CT10 PDFs and the puzzle of W lepton asymmetry

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The puzzle of the W lepton asymmetry

- Rapidity asymmetry $A_\ell(y_\ell)$ of charged lepton $\ell = e$ or μ in W boson decay provides important constraints on $d(x,Q)/u(x,Q)$ at $x > 0.1$

$$A_\ell(y_\ell) = \frac{d\sigma(p\bar{p} \to (W^+ \to \ell^+ \nu_\ell)X)/dy_\ell \; - \; d\sigma(p\bar{p} \to (W^- \to \ell^- \bar{\nu}_\ell)X)/dy_\ell}{d\sigma(p\bar{p} \to (W^+ \to \ell^+ \nu_\ell)X)/dy_\ell \; + \; d\sigma(p\bar{p} \to (W^- \to \ell^- \bar{\nu}_\ell)X)/dy_\ell}.$$

Berger, Halzen, Kim, Willenbrock, PRD 40, 83 (1989)

The puzzle of the W lepton asymmetry

- NLO calculations based on recent PDFs fail in describing the most precise $A_e(y_e)$ and $A_\mu(y_\mu)$ from D0 Run-2 (2008)

Agreement of PQCD with D0 $A_e(y_e)$	Order of α_s	χ^2/npt	Source
CTEQ6.6	NLO	191/36=5.5	*Our study*
CT10W	NLO	78/36=2.2	
ABKM'09	NNLO	540/24=22.5	*Catani, Ferrera, Grazzini, JHEP 05, 006 (2010)*
MSTW'08	NNLO	205/24=8.6	
JR09VF	NNLO	113/24=4.7	

- The puzzle: why do these decent PDFs fail to describe $A_\ell(y_\ell)$?
- We examine this question in the context of the recent CT10 PDF analysis

CT10 parton distribution functions (arXiv:1007.2241)

- Version 2 (Aug. 20, 2010):
  - extended discussion of the PDF fit to the Tevatron Run-2 W asymmetry data
  - search for deviations from NLO DGLAP evolution in the small-x HERA data
- New PDF sets in the LHAPDF library and on the CTEQ website:
  - CT10 and CT10W PDF best-fit sets and 44 eigenvector sets for $\alpha_s(M_Z) = 0.118$
  - 4 CT10AS PDFs for $\alpha_s(M_Z) = 0.116 - 0.120 \Rightarrow$ sufficient for calculating the PDF+α_s uncertainty by addition in quadrature (as explained in arXiv:1004.4624)
  - CT10/CT10W PDFs with 3 and 4 active flavors

CT10 parton distribution functions (arXiv:1007.2241)

Experimental data

- Combined HERA-1 neutral-current and charged-current DIS data with 114 correlated systematic effects
  - replaces 11 separate HERA-1 sets used in the CTEQ6.6 fit
- CDF Run-2 and D0 Run-2 inclusive jet production
- Tevatron Run-2 Z rapidity distributions from both CDF and D0
- W electron asymmetry from CDF II and D0 II; W muon asymmetry from D0 II (CT10W set)
- Other data sets inherited from CTEQ6.6

CT10 parton distribution functions (arXiv:1007.2241)

Developments in statistical techniques

- Experimental normalizations N_i are treated on the same footing as other correlated systematic errors
  - Minimum of χ^2 with respect to N_i is found algebraically
  - normalization shifts are automatically accounted for when producing the eigenvector sets
- Set all data weights of 1, unless otherwise specified
  - do not prefer some experiments over the other experiments
  - Exception: Run-2 W asymmetry data (see below)

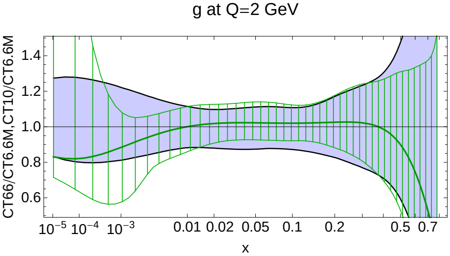
CT10 parton distribution functions (arXiv:1007.2241)

