Parton distribution functions at the new frontier

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- PDFs and the first LHC data
- Benchmarking of NLO PDFs
- NNLO contributions to CTEQ PDF analysis

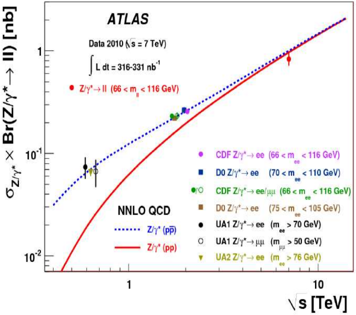
Rediscovering the PDFs at $\sqrt{s} = 7$ TeV

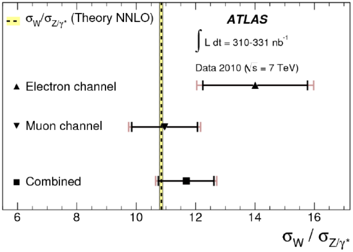
LHC produces rapidly improving constraints on QCD processes and parton distributions

First comparisons of PQCD to data in

- $pp \to (W \to \ell\nu)X$
- $pp \to (Z, \gamma^* \to \ell^+\ell^-)X$

Figures are from ATLAS. Similar results from CMS



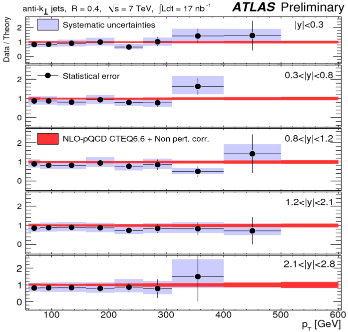


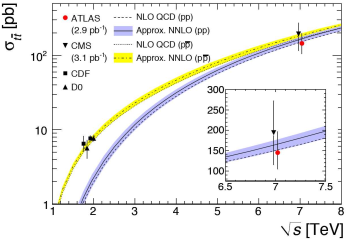
Rediscovering the PDFs at $\sqrt{s} = 7$ TeV

LHC produces rapidly improving constraints on QCD processes and parton distributions

First comparisons of PQCD to data in

- $pp \to \mathrm{j}X$ and $\mathrm{jj}X$
- $pp \to t\bar{t}X$
- other processes





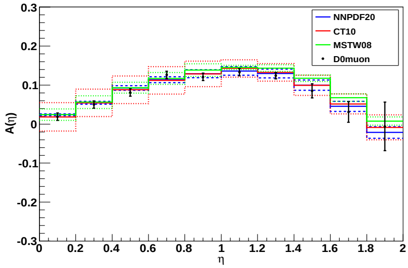
Figures are from ATLAS. Similar results from CMS

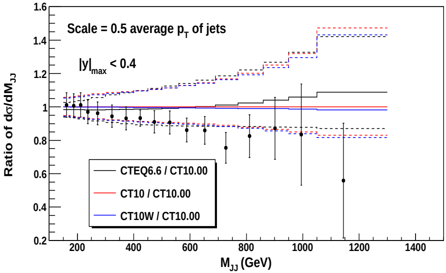
Influx of precise Tevatron Run-2 data

Run-2 W charge asymmetry and (di)jet data is testing limits of existing fixed-order NLO calculations

In both processes, experimental accuracy is high enough to start feeling effects beyond NLO and of resummations

I will focus mostly on LHC-related issues

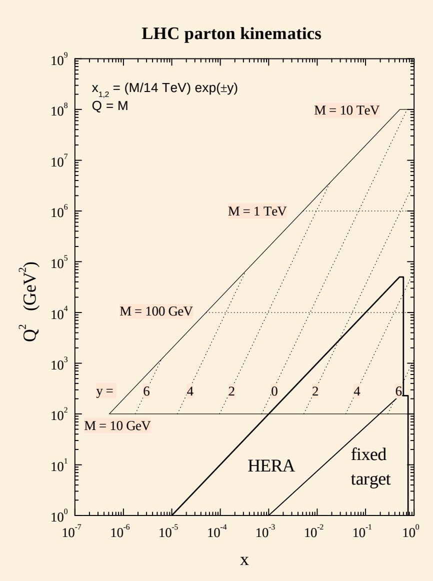




Parton distributions for the Large Hadron Collider

PDF's must be determined in a wide (x, Q) range with accuracy $\sim 1\%$ for purposes of...

