CTEQ

CTEQ Parton Distribution Functions and LHC Phenomenology: W/Z, Top and Higgs Physics

C.-P. Yuan
Michigan State University

June 7-15, 2013 @
BCVSPIN / Mitchell ASI 2013

Zhejiang University, Hangzhou

Two parts in this talk

- DIS 2013 talk: CT10 NNLO PDFs

- Some remarks about the precision of global analysis at LO, NLO and NNLO

CTEQ-Tung et al (TEA) Collaboration:

S. Dulat, J. Gao, M. Guzzi, T.J. Hou, J. Huston,
H.-L. Lai, Z. Li, P. Nadolsky, J. Pumplin, D. Stump,
C.-P. Yuan

CT10 NNLO and CT1X[1] NNLO PDFs

Pavel Nadolsky

Southern Methodist University
Dallas, TX, U.S.A.

for CTEQ-TEA group

S. Dulat, J. Gao, M. Guzzi, T.J. Hou, J. Huston, H.-L. Lai, Z. Li, J. Pumplin, C. Schmidt, D. Stump, C.-P. Yuan

April 23, 2013

[1]CT1X=CT12 or CT13

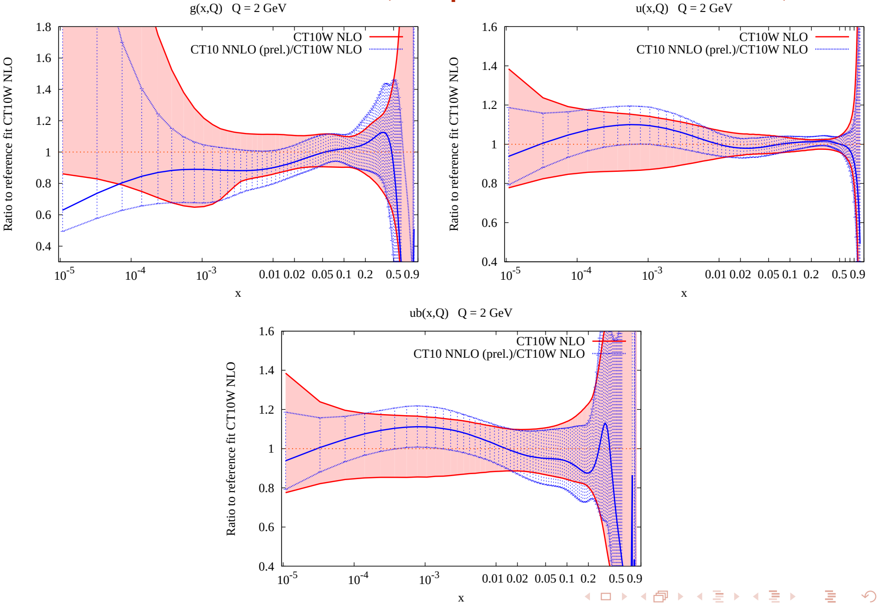
CT10 NNLO and CT1X NNLO PDFs

CT10 NNLO: distributed since 06-2012, officially published in **arXiv:1302.6246**, is an NNLO counterpart to either CT10 NLO or CT10W NLO

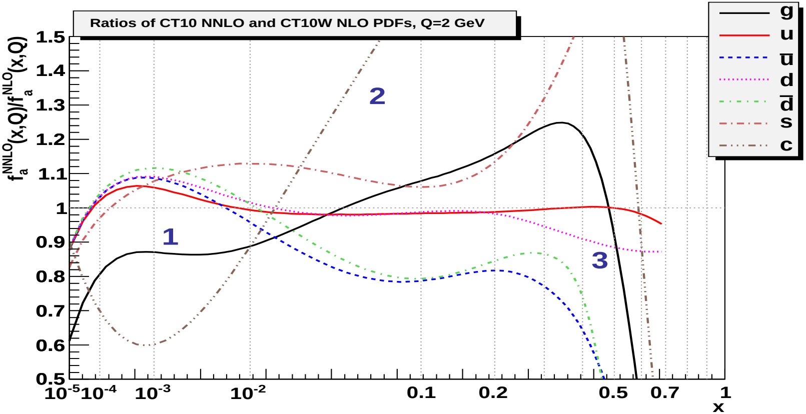
In good agreement with early LHC data

CT1X NNLO: – a preliminary extension of CT10 NNLO that includes latest HERA data on $F_L(x,Q)$ and $F_{2c}(x,Q)$, LHC 7 TeV data (ATLAS W & Z, ATLAS jets, CMS W asymmetry). So far, the new data provide minor improvements compared to the CT10 data set. We investigate its agreement with the CT10 data sets and await for more precise LHC data and new theory calculations to be included in the CT1X public release

CT10 NNLO error PDFs (compared to CT10W NLO)

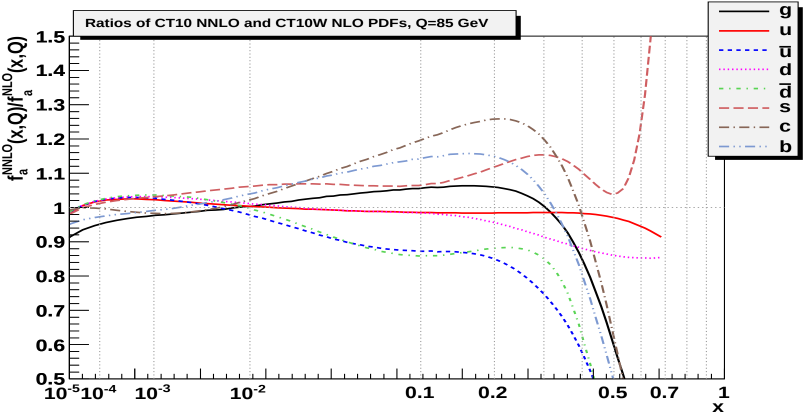


CT10 NNLO central PDFs, as ratios to NLO, Q=2 GeV



1. At $x < 10^{-2}$, $\mathcal{O}(\alpha_s^2)$ evolution suppresses $g(x,Q)$, increases $q(x,Q)$
2. $c(x,Q)$ and $b(x,Q)$ change as a result of the $\mathcal{O}(\alpha_s^2)$ GM VFN scheme
3. At $x > 0.1$, $g(x,Q)$ and $d(x,Q)$ are reduced by revised EW couplings, alternative treatment of correlated systematic errors, scale choices

