^2)$ enhancements.