Are PDFs still consistent with Tevatron data?

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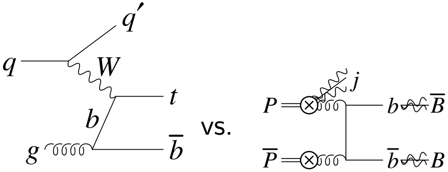

$$g_{\mathrm{DIS}} \stackrel{?}{=} g_{\mathrm{jets}}$$

NNLO t-channel single top and scales

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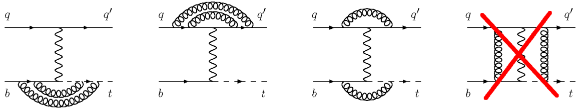

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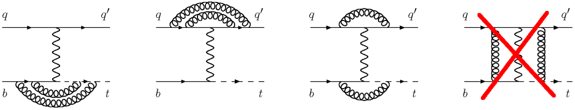


Top quark decay was recently included in Berger, Gao, Yuan, Zhu PRD 94, 071501 (16), but scales remained fixed at m_t.

I wanted to check these calculations by re-evaluating with the Double Deeply Inelastic Scattering (DDIS) scales instead of m_t

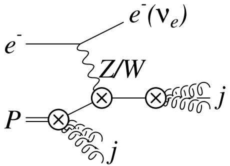
Why? Because the structure of heavy-quark PDFs and improved perturbation theory hangs on a formal relationship between perturbative orders.

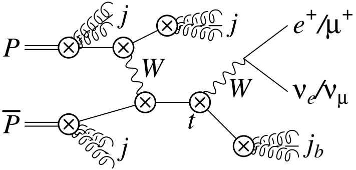
Note: I have not gotten to a check of the NNLO yet. This talk is about the first step: reconfirming the LO and NLO relationship with modern PDFs.

PDFs and scales - a subtlety

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

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





DIS is measured at 1 scale:

$\mu^2 = Q^2$

Double-DIS (DDIS) probes 2 scales:

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

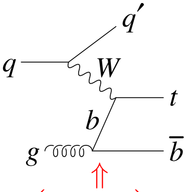
Fits can be done at LO or NLO to extract PDFs, but... the most important *mathematical* constraint is that a *calculation* must give the the same answer for these *inclusive* observables at LO or NLO.

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

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

Key features of t-channel single top (and PDFs)

W-gluon fusion (circa 1996)



$$\sim \alpha_s \ln\left(\frac{Q^2+m_t^2}{p_{T\bar{b}}^2+m_b^2}\right) + \mathcal{O}(\alpha_s)$$

$m_t \approx 35 m_b$! $\alpha_s \ln \sim .7\text{-}.8$

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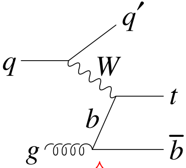

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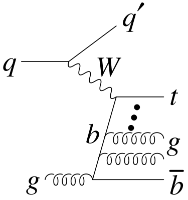

Each order adds

$$\frac{1}{n!}\left[\alpha_s \ln\left(\frac{Q^2+m_t^2}{m_b^2}\right)\right]^n$$

Looks bad for perturbative expansion…

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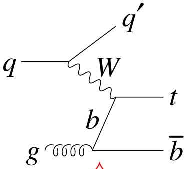

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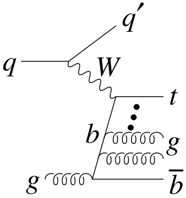

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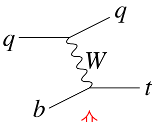
The DGLAP equation resums large logs into a b PDF

$$b(x,\mu^2) = \frac{\alpha_s(\mu^2)}{2\pi} \ln\left(\frac{\mu^2}{m_b^2}\right) \int_x^1 \frac{dz}{z} P_{bg}(z) g\left(\frac{x}{z},\mu^2\right)$$

New Leading Order



$\Uparrow$

$b \sim \alpha_s \ln\left(\frac{\mu^2}{m_b^2}\right) \times g$

Large delicate cancellations occur at NLO to keep the inclusive cross section the same between LO and NLO. (I want to check NNLO)

t-channel single top is a precision test of the entire framework

There are several coupled points that are tested:

1. Since t-channel single top is double-DIS, it too must give the same inclusive cross section at LO and NLO.
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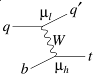

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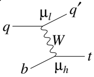

3. Any deviation is exaggerated, by loss of the delicate cancellation between the large $\ln(m_t^2/m_b^2)$ enhanced terms.