CT10 NNLO central PDFs, as ratios to NLO, Q=85 GeV



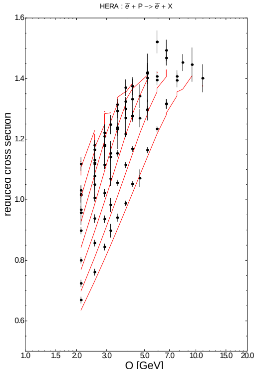
CT10 NNLO: agreement with data

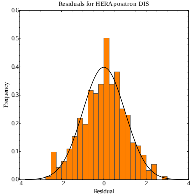
For the final CT10 NNLO, $\chi^2/N_{pt} = 2950/2641 = 1.11$ – slightly better than at NLO

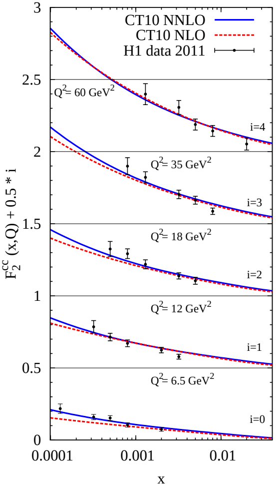
Experimental data set	N_{pt}	CT10NNLO	CT10W
Combined HERA1 NC and CC DIS [60]	579	1.07	1.17
BCDMS F_2^p [61]	339	1.16	1.14
BCDMS F_2^d [62]	251	1.16	1.12
NMC F_2^p [63]	201	1.66	1.71
NMC F_2^d/F_2^p [63]	123	1.23	1.28
CDHSW F_2^p [64]	85	0.83	0.66
CDHSW F_3^p [64]	96	0.81	0.75
CCFR F_2^p [65]	69	0.98	1.02
CCFR xF_3^p [66]	86	0.40	0.59
NuTeV neutrino dimuon SIDIS [67]	38	0.78	0.94
NuTeV antineutrino dimuon SIDIS [67]	33	0.86	0.91
CCFR neutrino dimuon SIDIS [68]	40	1.20	1.25
CCFR antineutrino dimuon SIDIS [68]	38	0.70	0.78
H1 F_2^c [69]	8	1.17	1.26
H1 σ_r^c for $c\bar{c}$ [70, 71]	10	1.63	1.54
ZEUS F_2^c [72]	18	0.74	0.90
ZEUS F_2^c [73]	27	0.62	0.76
E605 Drell-Yan process, $\sigma(pA)$ [74]	119	0.80	0.81
E866 Drell Yan process, $\sigma(pd)/(2\sigma(pp))$ [75]	15	0.65	0.64
E866 Drell-Yan process, $\sigma(pp)$ [76]	184	1.27	1.21
CDF Run-1 W charge asymmetry [77]	11	1.22	1.24
CDF Run-2 W charge asymmetry [78]	11	1.04	1.02
DØ Run-2 $W \to e\nu_e$ charge asymmetry [79]	12	2.17	2.11
DØ Run-2 $W \to \mu\nu_\mu$ charge asymmetry [80]	9	1.65	1.49
DØ Run-2 Z rapidity distribution [81]	28	0.56	0.54
CDF Run-2 Z rapidity distribution [82]	29	1.60	1.44
CDF Run-2 inclusive jet production [83]	72	1.42	1.55
DØ Run-2 inclusive jet production [84]	110	1.04	1.13
Total:	**2641**	**1.11**	**1.13**

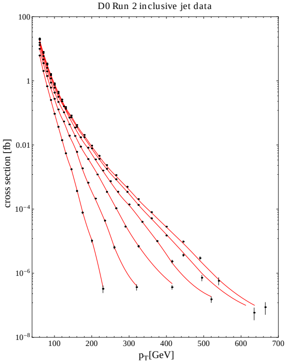
TABLE I: Experimental data sets examined in the CT10NNLO and CT10W NLO analyses, together with their χ^2 values.

CT10 NNLO vs. fitted experiments



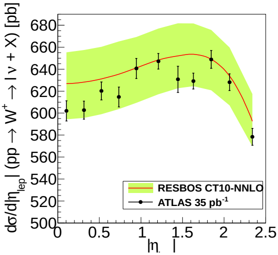


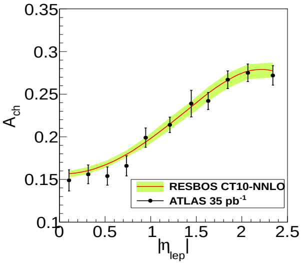


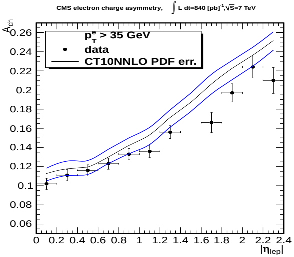


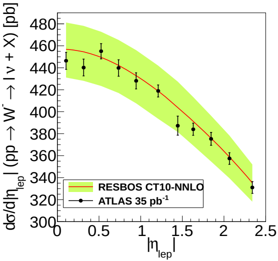
Good general agreement

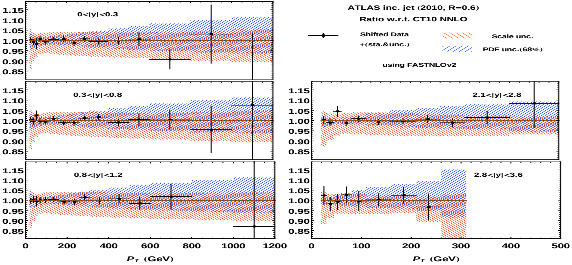
CT10 NNLO describes well LHC 7 TeV experiments











Post-CT10 analysis

Investigate

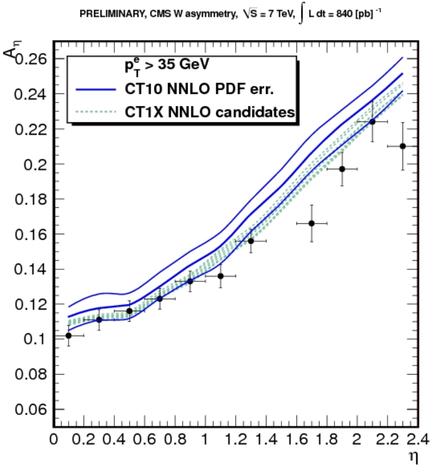
- impact of LHC data on quark flavor decomposition, gluon PDF
- dependence on correlated systematic effects (both of theoretical and experimental origin)
- photon PDFs in the proton
- heavy-flavor mass dependence (talk by M. Guzzi), impact of combined HERA $F_{2c}(x, Q)$ data, update intrinsic charm PDFs

CT10/CT1X NNLO vs. CMS 7 TeV W charge asymmetry (840 pb^{-1})

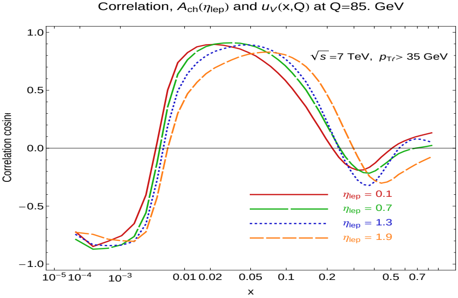
The blue band is the CT10 NNLO PDF uncertainty.

