Cleaning up t-channel single top: Anomalous couplings and complete NLO

Zack Sullivan

Illinois Institute of Technology
CTEQ Collaboration

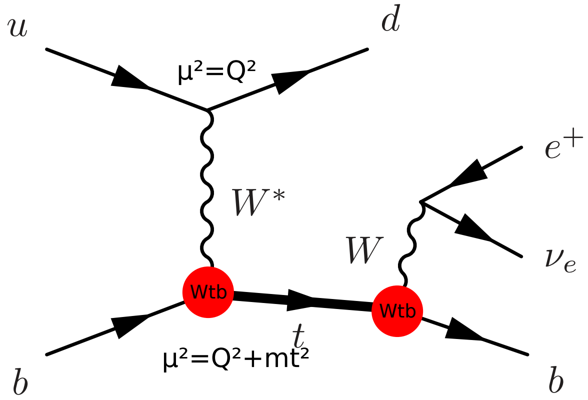
November 10, 2018

with Tobias Neumann
(will be included in next version of MCFM)

Outline

1. Motivation
2. SMEFT modeling at NLO
3. Current status

t-channel single-top-quark production

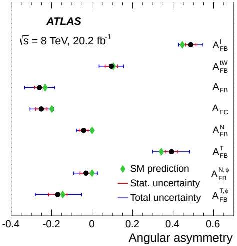


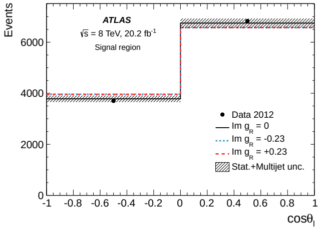
ATLAS anomalous couplings

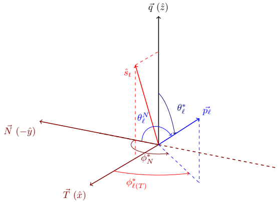
- In ZS, PRD 72, 094034 (2005), I demonstrated SM angular correlations were stable at NLO for t-channel single top when using DDIS scales.
- ATLAS uses these correlations to look for Im g_R couplings.

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\,\bar{b}\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t W_{\mu}^{-} - \frac{g}{\sqrt{2}}\,\bar{b}\,\frac{i\sigma^{\mu\nu} q_{\nu}}{m_W}\left(g_L P_L + g_R P_R\right) t W_{\mu}^{-} + \text{h.c.}$$

- For predictions, ATLAS uses:
  SM NLO: POWHEG BOX, 4f scheme, $\mu^2 = p_{Tb}^2 + m_b^2$, on-shell top, CT10 PDFs
  BSM: LO protos, CTEQ 6 PDFs





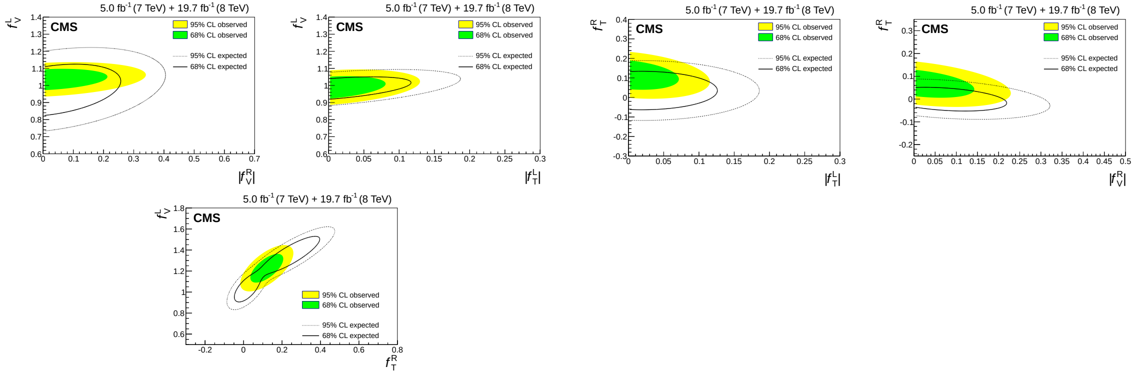


JHEP04(17)124

CMS anomalous couplings

- CMS uses neural nets with predictions from:
  SM& BSM NLO: CompHEP LO + matching to simulate NLO
- CMS extracts $F_V^{L/R} \equiv V_{L/R}$, $F_T^{L/R} \equiv g_{L/R}$.

JHEP02(17)028



We want to provide full NLO signal predictions in a SMEFT framework.