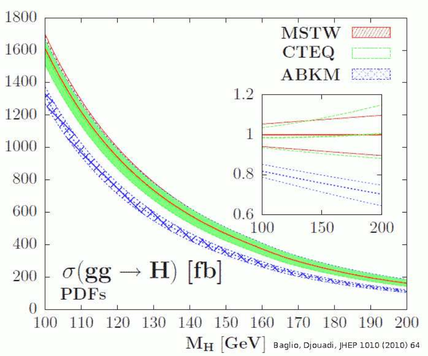
- monitoring of the LHC luminosity, calibration of detectors
- tests of electroweak symmetry breaking (EWSB)
- searches for Higgs bosons, supersymmetry, etc
- discrimination between new physics models
- precision tests of hadronic structure



Key Tevatron/LHC measurements require trustworthy PDFs

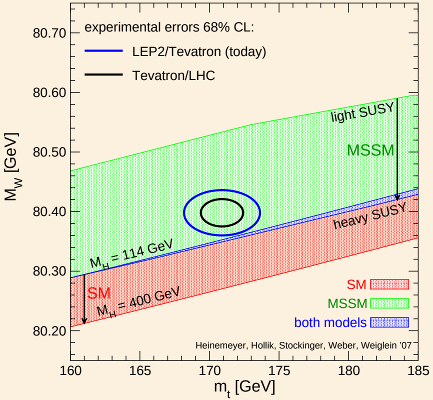
For example, leading syst. uncertainties in tests of electroweak symmetry breaking are due to insufficiently known PDFs

$gg \to H$ at the Tevatron



δ_{PDF} and δ_{α_s} dominate δM_H

EW fits + direct Higgs searches



SM band: $114 \le M_H \le 400$ GeV
SUSY band: random scan

Recent public PDF sets

Global PDF analyses *(DIS, vector boson, and jet production data)*

- **CTEQ-TEA** (Tung et al.)
  - Latest NLO PDF sets: **CT10** and **CT10W**
    (*Guzzi, Huston, Lai, Li, P.N., Pumplin,Stump, Yuan, arXiv:1007.2241*)
- Martin, Roberts, Thorne, Watt (**MSTW'08**)
- Neural Network PDF (**NNPDF2.1**)

DIS-based analyses – DIS data + select other sets

- Alekhin, Blümlein, Moch (**ABM'09**)
- **HERAPDF1.0, prelim. HERAPDF1.5**
- Gluck, Jimenez-Delgado, Reya (**GJR'08**)

Each analysis is different. No single PDF set outperforms other sets in all situations. Pre-2007 PDFs are obsolete.

Origin of differences between PDF sets

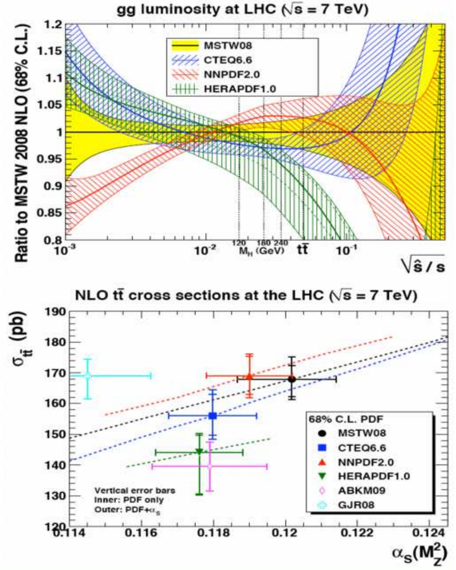
- **NNLO QCD** terms *(ABM, GJR, MSTW; Prel.: CTEQ, HERAPDF, NNPDF)*;
  Full heavy-quark mass dependence at NLO *(all sets)*
  - NNLO contributions are necessary, but not sufficient for NNLO accuracy
- **Selection of data**: global analyses vs. DIS-based ones
- **Statistical treatment**: Monte-Carlo sampling (NNPDF), analytical minimization of χ^2 (other groups)
- Treatment of experimental systematic uncertainties
- **Definitions of PDF uncertainties**
- **Initial PDF parametrizations**: neural networks (NNPDF), 2-5 parameter forms per flavor (other fits)
- Values of $\alpha_s(M_Z)$, m_c, and m_b and their treatment
- **Differences in NLO codes** used by PDF fits

Benchmarking of NLO cross sections: $pp \to t\bar{t}X$

Comparisons of NLO parton luminosities and cross sections based on different PDFs, shown as ratios to MSTW'08

(G. Watt, contributed to the PDF4LHC study of benchmark processes, arXiv:1101.0536)

Similar, but not always overlapping, gluon-gluon luminosity bands



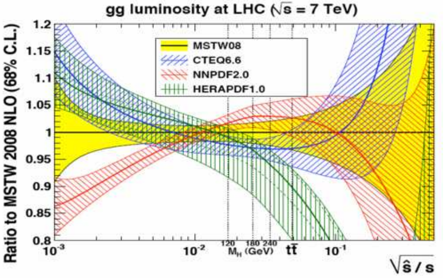
Benchmarking of NLO cross sections: $pp \to t\bar{t}X$