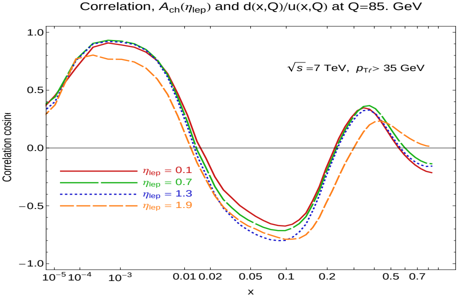
The green curves are from the CT1X fits with varied PDF parametrizations and varied weights for D0 Run-2 W asymmetry, CMS W asymmetry.

A fit including ATLAS, but not CMS, 7 TeV data leads to similar result as CT1X.



CT10: surprising correlation of LHC W asymmetry with valence PDFs





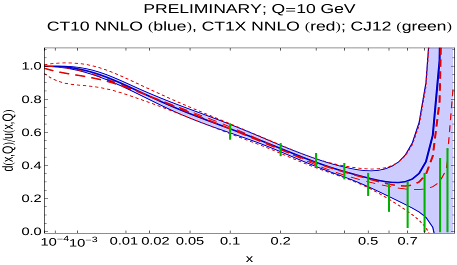
In the CT10 NNLO analysis, the CMS 7 TeV W asymmetry data is strongly correlated with valence PDFs $q_V = q - \bar{q}$ at small x

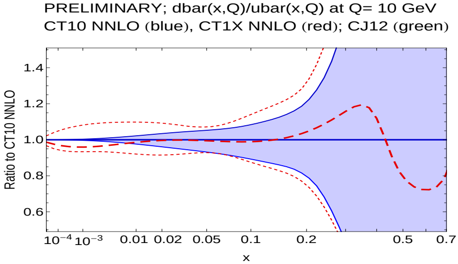
(arXiv:1302.6246),

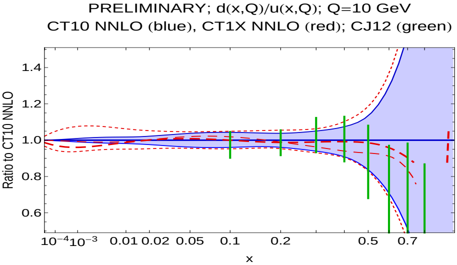
assuming $u_V(x, Q_0),\ d_V(x, Q_0) \propto x^{A_{1v}}$ with the same power A_{1v} at $x \to 0$; and $\bar{u}(x, Q_0),\ \bar{d}(x, Q_0) \propto x^{A_{1\bar{q}}}$ with the same $A_{1\bar{q}}$ at $x \to 0$

In CT1X candidates, we allow for $\{d_V/u_V \neq$ const, $\bar{d}/\bar{u} \neq 1\}$ at $x \to 0$, obtain less correlation with q'_Vs

d/u and $\bar{d}/\bar{u}$: CT1X NNLO (prelim.) vs. CT10 NNLO and CJ 12 analysis of large-x DIS







CT1X PDF uncertainty is larger at $x \to 0$ and 1, is compatible with the d/u band from the CJ12 analysis *(Owens et al., 1212.1702)* of large-x DIS for PDFs+nuclear+higher-twist corrections

Constraining the gluon PDF in the Higgs production region

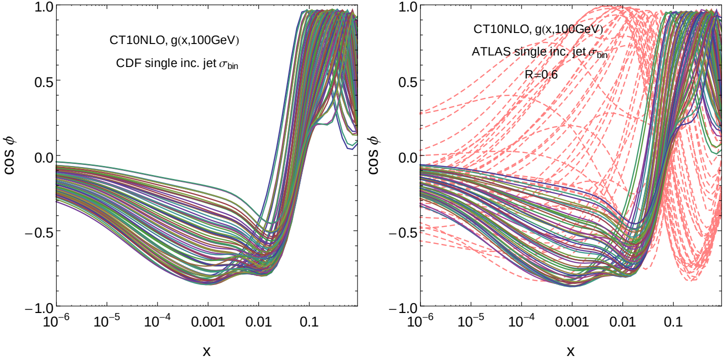
(S. Dulat, J. Gao, T.J. Hou, C. Schmidt, et al.)

The goal: find ways to reduce PDF uncertainty on $g(x, Q)$ at $x \sim 0.01$ relevant for Higgs production

- Determine experiments sensitive to $g(x, Q)$ at small x, besides the HERA DIS data
  - LHC jet production, to some extent $t\bar{t}$ production
- Obtain reliable (N)NLO predictions for these processes; benchmarking of MEKS, ApplGrid, FastNLO codes for NLO inclusive jet production
- Understand theoretical and experimental systematic errors on $g(x, Q)$

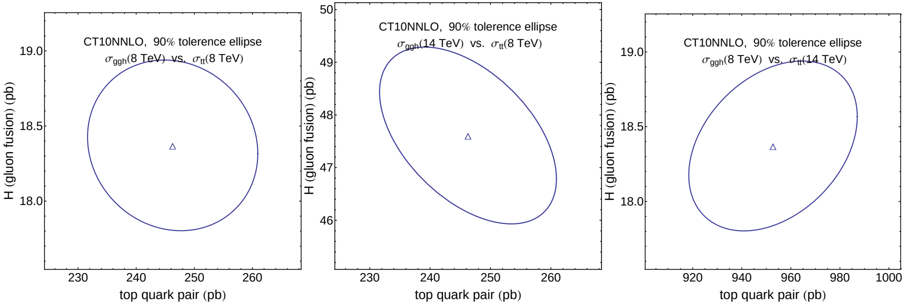
Correlations of $g(x, Q)$, Higgs, inclusive jet, and $t\bar{t}$ cross sections