Revised functional forms at the input scale

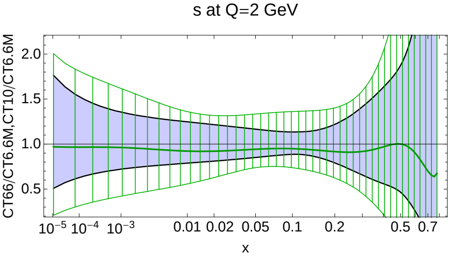
- More data constraints ⇒more flexible (=less biased) parametrizations for $g(x, Q_0)$, $d(x, Q_0)$, and $s(x, Q_0)$
- $R_s = \lim_{x\to 0} (s(x) + \bar{s}(x)) / (\bar{u}(x) + \bar{d}(x))$ is not constrained by the data ⇒large uncertainty in $s(x)$ at $x \to 0$
  - allow R_s to vary in the fit, but softly constrain it by a penalty on χ^2 to satisfy $0.4 < R_s < 1$

More flexible parametrizations

CT10(green) vs. CT6.6(blue)



$g(x, Q)$: large uncertainty at $x < 10^{-3}$, despite tighter constraints by the combined HERA data



$s(x, Q)$: wider uncertainty, covers both CTEQ6.6 and MSTW'08

CT10: agreement between data sets

- Good overall agreement: $\chi^2/d.o.f. = 3000/2750 = 1.1$
- Some tensions are also observed:
  - **Tevatron single-inclusive jet production:** Run-1 and Run-2 sets are moderately (in)compatible *(arXiv:0904.2424)*
  - **D0 Run-2 W lepton asymmetry:** apparently disagrees with constraints on d/u by the NMC and BCDMS data on $F_2^{p,d}(x,Q)$
- Two series of PDFs are produced:
  - **CT10:** no Run-2 W asymmetry data are included
  - **CT10W:** with Run-2 W asymmetry, with an extra χ^2 weight
  - **Theoretical cross sections:** computed by ResBos; include the most important part of resummed NNLO corrections

How we calculate $A_\ell(y_\ell)$

- Selection cuts on p_T^ℓ of ℓ emphasize sensitivity to $d(x,\mu)/u(x,\mu)$ in different x ranges
- **Default calculation:** $A_\ell(y)$ at NNLL-NLO, using lookup tables for $\sigma(p_T^\ell, y_\ell)_{NNLL+NLO}/\sigma(p_T^\ell, y_\ell)_{LO}$ from ResBos *(Balazs, Yuan, PRD 56, 5558 (1997); Landry, Brock, P.N. Yuan, PRD67, 073016 (2003))*.
- **Cross check:** include NNLO corrections at $Q_T \approx M_W$ *(Arnold & Reno, 1989)*; $A_\ell(y_\ell)$ changes by a few percent at the highest y_ℓ and $p_T > 35$ GeV
  - magnitude of changes is comparable with full NNLO terms in Catani, Ferrera, and Grazzini, JHEP 05, 006 (2010)
  - changes are small compared to the current experimental errors

Comparison of CT10 and CT10W fits

- CDF Run-1 and Run-2 $A_\ell(y)$ data agree with $F_2^p(x,Q)/F_2^d(x,Q)$
- Good fits to D0 electron (e) asymmetry data are possible without NMC and BCDMS; and vice versa
- No acceptable fit to D0 II e asymmetry and NMC/BCDMS data can be achieved, if they are included on the same footing
- Tension between Run-2 e asymmetry and D0 Run-2 μ asymmetry
- Reasonable agreement between Run-2 e W asymmetry data and Z y data

Comparison of CT10 and CT10W fits

- With special emphasis on D0 II e asymmetry data (χ^2 weight>1), it is possible to obtain a reasonable agreement for W asymmetry ($\chi^2/d.o.f. = 1-2$) , with some remaining tension with NMC & BCDMS $F_2^d(x,Q)$ and $F_2^p(x,Q)$ at $x > 0.4$

Resolution of the puzzle

$A_\ell(y_\ell)$ is a sensitive probe of the slope s_{du} of $d(x, M_W)/u(x, M_W)$

At LO:

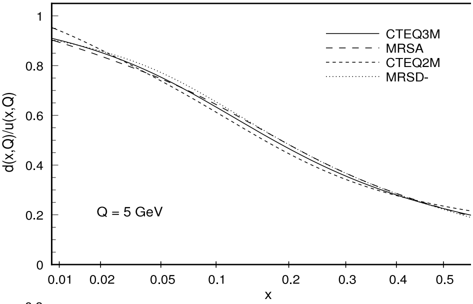
$$A_\ell(y_\ell) \sim A_\ell(y_W) \propto \frac{1}{x_1 - x_2}\left[\frac{d(x_1, M_W)}{u(x_1, M_W)} - \frac{d(x_2, M_W)}{u(x_2, M_W)}\right] = s_{du}$$