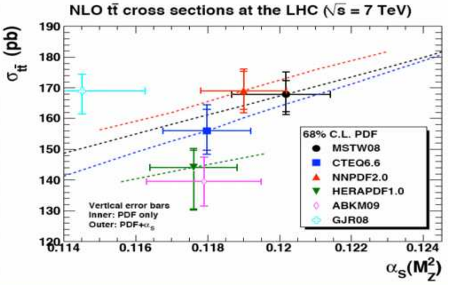
$t\bar{t}$ cross sections fall into two groups differing by more than 1σ

This is partly explained by differences in assumed α_s values, as indicated by the curves

$\Rightarrow$ Active efforts to understand PDF-α_s correlations and reduce uncertainties in $t\bar{t}$ and Higgs cross sections

Martin et al.: arXiv:0905.3531;
Lai et al.: arXiv:1004.4624
Ubiali et al.: arXiv:1005.0397
Alekhin, Bluemlein, Moch: arXiv:1101.5261





Practical evaluation of the combined PDF+α_s uncertainty

Several prescriptions of varying complexity for combining the PDF and α_s uncertainties exist

In arXiv:1004.4624, we show that **addition of the α_s and PDF uncertainties in quadrature is entirely adequate in most practical situations**

Theorem

In the quadratic approximation, the total α_s+PDF uncertainty $\Delta\sigma$ for the CT10 set, for $\alpha_s(M_Z) = 0.118 \pm 0.002$, is obtained by

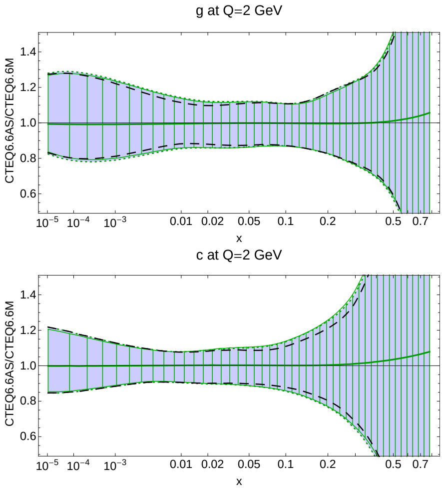
$$\Delta X = \sqrt{\Delta X^2_{CTEQ6.6} + \Delta X^2_{\alpha_s}},$$

where

- $\Delta X_{CTEQ6.6}$ *is the CTEQ6.6 PDF uncertainty from 44 PDFs with the same* $\alpha_s(M_Z) = 0.118$
- $\Delta X_{\alpha_s} = (X_{0.120} - X_{0.116})/2$ *is the* α_s *uncertainty computed with two central CTEQ6.6AS PDFs for* $\alpha_s(M_Z) = 0.116$ *and* 0.120

Quadrature addition reproduces the exact PDF+α_s uncertainty

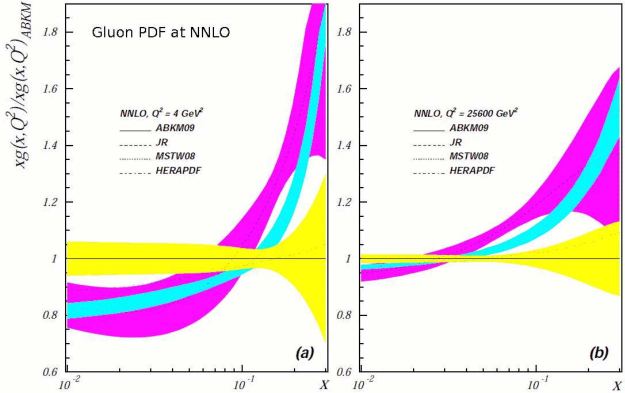
Total PDF+α_s errors ΔX are the **same** when found (a) from a full fit with floating α_s, or (b) by adding ΔX_{PDF} and ΔX_{α_s} in quadrature



- black – CTEQ6.6 PDF uncertainty
- Blue filled – PDF+α_s uncertainty of the fit with floating $\alpha_s(M_Z)$
- Green hatched – PDF+α_s uncertainty added in quadrature

Comparisons of NNLO PDFs

Alekhin, Bluëmlein, Jimenez-Delgado, Moch, Reya, arXiv:1011.6259



NNLO bands of MSTW and DIS-based analyses don't overlap

Practical problem: how to evaluate the PDF uncertainty in ATLAS/CMS analyses from incompatible inputs?