PDF correlation analysis *(J. Gao, prelim.)*: LHC inclusive jet production directly probes $g(x, Q)$ at $x < 0.05$ (red lines), in contrast to the Tevatron that constrains this range by momentum sum rule



Correlations of $g(x,Q)$, Higgs, inclusive jet, and $t\bar{t}$ cross sections

$\sigma(t\bar{t})$ and $\sigma(ggH)$ at the LHC are not correlated at the same $\sqrt{s}$, mildly (anti-)correlated at different $\sqrt{s}$



MEKS: an advanced NLO calculation for inclusive jet cross sections

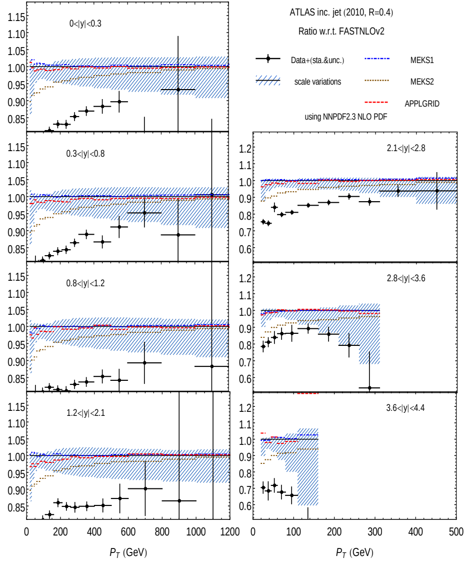
J. Gao, Z. Liang, D. E. Soper, H.-L. Lai, P.N., and C.-P. Yuan, arXiv:1207.0513

Global PDF fits use different programs to compute NLO jet cross sections: **EKS** (CT10 NLO), **FastNLO** (CT10 NNLO and MSTW'08), **APPLgrid** (NNPDF2.3).

- Non-negligible differences between these codes were identified in 2011.
- We developed a modernized EKS program (MEKS) that provides an alternative to the NLOJET++ program in precision calculations for the Tevatron/LHC.
  - The old EKS required tuning for each jet observable, was not parallelizable and difficult to use
- By comparing MEKS and FastNLO, we brought them into agreement to a percent-level accuracy

Benchmark comparison of NLO programs for inclusive jet production

J. Gao, Z. Liang, D. Soper, H.-L. Lai, P.N., C.-P. Yuan, 1207.0513 ; R. Ball et al., 1211.5142

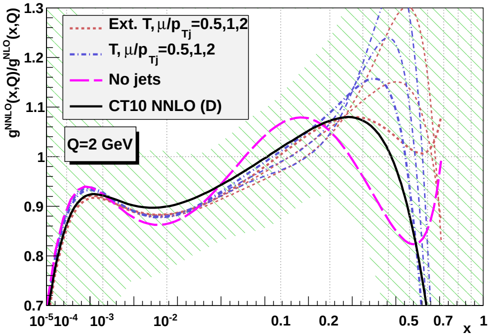


- "QCD scale: p_T of jet"
- FASTNLOv1: average p_T of each bin
- FASTNLOv2: individual jet p_T
- APPLGRID: hardest jet p_T in each rapidity bin
- MEKS1: individual jet p_T
- MEKS2: hardest jet p_T

Experim. syst. errors are not included

Systematic effects in NNLO fits and the gluon PDF

$g(x, Q)$ at $x > 0.1$ is sensitive to systematic effects from...



- **theory:** QCD scale dependence of NLO inclusive jet cross sections
- **experiment:** interpretation of correlated systematic errors for inclusive jet production

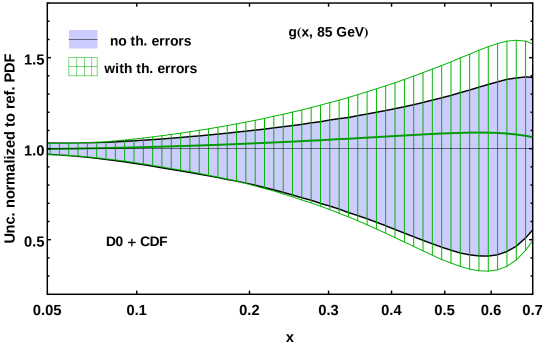
Both types of effects were explored. The CT10 NNLO gluon error sets are constructed so as to span the full range of uncertainty due to experimental errors, corr. syst. errors, and various scale choices

CT1X: scale uncertainty of NLO jet cross sections

J. Gao, P.N., in progress

In the CTEQ6X analyses, Tevatron Run-1 jet cross sections used $\mu_R = \mu_F = p_T^{jet}/2$ that minimized $\sigma_{NLO}(p_T^{jet}, \eta^{jet})/\sigma_{LO}(p_T^{jet}, \eta^{jet}) - 1$ at $|\eta^{jet}| \lesssim 1$. This is not possible for all p_T^{jet} and η^{jet} covered by Tevatron Run-2 and LHC incl. jet production.

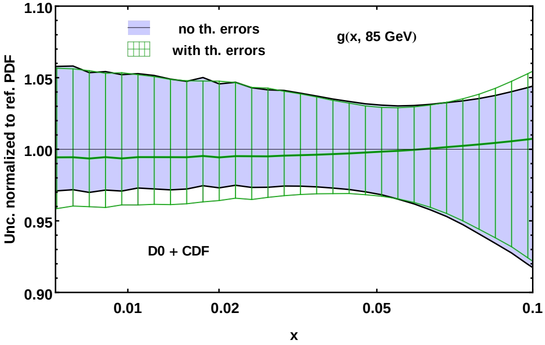
Some CT1X fits include the scale uncertainty of jet cross sections into the PDF uncertainty by a method similar to Cacciari and Houdeau's



Gluon PDF uncertainties at 90% C.L. for the fits with and without theoretical errors. The net gluon PDF uncertainty is increased at $x > 0.1$ by about 20%

PRELIMINARY

CT1X: scale uncertainty of NLO jet cross sections



The gluon PDFs in the moderate x region is also affected by the scale dependence as a result of the momentum sum rule