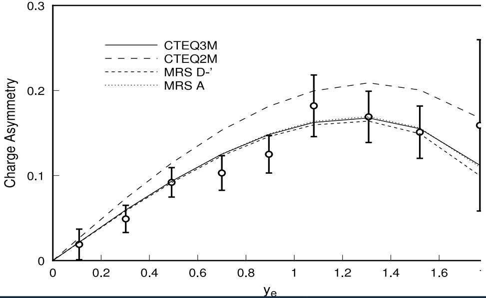
$$x_{1,2} = \frac{Q}{\sqrt{s}} e^{\pm y_W}$$

Small changes in s_{du} cause significant variations in A_ℓ

Berger, Halzen, Kim, Willenbrock, PRD 40, 83 (1989); Martin, Stirling, Roberts, MPLA 4, 1135 (1989); Phys. Rev. D50, 6734 (1994); Lai et al., PRD 51, 4763 (1995)

Resolution of the puzzle





Small changes in s_{du} cause significant variations in A_ℓ

$F_2^d(x,Q)/F_2^p(x,Q)$ does not constrain s_{du} in such direct way

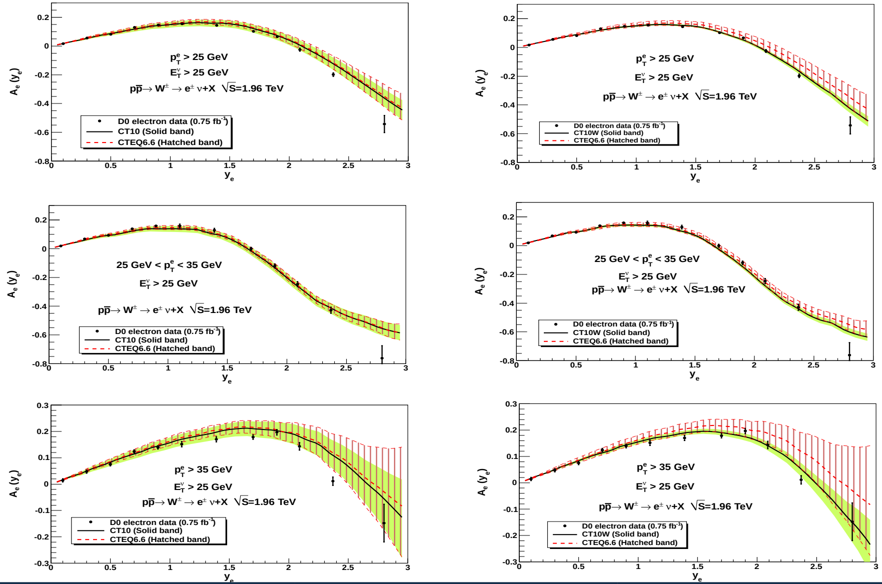
Lai et al., PRD 51, 4763 (1995)

CT10 and CT10W predictions for D0 Run-2 W asy

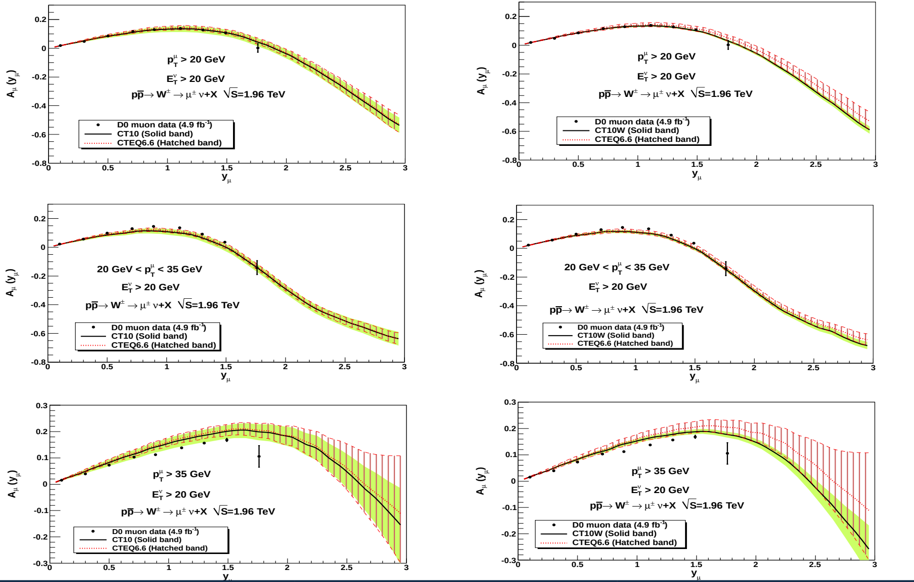
- CT10W agrees better with W asy data; has smaller uncertainty than CTEQ6.6 or CT10
- Only the 2nd bin of $A_\mu(y_\mu)$ is compatible with 3 bins of $A_e(y_e)$ and the rest of hadronic data