$\Rightarrow$ PDF4LHC interim recommendation for combining PDF uncertainties *(Botje et al., arXiv:1101.0538)*

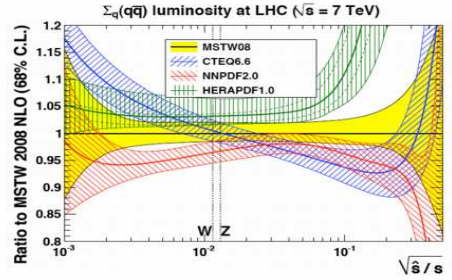
Benchmarking: $W^{\pm}$ production at NLO

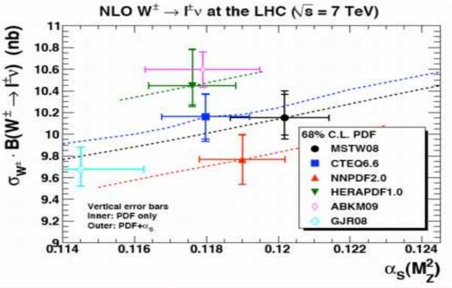
CTEQ and MSTW predictions for cross sections and uncertainty are in good agreement

ABM and HERAPDF are higher, NNPDF2.0 is below because of zero-mass approximation for c and b

Most differences (up to 6%) are explained by dependence on heavy-quark scheme and charm mass m_c in DIS

For comparison, NNLO correction to $\sigma_{W,Z}$ is ≈2%

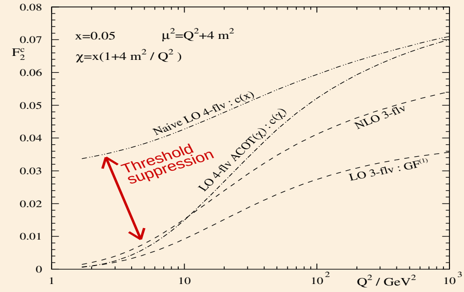


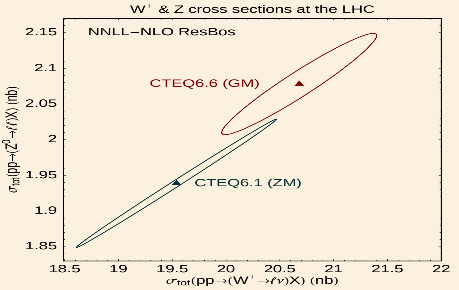


The Les Houches Heavy Quark Benchmark Study

General-mass (and not zero-mass of fixed-flavor number) treatment of c, b mass terms in DIS is essential for predicting precision W, Z cross sections at the LHC *(Tung et al., hep-ph/0611254)*

Variations in realizations of the GM scheme cause substantial differences in the PDFs





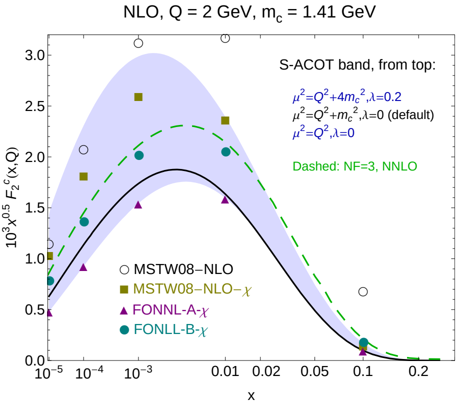
Mass schemes and their free parameters

PDF set	Mass scheme
ABM	Buza-Matiounine-Smith-van Neerven; (3-flav. in practice)
CTEQ	Simplified Aivazis-Collins-Olness-Tung
GJR	3-flavor
HERAPDF	Modified Thorne-Roberts
MSTW	Modified Thorne-Roberts/S-ACOT
NNPDF	FONLL

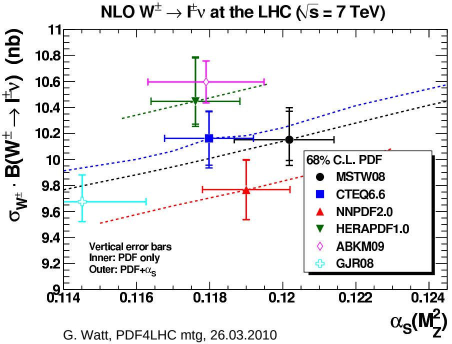
- All schemes are now available at NNLO.
- All depend significantly on **tunable parameters**: input charm mass m_c and factorization scale μ
- GM schemes also depend on matching conditions between 3- and 4-flavor schemes
  - in S-ACOT: controlled by a rescaling variable ζ

Input parameters of the S-ACOT scheme

At NLO, the m_c, μ, and ζ parameters of CTEQ PDFs are tuned to best describe the DIS data