PRELIMINARY

Definitions of the covariance matrix

arXiv:1302.6246, appendix in R. Ball et al., arXiv:1211.5142

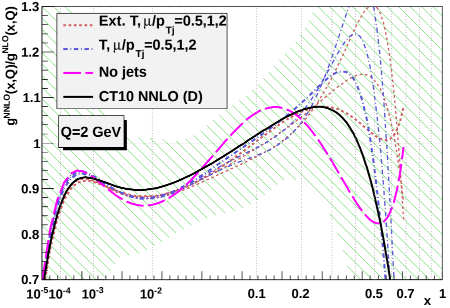
$$\chi^2 = \sum_{\{\text{exp.}\}} \left[\sum_{k=1}^{N_{pts}} \frac{1}{s_k^2} \left(D_k - T_k(\{a\}) - \sum_{\alpha=1}^{N_\lambda} \lambda_\alpha \beta_{k\alpha} \right)^2 + \sum_{\alpha=1}^{K_e} \lambda_\alpha^2 \right]$$

The experimental correlated systematic errors $\beta_{k\alpha}$ are often published as percentages. It can be taken to be a percentage of the theoretical prediction T_k ("truth") or the experimental datum D_k.

1. **Experimental (D) prescription:** normalize all $\beta_{k\alpha}$ to D_k
2. T **(T_0) prescription:** normalize luminosity & other multiplicative errors to (fixed) T_k, additive errors to D_k
3. **Extended** T **(T_0) prescription:** normalize all errors to (fixed) T_k

The methods are numerically equivalent if T_k is close to D_k. Additive (multiplicative) errors are to be normalized to T_k (D_k) to avoid/reduce biases. The available experimental data usually do not specify if the errors are additive or multiplicative.

Impact on the gluon PDF



The central CT10 NNLO uses the D method, $\mu = p_T$ for Tevatron jets, which softens large-p_T jet cross sections and may compensate for the missing NNLO correction.

Extended T method is used for other experiments (which have the NNLO correction).

CT10 NLO cross sections use the ext. T method throughout.

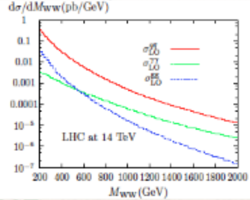
The NNLO error band encloses parametrizations obtained with the extended T method for all expts., other QCD scales for jets, and no jets in the fit. No d'Agostini's bias was detected for fixed $\alpha_s(M_Z)$. (Some downward bias may exist with method D and free $\alpha_s(M_Z)$).

Photon PDFs: Carl Schmidt

PRELIMINARY

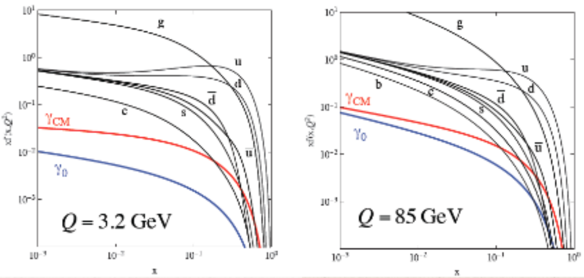
2) Photon induced processes can be kinematically enhanced.

$\gamma\gamma \rightarrow W^+W^-$ asymptotically $\hat{\sigma}_{\gamma\gamma} \approx 8\pi\alpha^2/M_W^2$



significant fraction of high mass WW pairs from γγ, even after kinematic cuts

Bierweiler et al., JHEP 1211 (2012) 093



photon PDFs can be larger than anti-quarks at high x

the LHC (and higher energy machines) is a γγ factory

Snowmass+Les Houches project: investigate this

CT10IC (intrinsic charm at NNLO)

S. Dulat, T.J. Hou, J. Pumplin, C.-P. Yuan,...

This is an update of CTEQ6.6 IC PDFs *(arXiv:0802.0007)*, but with the CT10 NNLO setup.

We consider two intrinsic charm models:

- BHPS1 and BHPS5: enhanced IC at $x > 0.1$ *(S. J. Brodsky, P. Hoyer, C. Peterson, and N. Sakai, Phys. Lett. B93, 451 (1980).)*
- SEA2 and SEA4: sea-like IC contributing at all x

In the CT10IC fits, we replaced the HERA charm data sets by the combined F_{2c} data.

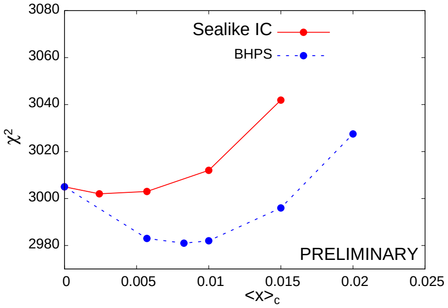
CT10IC at NNLO

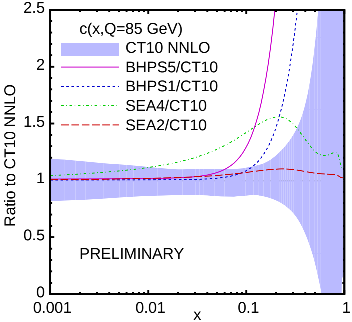
The goodness of fit χ^2 versus the momentum fraction of intrinsic charm,

$$\langle x \rangle_c = \int_0^1 dx\,(c(x, m_c) + \bar{c}(x, m_c))$$

	BHPS	SEA
$\langle x \rangle_c$	0.57%, 2%	0.57%, 1.5%

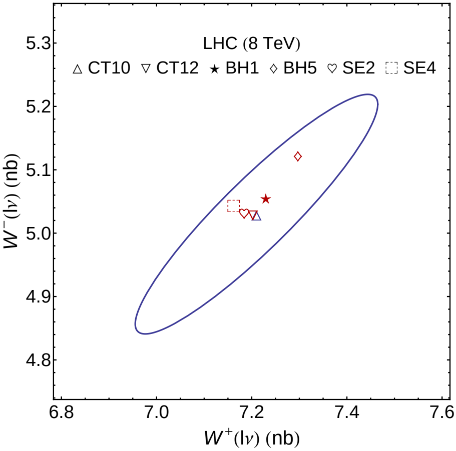
The charm PDFs in the 4 CT10IC fits, as compared to the CT10NNLO error band.