First we need to clean up the SM predictions

- There are many calculations of SM t-channel single top.
  - These include fixed order (LO, NLO, NNLO), resummation and parton showering
- Even at NLO this is not trivial:
  - These include 4-flavor scheme, 5-flavor scheme, on-shell top, stable top, off-shell top, non-resonant contributions, etc.
- An incomplete list of recent calculations:

(partial) NNLO: Brucherseifer, Caola, Melnikov '14 (stable top); Berger, Gao, Yuan, Zhu '16 '17 (on-shell but with decay), IBP reduction for full result: Assadolimani, Kant, Tausk, Uwer '14;

NNLL threshold resummation: Kidonakis '12

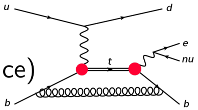
NLO 4/5-flavor, on-shell (in MCFM): Campbell, Ellis, Tramontano '04; Campbell, Frederix, Frixione, Maltoni, Tramontano '09; Campbell, Ellis '12; (in POWHEG and aMC@NLO): Frederix, Re, Torrielli '12;

NLO off-shell + non-resonant + parton shower: Prestel, Torrielli, Papanastasiou, Frederix, Frixione, Hirschi, Maltoni '13 '16;

NLO with analytic transverse momentum dependent resummation: Cao, Sun, Bin Yan, C.P. Yuan, F. Yuan '18

Our “real” goal is to go to fully differential NNLO

- Current NNLO corrections to the inclusive cross section are $\sim 1\%$ at the LHC.
  BUT they disagree at 100% of the size of the correction...
  "We found a difference of $\sim 1\%$ on the NNLO cross sections." (Berger, Gao, Yuan, Zhu '16)
- We need to clean this up. This process is used for top-quark mass extraction, V_{tb}, as a background to Higgs, new physics, etc.
- Along the way we want to address:
  - Off-shell top quark effects (we've got them at NLO w/ full IS/FS interference)
  - Allow for DDIS scales ($\mu_l^2 = Q^2$, $\mu_h^2 = Q^2 + m_t^2$)
    This is most critical, all current NNLO used fixed $\mu = m_t$
    — ruins analytic relationship between orders



- We want DDIS scale dependence in order to address a $4\sigma+$ problem with PDF sets.

Long game: Tracking down 4σ PDF problem

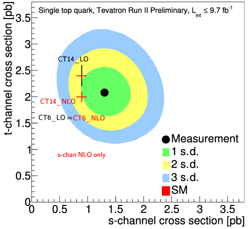
Tevatron (1.96 TeV) $t+\bar{t}$ inclusive cross section

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
CTEQ14llo/nlo	2.39	2.00	(20% deviation!)
HERAPDF1.5lo/nlo	1.965	1.798	(9.3% deviation!)
HERAPDF2lo/nlo	1.910	1.762	(8.4% deviation) NLO 12% too small
NNPDF30lo/nlo	2.33	2.21	(5.4% deviation) NLO 10% too big

Total PDF uncertainty expected to be $+8.8-7.3\%$ at 90% C.L.

NNPDF/HERA *NLO* differ from each other by 4σ!
LO is not equal to NLO any more!
We do *not* get back to Tevatron data!

ZS, arXiv:1711.04018



Outline

SMEFT framework

We want to take a systematic approach to Standard Model Effective Field Theory (SMEFT) precision calculations

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_k \sum_i \frac{C_{i,k}}{\Lambda^k} \mathcal{O}_{i,k}$$

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q^{(1)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W^I_{\mu\nu}$	$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

Buchmueller, Wyler '86; Gradkowski, Iskrzynski, Misiak, Rosiek '10

SMEFT and anomalous couplings

- LO relationship between anomalous couplings and SMEFT

$$\mathcal{L}_{tbW} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W_{\mu}^{-} + \text{h.c.}$$
$$-\frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}\left(g_L P_L + g_R P_R\right) t\, W_{\mu}^{-} + \text{h.c.}$$

EFT correspondence:

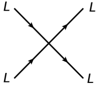
$$\delta V_L = \left(C_{\phi q}^{(3)*} + \frac{g}{2}\text{Re}\, C_{qW}\right)\frac{v^2}{\Lambda^2}\,, \quad \delta g_L = \sqrt{2}C_{dW}^{*}\frac{v^2}{\Lambda^2}\,,$$
$$\delta V_R = \frac{1}{2}C_{\phi\phi}^{*}\frac{v^2}{\Lambda^2}\,, \quad \delta g_R = \sqrt{2}C_{uW}\frac{v^2}{\Lambda^2}$$

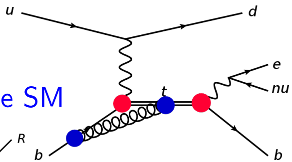
- Lots of recent work has gone into anomalous couplings
  LO EFT, anomalous couplings: Aguilar-Saavedra '08 '09; Bach, Ohl '12
  Analysis and fit to observables, specific model interpretation: Cao, Bin Yan, Yu, Zhang '15
  up to including NLO EFT effects: Zhang, Willenbrock '11; Franzosi, Zhang '15; Zhang '14,'16
  connection to flavor physics and low energy precision measurements: Alioli, Cirigliano, Dekens, Vries, Mereghetti '17

  partial NLO SMEFT calculation with limited set of operators: Beurs, Laenen, Vreeswijk, Vryonidou '18
- NLO SMEFT corrections have been shown to be important