$\Rightarrow$ Figures

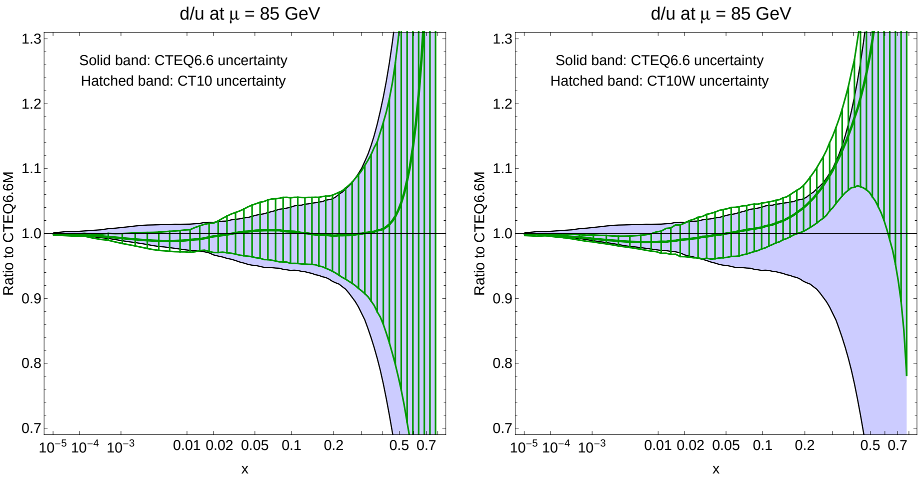
CT10 and CT10W predictions for $A_e(y_e)$ (D0 Run-2)



CT10 and CT10W predictions for $A_\mu(y_\mu)$ (D0 Run-2)