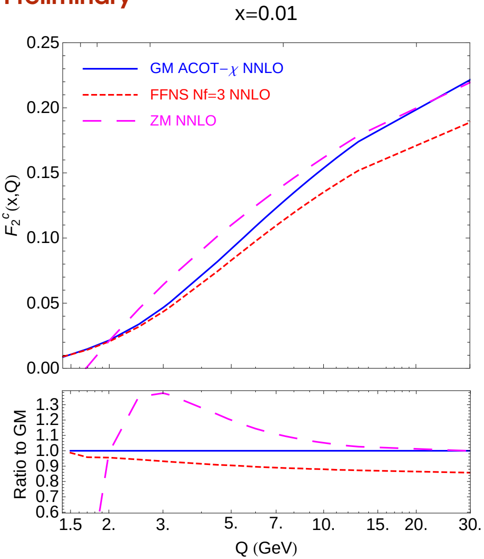
2009 Les Houches HQ benchmarks with toy PDFs; default $\mu = Q$



W, Z cross sections; $m_c = 1.3$ GeV in CTEQ6.6

New: $F_2^{(c)}(x,Q^2)$ in S-ACOT scheme at NNLO

Preliminary



NNLO calculation for $F_{2,L}^c(x,Q)$ is implemented in the CTEQ fit *(Guzzi, Lai, P.N., Yuan, in preparation)*

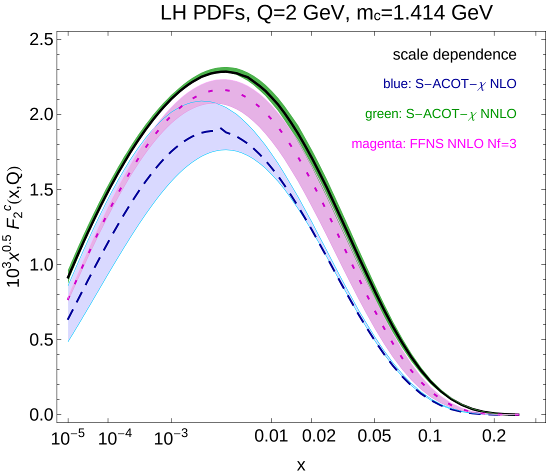
ACOT reduces to FFNS at $Q \approx m_c$ and to ZM at $Q \gg m_c$

Les Houches toy PDFs, evolved at NNLO with threshold matching terms

NNLO results for $F_2^{(c)}(x, Q^2)$ - Preliminary

At NNLO and $Q \approx m_c$:

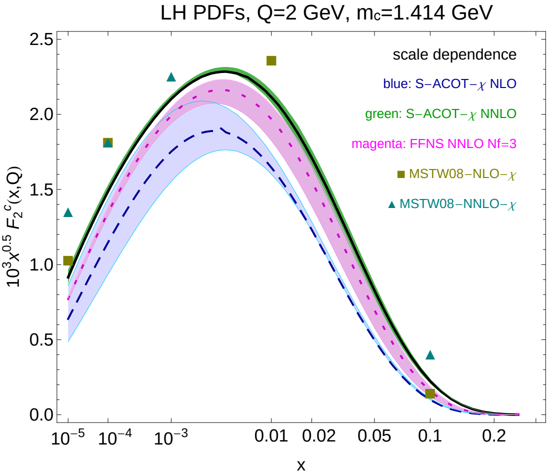
■ S-ACOT-$\chi \approx$ FFN($N_f = 3$) without tuning



NNLO results for $F_2^{(c)}(x, Q^2)$ - Preliminary

At NNLO and $Q \approx m_c$:

- S-ACOT-$\chi \approx$ FFN($N_f = 3$) without tuning
- It is close to other NNLO schemes



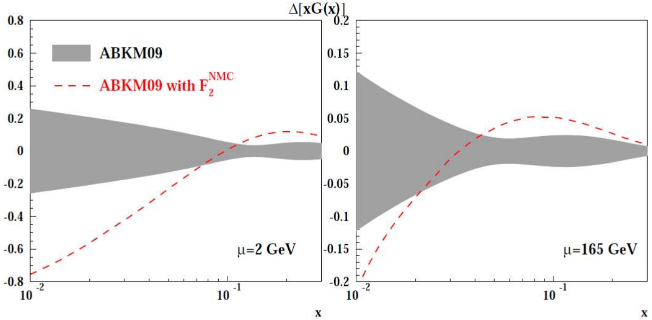
Conclusions

- PDF analysis groups are progressing toward a genuine NNLO accuracy of their PDFs
- In the CTEQ-TEA fit, an NNLO calculation for $F_{2,L}^{c,b}$ in the S-ACOT scheme is demonstrated to be viable.
  Details: M. Guzzi, Les Houches Workshop on QCD, Feb 14, 2011
- This is the most challenging component of the NNLO CTEQ PDF analysis, to be made available soon.
- NNLO predictions are stable and show a remarkable reduction in the dependence on free parameters, compared to NLO.
- **arXiv:1101.0561**: synopsis of recent CTEQ-TEA publications
  - CT10W fit to Run-2 W charge asymmetry;
    PDFs for leading-order showering programs; constraints on color-octet fermions