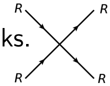
Subtleties with NLO SMEFT and beyond

- NLO QCD expansion of SMEFT amplitude to order $1/\Lambda^2$
  - At NLO in QCD operators begin to shift V_L (Q_{uW}), or mix g_R $(Q_{\phi q})$ with anomalous ttg (Q_{uG}), 4-fermion interference with the LLLL operator





- In addition we include terms of $\mathcal{O}\left(\frac{1}{\Lambda^4}\right)$ that do not interfere w/the SM
  - bbg (Q_{dG}), V_R $(Q_{\phi ud})$, and g_L (Q_{dW})
  - RRRR comes from integrating out a W_R' or vector-like quarks.



- All of this will be included at full NLO in MCFM including:
  - semi-leptonic decays with off-shell top effects in the complex mass scheme and full IS/FS intereference
  - Mutiple scale choices — most importantly DDIS
  - b flavor tracking in jets (restored — recent versions broke it)

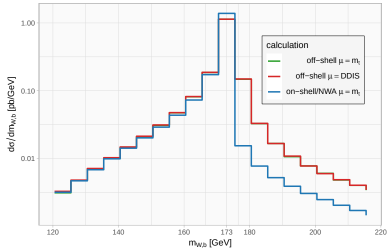
Outline

Current status of the calculation

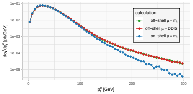
So far we have:

- coded into MCFM: NLO SM, $1/\Lambda^2$ terms.
- We are currently debugging the $1/\Lambda^4$ terms.
- We have checked that we reproduce the inclusive cross section, and some differential distributions for various scale choices.
- Non-resonant tops have a significant effect on some important distributions.

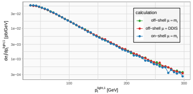
Topmass



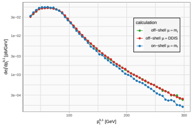
p_{Te}



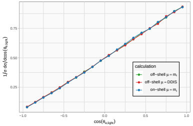
Leading recoil jet p_{Tj_1}



Leading b jet: p_{Tb_1}



Angular correlation $\cos\theta_{ej_1}$



The near future (and far)

The next release of MCFM will include the full NLO t-channel calculation including:

- semi-leptonic decays with off-shell top effects in the complex mass scheme, including IS/FS interference
- Mutiple scale choices — most importantly DDIS
- b flavor tracking in jets (restored)
- All of the above also for:
  - all relevant SMEFT couplings that interfere w/ the SM to $\mathcal{O}\left(\frac{1}{\Lambda^2}\right)$ (Q_{uW}, $Q_{\phi q}$, Q_{uG}, LLLL)
  - we also include operators that enter the cross section at $\mathcal{O}\left(\frac{1}{\Lambda^4}\right)$ from the expansion of the amplitude to $\mathcal{O}\left(\frac{1}{\Lambda^2}\right)$ (Q_{dG}, $Q_{\phi ud}$, Q_{dW}, RRRR)

Next we will move to NNLO t-channel single top

Once NNLO is ready, we will start tracking down which data sets are causing the PDFs to no longer agree at Tevatron energies.

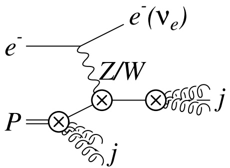
THANK YOU

Backup Slides

PDFs and scales — a subtlety

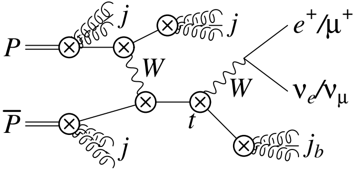
Standard lore says that the choice of scale in a perturbative calculation is arbitrary. . . Standard lore is not quite correct.

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



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

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

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

How well does this work? Well, it used to. . .

Z.S. arXiv:1711.04018 [hep-ph]

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

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

How well does this work? Well, it used to. . .