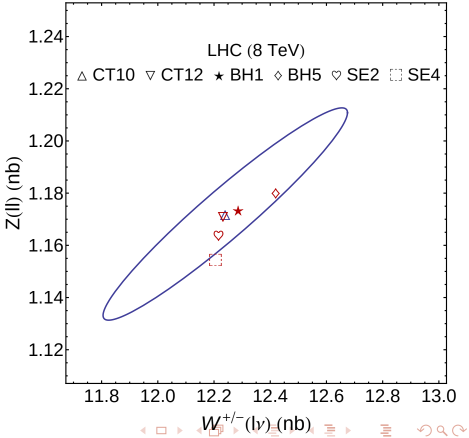




Changes in LHC total cross sections due to Intrinsic Charm

The 4 new points, the star, diamond, heart, and empty square, for results from BHPS1, BHPS5, SEA2 and SEA4, respectively. The ellipses are for CT10NNLO.





Conclusions and prospects

– The full set of CT10 NNLO PDFs (pre-LHC data only; main and α_s series) is released in arXiv:1302.6246. It shows good agreement with LHC data.

– The CT1X (N)NLO analysis (in progress) will include the latest LHC data on W, Z, and jet production; have more flexible (anti-)quark PDFs, larger uncertainties on d/u, $\bar{d}/\bar{u}$; be compatible with CJ12 constraints on d/u at $x > 0.1$.

– Benchmarking of NLO codes (MEKS, NLOJET++/ApplGrid/FastNLO) for inclusive jet production is completed. MEKS is independent from NLOJET++ and available from HepForge.

– Preliminary results on detailed constraints on the gluon PDF in Higgs production region, photon PDFs, and CT10 NNLO PDFs with intrinsic charm

Backup slides

CT10 PDF sets: the naming conventions

- **Two NLO PDF sets**, without/with Tevatron Run-2 data on W charge asymmetry A_ℓ c

  CT10 NLO does not include
  CT10W NLO includes
  4 $p_{T\ell}$ bins of D0 Run-2 A_ℓ data

$\Rightarrow$ CT10 and CT10W sets differ mainly in the behavior of $d(x,Q)/u(x,Q)$ at $x > 0.1$

- **One NNLO PDF set:** only 2 inclusive $p_{T\ell}$ bins of D0 Run-2 A_ℓ data are included that have smallest theory uncertainties

- **The NNLO set is a counterpart of both CT10 NLO and CT10W NLO. It uses only a part of the A_ℓ data sample that distinguishes between CT10 NLO and CT10W NLO.**