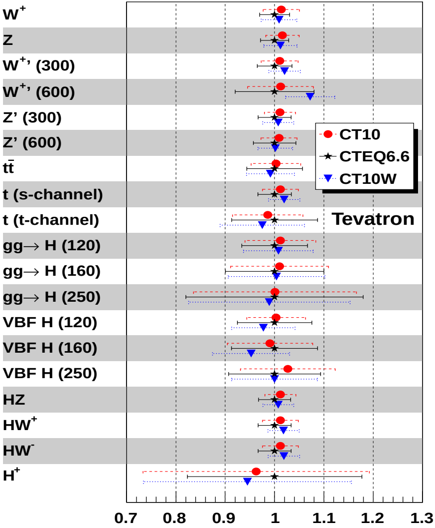
$d(x,Q)/u(x,Q)$ at $Q = 85$ GeV

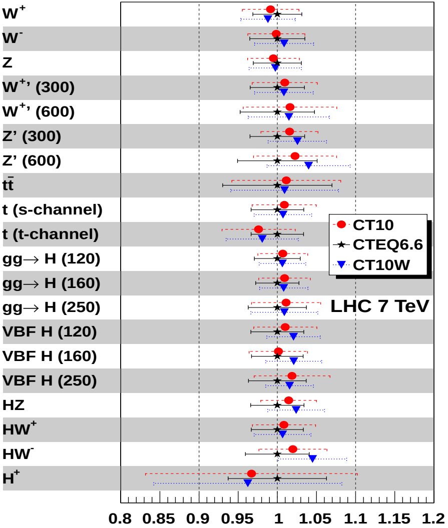


CT10W prefers larger d/u, has smaller uncertainty than CTEQ6.6 or CT10

CT10 & CT10W predictions for the LHC & Tevatron

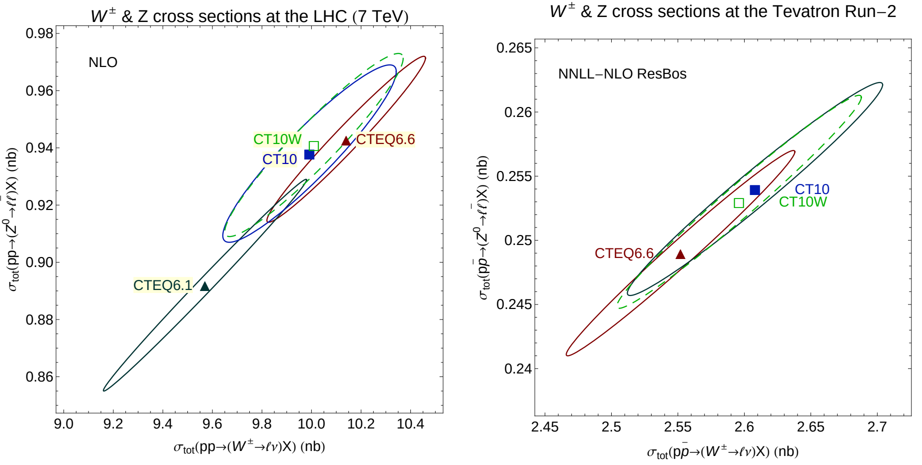
Total cross sections





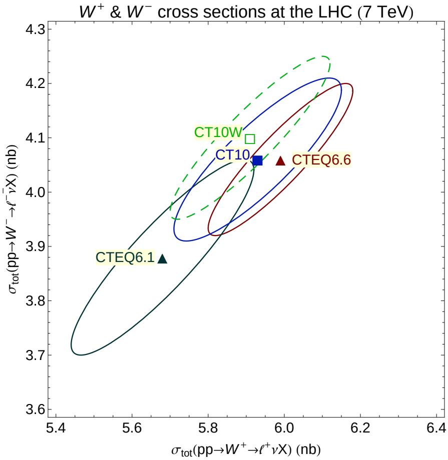
CT10 & CT10W predictions for the LHC

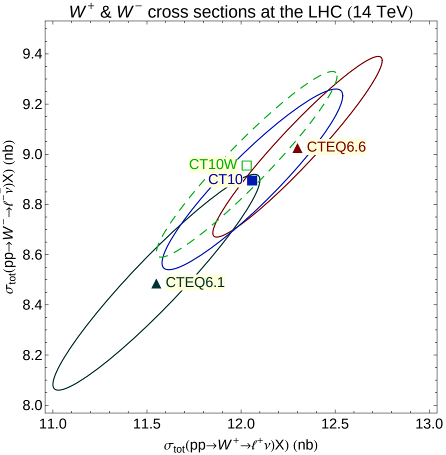
$W^{\pm}$ and Z^0 total cross sections



CT10 & CT10W predictions for the LHC & Tevatron

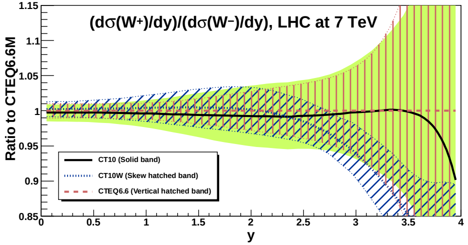
W^+ and W^- total cross sections

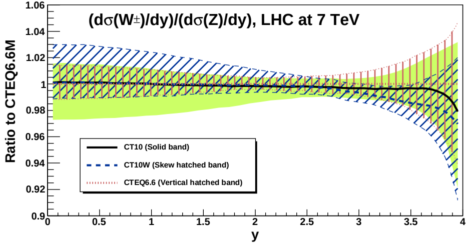




CT10 & CT10W predictions for the LHC

$\sigma(W^+)/\sigma(W^-)$ and $\sigma(W^\pm)/\sigma(Z^0)$ vs. $y_{W/Z}$





Summary

Tevatron Run-2 W asymmetry data...

...become increasingly complete and precise (measurements by both CDF and D0; electron and muon channels)

...cannot be explained based on the d/u ratio found from the low-Q DIS data (mostly NMC and BCDMS)

- Several cross checks of the theoretical calculation for W asymmetry (resummed NNLL+partial NNLO in ResBos); no problems were found
- Higher-twist and nuclear corrections in the large-x BCDMS/NMC deuterium data are the usual suspects

  (Virchaux and Milsztajn; Alekhin; Accardi et al.)
- CT10 and CT10W sets of PDFs for practical applications, without and with constraints from the Run-2 W asymmetry