Strictly speaking single-top data is *not used* in fits, but it analytically maps onto DIS and $b(x,\mu) = \mathrm{const} \times g(x,\mu)$, so it better work.

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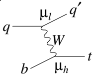

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The point here is this process places some of the most stringent constraints on the entire framework of improved perturbation theory, massive quark PDFs, and maybe even the universality of PDFs themselves. . .

So, I started with reconfirmation of Tevatron results at LO and NLO with modern PDFs (those w/NNLO versions). . .

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

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	$< 0.5\%$
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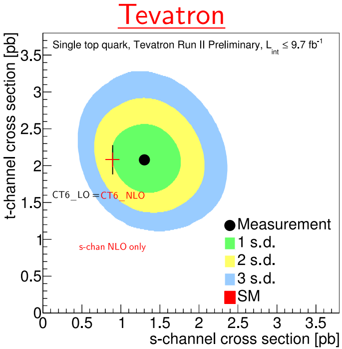
CTEQ14llo/nlo	2.39	2.00	(20% deviation!)
HERAPDF1.5lo/nlo	1.965	1.798	(9.3% deviation!)
HERAPDF2lo/nlo	1.910	1.762	(8.4% deviation) NLO 12% too small
NNPDF30lo/nlo	2.33	2.21	(5.4% deviation) NLO 10% too big

Total PDF uncertainty expected to be $+8.8 - 7.3\%$ at 90% C.L.
NNPDF/HERA *NLO* differ from each other by 5σ!

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

LO at Tevatron shifted, LHC not much change



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 $< 0.1\%$)

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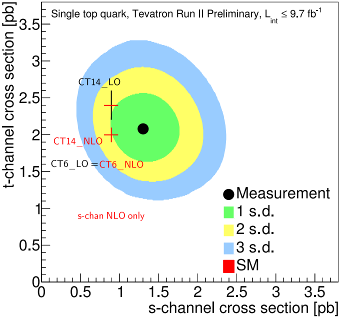

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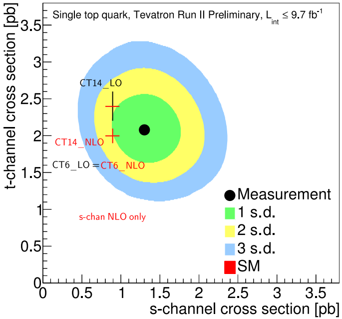

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LHC 13 TeV

CMS has measured:

t 141.5 ± 12.2 pb

$\bar{t}$ 81.0 ± 10.4 pb

		LO (pb)	NLO (pb)
	CTEQ 6	141	140
t	CTEQ 14	134	137
	NNPDF 30	147	145
	CTEQ 6	79.2	80.8
$\bar{t}$	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? Down the rabbit hole. . .

It is now standard to access PDFs through the LHAPDF interface.

- 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.

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    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? Down the rabbit hole...

- NNPDF has several NLO fits purporting to use data subsets

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PDF	LO (pb)	NLO (pb)	
NNPDF30lo/nlo	2.33	2.21	(5% deviation)
NNPDF30 (no LHC)	(2.33)	2.22	(5% deviation)
NNPDF30 (HERA)	(2.33)	2.10	11%!

- Curiously, LHC data has *no* effect on the NLO calculation.
  NLO agreement is clearly a numerical accident, as this is the x and Q^2 region used to fit the gluon (which is $\propto b$ PDF)
- Unfortunately, there are no public LO fits varying these data sets to compare to.
- HERA only seems worse! If this is DDIS, shouldn't it be better?
  Let's ask HERA.

What happened? Down the rabbit hole. . .

- HERA fits DIS directly.

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

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 DIS is not directly sensitive to the gluon.
  - HERA "JETS" uses charm and multijets (technically differential DIS). Recall $\sigma \sim \ln\left(\frac{Q^2}{p_T^2}\right)$ in the massless case.
  - This data is part of DIS and should improve the agreement.
  - One thing is clear: vastly more studies of LO are needed

Could there be something deeper going on?

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

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

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   — 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. In most other processes it is numerically hidden.

Conclusions

Are PDFs still consistent with Tevatron data?

Of course they are, but as data improves we should keep an eye on them.

Here are several projects (of increasing complexity) to consider:

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4. Explore whether we need to radically change how we think about the gluon d.o.f. as embedded in PDFs to account for different processes being sensitive to different d.o.f. for today's high precision data.

Let's get some Collaborative efforts going!

THANK YOU