Backup slides

Effect of NMC data on $\alpha_s(M_Z)$ and gluon PDF

Alekhin, Blümlein, Moch, arXiv:1101.5261



An ABM fit to the NMC F_2 data (as it is done in other PDF analyses) leads to significant differences in gluon PDF and $\alpha_s(M_Z)$

ABM recommend to fit to NMC reduced DIS cross sections, their default choice

However, other groups do not observe such strong effect of the NMC data on α_s

Parton Distribution Uncertainties using Smoothness Prior
A. Glazov, S. Moch, and V. Radescu, arXiv:1009.6170

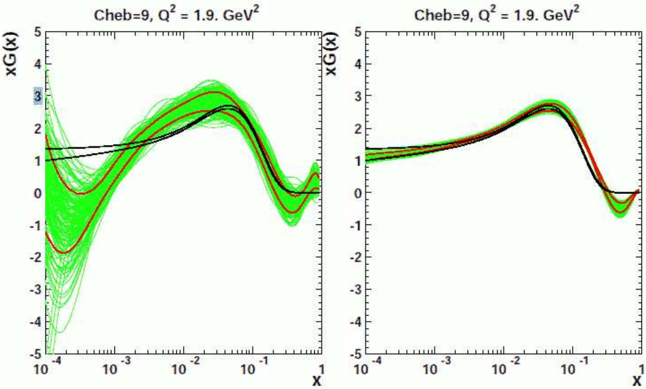
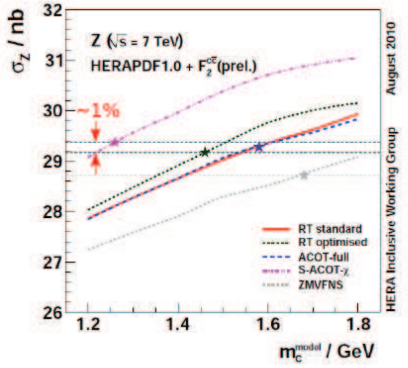


Figure 1: The gluon PDF $xg(x)$ at the starting scale $Q_0^2 = 1.9$ GeV^2. The green lines show fits to individual replicas of the data, the red lines show the RMS over the replicas. The black lines correspond to the error band of the gluon distribution using a standard parameterization and it is to be compared to the case of the Chebyshev parameterization. On the left hand side, the gluon distribution is shown using an unconstrained Chebyshev expansion to order nine, see Eq. (3), while on the right hand side the same distribution is displayed but with a tight length penalty $\alpha = 5000$ GeV^{-1} applied.

Z cross sections at LHC



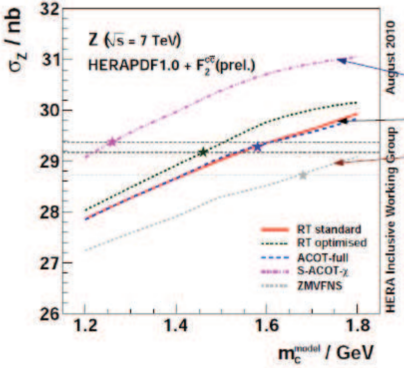
(★ indicate σ with PDFs at m_c^{model}(opt))

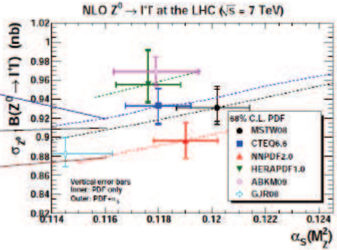
- cross section predictions for each scheme vary ~7% for $1.2 < m_c^{model} < 1.8$ GeV
- predictions for all schemes vary ~7% for given m_c^{model}

BUT:

- predictions for m_c^{model} (opt) has much smaller spread: <1% (~2% with ZMVFNS)