Compare the quality of global fits at LO,NLO and NNLO

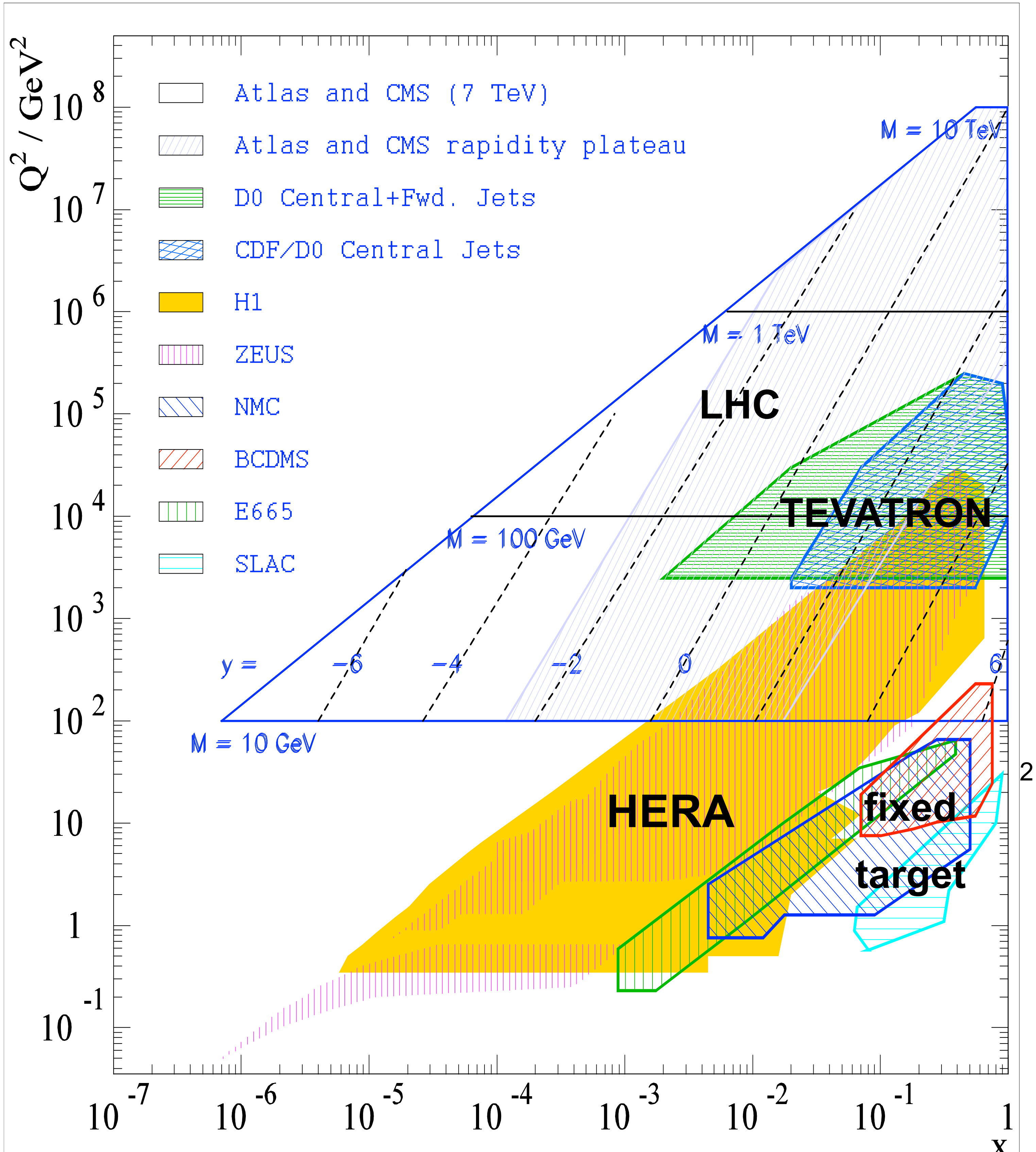
- Chi-square per data point is about

1.1 at NNLO and NLO,

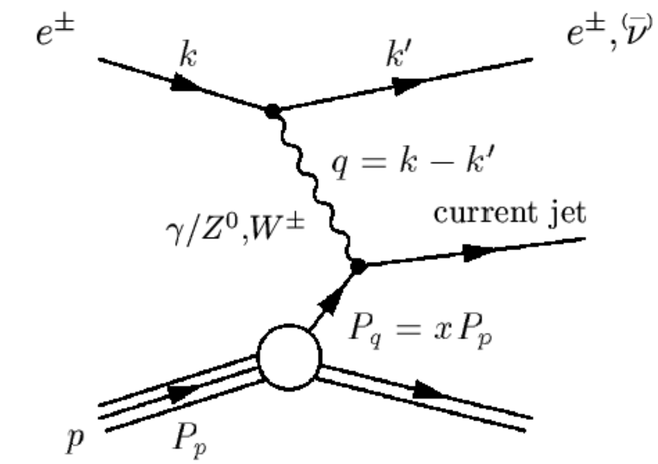
while it is about 1.5 at LO.

- The overall data points included in the global analysis is at the order of 3000, including DIS, Drell-Yan (W/Z) and jet data.

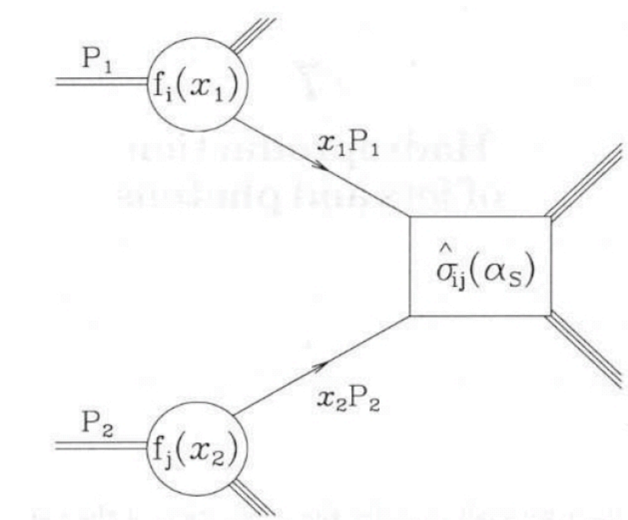
Experimental access to the proton structure



HERA: low and medium x



LHC: important constraints on g(x), flavour separation



Fixed Target: high x, nuclear PDFs

ID	Experimental data set	N_{pt}	CT10 NNLO	CT10 NLO	CT10 LO
159	Combined HERA1 DIS [?]	579	1.07	1.05	1.54
101	BCDMS F_2^p [?]	339	1.16	1.13	1.24
102	BCDMS F_2^d [?]	251	1.16	1.04	1.13
103	NMC F_2^p [?]	201	1.66	1.71	2.19
104	NMC F_2^d/F_2^p [?]	123	1.23	1.01	0.95
108	CDHSW F_2^p [?]	85	0.83	0.73	0.94
109	CDHSW F_3^p [?]	96	0.81	0.70	0.87
110	CCFR F_2^p [?]	69	0.98	1.04	2.29
111	CCFR xF_3^p [?]	86	0.40	0.37	0.66
124	NuTeV ν di-μ SIDIS [?]	38	0.78	0.91	0.72
125	NuTeV $\overline{\nu}$ di-μ SIDIS [?]	33	0.86	0.83	1.47
126	CCFR ν di-μ SIDIS [?]	40	1.20	1.27	0.73
127	CCFR $overline\nu$ di-μ SIDIS [?]	38	0.70	0.79	0.63
140	H1 F_2^c [?]	8	1.17	1.30	3.60
143	H1 $\tilde{\sigma}^{c\overline{c}}$ [?]	10	1.63	1.55	3.19
145	H1 $\tilde{\sigma}^{bb}$ [?]	10		0.78	
156	ZEUS F_2^c [?]	18	0.74	0.95	3.34
157	ZEUS F_2^c [?]	27	0.62	0.81	2.78
201	E605 DY process $\sigma(pA)$ [?]	119	0.80	0.79	0.78
203	E866 DY process $\sigma(pd)/(2\sigma(pp))$ [?]	15	0.65	0.45	0.55
204	E866 DY process $\sigma(pp)$ [?]	184	1.27	1.292	1.38
225	CDF Run-1 W charge asymmetry [?]	11	1.22	0.78	1.57
227	CDF Run-2 W charge asymmetry [?]	11	1.04	1.33	0.99
231	Run-2 W charge asymmetry [?]	12	2.17		1.91
234	Run-2 W charge asymmetry [?]	9	1.65		1.22
260	Run-2 Z rapidity dist. [?]	28	0.56	0.57	1.83
261	CDF Run-2 Z rapidity dist. [?]	29	1.60	1.76	4.47
504	CDF Run-2 inclusive jet [?]	72	1.42	1.56	1.85
514	Run-2 inclusive jet [?]	110	1.04	1.14	1.63
505	CDF Run-2 inclusive jet [?]	33		1.64	
515	Run-2 inclusive jet [?]	90		0.76	
	Totals N_{pt}:		2641	2753	2641
	Totals χ^2 :		3026	2954	3870

Momentum fraction of partons inside proton

@ 1.3 GeV
in CT10 PDF analyses

	NNLO	NLO	LO
d_v	0.139	0.131	0.118
u_v	0.322	0.318	0.292
gluon	0.377	0.391	0.429
$2\bar{u}$	0.062	0.063	0.070
$2\bar{d}$	0.062	0.063	0.070
$s+\bar{s}$	0.038	0.035	0.022
$c+\bar{c}$	0.000	0.000	0.000

PDF evolution at LO, NLO and NNLO

- PDF evolves differently at LO, NLO and NNLO
- CT10NNLO PDFs at various Q values
- CT10NNLO PDF error bands