Z.S. arXiv:1711.04018 [hep-ph]

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

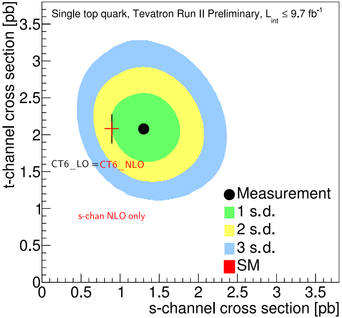
PDF	LO (pb)	NLO (pb)	
CTEQ4L/4M	2.26	2.41	(6% not great, known α_s bug)
CTEQ5L/5M1	2.08	2.07	$< 0.5\%$ (bug fixed)
CTEQ6L1/6M	2.07	2.086	$< 0.5\%$
CTEQ6L1/6M	1.83	2.086	Scales set to m_t, 12% as expected
CTEQ14llo/nlo	2.39	2.00	(20% deviation!)
HERAPDF1.5lo/nlo	1.965	1.798	(9.3% deviation!)
HERAPDF2lo/nlo	1.910	1.762	(8.4% deviation)
NNPDF30lo/nlo	2.33	2.21	(5.4% deviation)

Total PDF uncertainty expected to be $+8.8 - 7.3\%$ at 90% C.L.

1. LO is not equal to NLO any more! We do *not* get back to data!
2. NLO calculations w/ different PDFs disagree by $\sim 5\sigma$!

LO at Tevatron shifted, LHC not much help

Tevatron



I modified 1503.05027

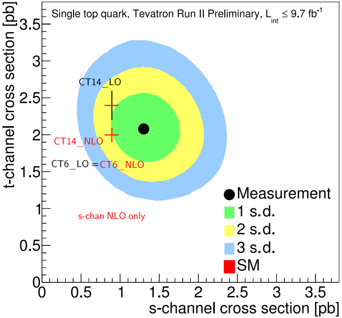
t-channel scale uncertainties shown (LO and NLO)

1σ PDF uncertainties similar to NLO scale uncertainty

(NLO s-channel: CTEQ 6 $\equiv$ CTEQ 14 to $< 0.1\%$)

LO at Tevatron shifted, LHC not much help

Tevatron



I modified 1503.05027

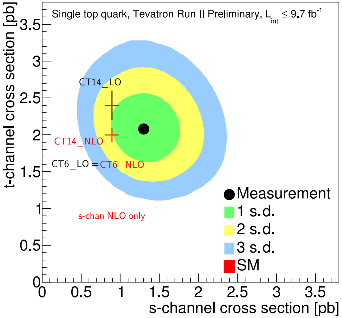
t-channel scale uncertainties shown (LO and NLO)

1σ PDF uncertainties similar to NLO scale uncertainty

(NLO s-channel: CTEQ 6 $\equiv$ CTEQ 14 to $< 0.1\%$)

LO at Tevatron shifted, LHC not much help

Tevatron



I modified 1503.05027

LHC 13 TeV

CMS has measured: t 141.5 ± 12.2 pb; $\bar{t}$ 81.0 ± 10.4 pb

		LO (pb)	NLO (pb)
t	CTEQ 6	141	140
	CTEQ 14	134	137
	NNPDF 30	147	145
$\bar{t}$	CTEQ 6	79.2	80.8
	CTEQ 14	76.4	79.5
	NNPDF 30	85.4	85.6

LHC LO/NLO agree to 2% or better

t-channel scale uncertainties shown (LO and NLO)

1σ PDF uncertainties similar to NLO scale uncertainty

(NLO s-channel: CTEQ 6 $\equiv$ CTEQ 14 to $< 0.1\%$)

What happened? We aren't certain yet. . .

- Perhaps like CTEQ 4, α_s in LHAPDF is off.
  - In fact it was off in LHAPDF 5 with multisets on, this same t-channel calculation found it . . . it is now fixed in LHAPDF 6.
- Maybe LHAPDF is not a good reproduction of the fits.
  - There are small differences, but they are $\leq 0.1\%$

    Still be warned, it can take millions of events at NLO or NNLO to reproduce cross sections if there are large cancellations.
- Maybe the LO fits are just poor.
  - This is a distinct possibility. Mostly NLO (or higher) distributions are fit, then LO formally extracted, but not always with as much data.

What has changed since the days of CTEQ 6?

LHC data has been added, HERA has been updated.

What happened? We aren't certain yet. . .

- Perhaps like CTEQ 4, α_s in LHAPDF is off.
  - In fact it was off in LHAPDF 5 with multisets on, this same *t*-channel calculation found it . . . it is now fixed in LHAPDF 6.
- Maybe LHAPDF is not a good reproduction of the fits.
  - There are small differences, but they are $\leq 0.1\%$
    Still be warned, it can take millions of events at NLO or NNLO to reproduce cross sections if there are large cancellations.
- Maybe the LO fits are just poor.
  - This is a distinct possibility. Mostly NLO (or higher) distributions are fit, then LO formally extracted, but not always with as much data.

What has changed since the days of CTEQ 6?

LHC data has been added, HERA has been updated.

- HERA fits DIS directly.

PDF	LO (pb)	NLO (pb)	
HERAPDF2lo/nlo	1.910	1.762	(8% deviation)
HERA20 ("JETS")	(1.910)	1.830	4% — $+c$, dijets, α_s

HERA "JETS" uses charm and multijets (technically differential DIS).