Z cross sections at LHC



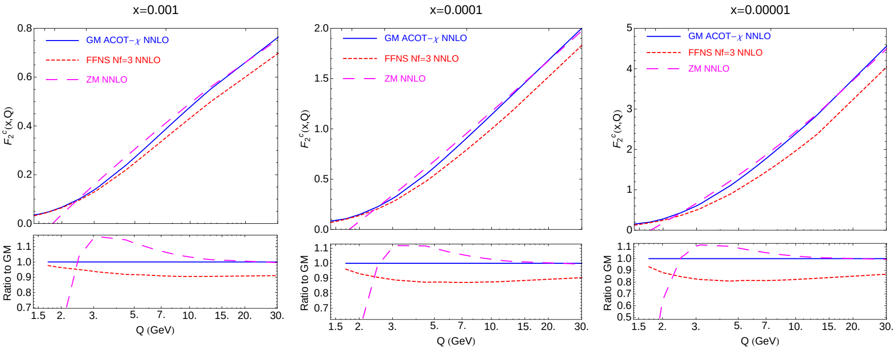


- comparison of Z cross sections as a function of $\alpha_S(M_Z^2)$
  G.Watt, PDF4LHC 26.03.2010

(★ indicate σ with PDFs at m_c^{model}(opt))

→ could explain part of existing differences between PDFs

$F_2^{(c)}(x, Q^2)$ at NNLO, other x bins - Preliminary



Simplified Aivazis-Collins-Olness-Tung scheme

ACOT, PRD 50 3102 (1994); Collins, PRD 58 (1998) 094002; Kramer, Olness, Soper, PRD (2000) 096007

- The default mass scheme of CTEQ6.6 and CT10 PDFs
- Based upon, and closely follows, the proof of QCD factorization for DIS with massive quarks *(Collins, 1998)*
- Relatively simple, compared to BMSN or TR schemes
  - One value of N_f (and one PDF set) in each Q range
  - Straightforward matching based on kinematical rescaling
  - Sets $m_Q = 0$ in ME with incoming c or b
- Reduces to the ZM $\overline{MS}$ scheme at $Q^2 \gg m_Q^2$, without additional renormalization
- Reduces to the FFN scheme at $Q^2 \approx m_Q^2$
  - has reduced dependence on tunable parameters at NNLO

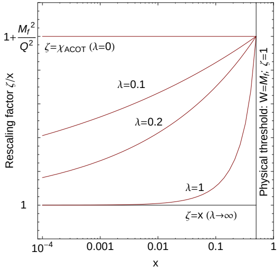
S-ACOT input parameters

At $Q \approx m_c$, F_2^c depends significantly on

1. **Charm mass:** $m_c = 1.3$ GeV in CT10
2. **Factorization scale:** $\mu = \sqrt{Q^2 + \kappa m_c^2}$; $\kappa = 1$ in CT10
3. **Rescaling variable** $\zeta(\lambda)$ for matching in $\gamma^* c$ channels
   (*Tung et al., hep-ph/0110247; Nadolsky, Tung, PRD79, 113014 (2009)*)

$$F_i(x, Q^2) = \sum_{a,b} \int_\zeta^1 \frac{d\xi}{\xi} \, f_a(\xi, \mu)\, C^a_{b,\lambda}\left(\frac{\zeta}{\xi}, \frac{Q}{\mu}, \frac{m_i}{\mu}\right)$$

$$x = \zeta \Big/ \left(1 + \zeta^\lambda \cdot (4m_c^2)/Q^2\right), \text{ with } 0 \le \lambda \lesssim 1$$

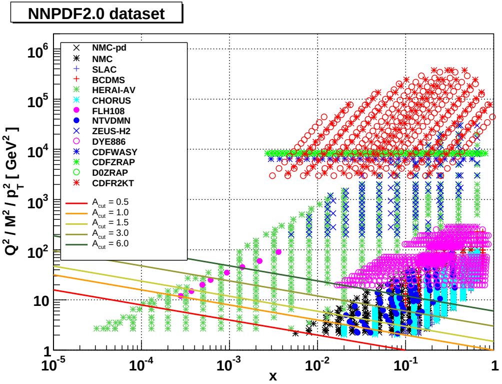


CT10 uses

$$\zeta(0) \equiv \chi \equiv x\left(1 + 4m_c^2/Q^2\right),$$

motivated by momentum conservation

2. A_{cut} fits to combined HERA data



Fitting procedure:

- Include only DIS data above an A_{cut} line
- Compare the resulting PDFs with DIS data below the A_{cut} line, in a region that is "connected" by DGLAP evolution

A_{cut} fits to combined HERA data

Motivation: understand relatively high $\chi^2/Npt \approx 1.18$ in the CT10 fit to the combined HERA-1 data

Increase in χ^2 is distributed uniformly in x and Q^2; also, $\chi^2/Npt \approx 1.14$ in NNPDF2.0

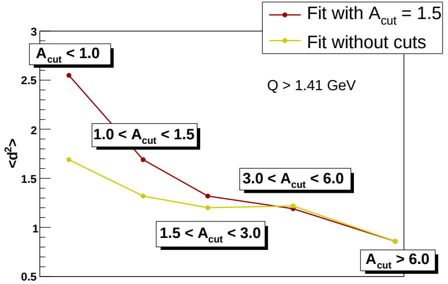
An alternative procedure: examine dependence on a variable $A_{gs} = Q^2 x^{0.3}$ suggested by geometric scaling (*gs*) models

Stasto, Golec-Biernat, Kwiecinski, PRL, 86, 596 (2001); Caola, Forte, PRL, 101, 022001 (2008)

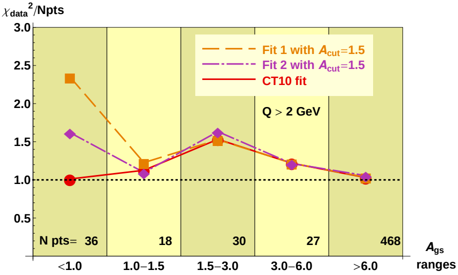
NNPDF PDFs fitted only to the data at $A_{gs} > A_{cut} = 1.5$ show 2σ disagreement with the "DGLAP-connected" data at $A_{gs} = 0.5 - 1.5$ *(Caola, Forte, Rojo, PL B686, 127 (2010); arXiv:1007.5405)*

HERAPDF also observe differences between fits with and without data at lowest Q, but their significance can't be easily compared against NNPDF

CT10: A_{cut} fits to DIS data at $Q > Q_0 = 2$ GeV



Caola, Forte, Rojo, arXiv:1007.5405v2



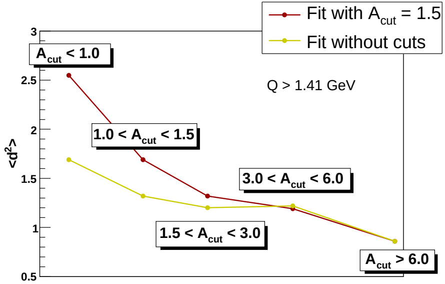
NNPDF2.0

$$d_i^2 = \frac{(\text{Data} - \text{Theory})^2}{\sigma^2_{\text{data}} + \sigma^2_{\text{theory}}}$$

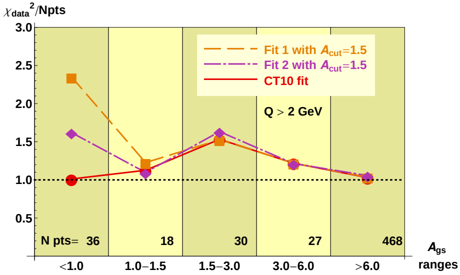
Only statistical uncertainties?

Systematic increase in $\langle d^2 \rangle$ as A_{gs} decreases, even without an A_{gs} cut on the data

CT10: A_{cut} fits to DIS data at $Q > Q_0 = 2$ GeV



Caola, Forte, Rojo, arXiv:1007.5405v2



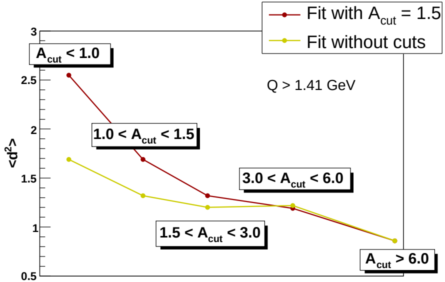
CT10

Two CT10-like fits to data at $A_{gs} > 1.5$, with different parametrizations of $g(x, Q)$

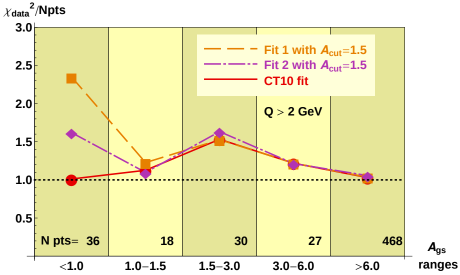
$$\chi_i^2 = \frac{(\text{Shifted Data} - \text{Theory})^2}{\sigma_{uncor}^2}$$

Large syst. shifts at $A_{gs} < 1.0$, in a pattern that could mimic a slower Q^2 evolution

CT10: A_{cut} fits to DIS data at $Q > Q_0 = 2$ GeV



Caola, Forte, Rojo, arXiv:1007.5405v2



CT10, cont.

$\delta\chi^2 \sim 0$ at $A_{gs} > 1.0$
(no difference)

$\delta\chi^2 = 0 - 1.5$ at $A_{gs} < 1.0$,
with large uncertainty

$\Rightarrow$ Disagreement with the "DGLAP-connected" data at $A_{gs} < A_{cut}$ is not supported in the CT10 fit, given the instability of the PDFs from the A_{cut} fits at $A_{gs} < A_{cut}$