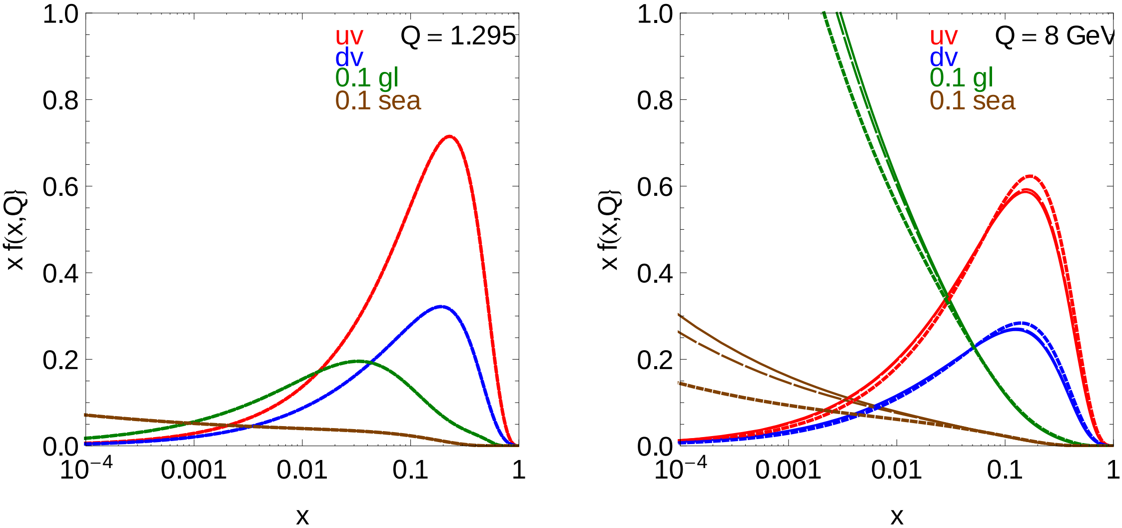


Figure 1: Comparison of NNLO, NLO, and LO evolution of parton distribution functions, $f(x, Q)$. The left graph shows the initial values for a set of PDFs; these are the CT10-NNLO PDFs at the input Q scale, $Q = 1.3\,\mathrm{GeV}$. The right graph shows the evolved PDFs for $Q = 8\,\mathrm{GeV}$, for three approximations of the evolution equations: solid curves = NNLO; dashed curves = NLO; dotted curves = LO.

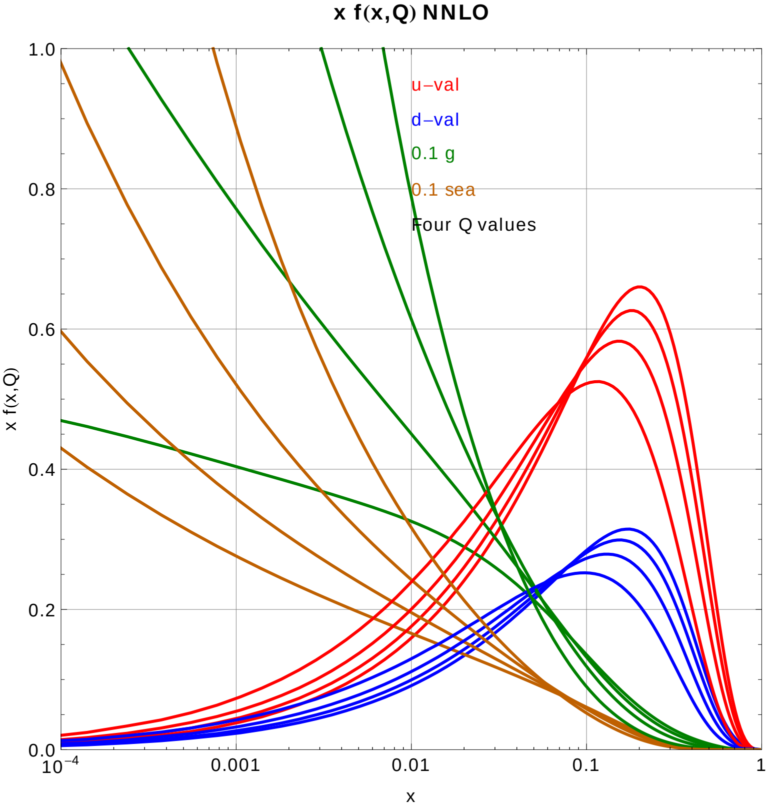


Figure 2: CT10-NNLO parton distribution functions. This figure shows the *central fit* for the CT10-NNLO analysis. The graph shows $x\,u_{\text{valence}} = x(u - \overline{u}), x\,d_{\text{valence}} = x(d - \overline{d}), 0.10\,x\,g$ and $0.10\,x\,\overline{q}$sea as functions of x for 4 values of Q. The values of Q are $2, 3.16, 8, 85$ GeV. Sea $= 2(\overline{d} + \overline{u} + \overline{s})$.

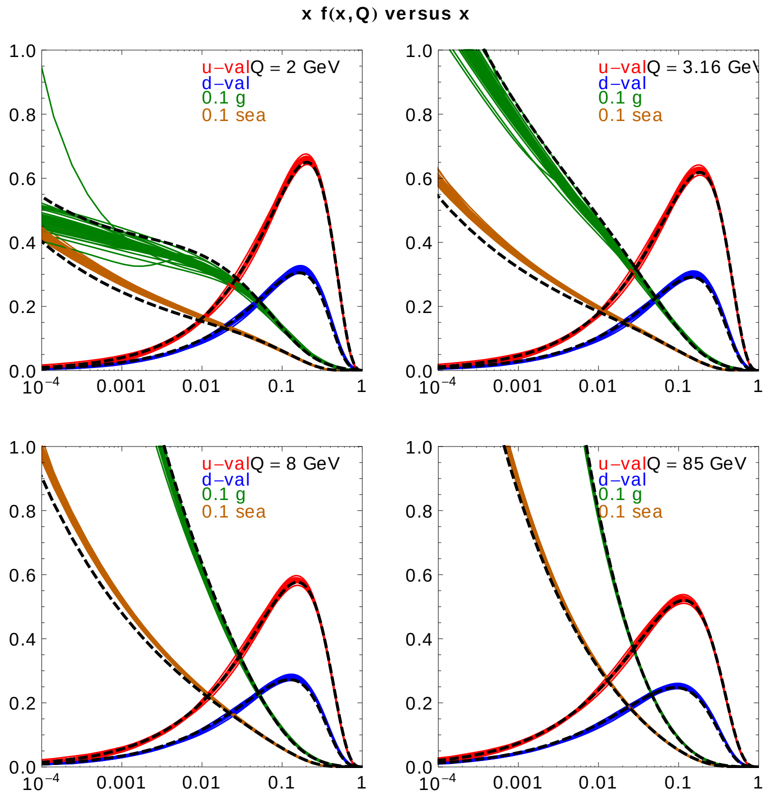
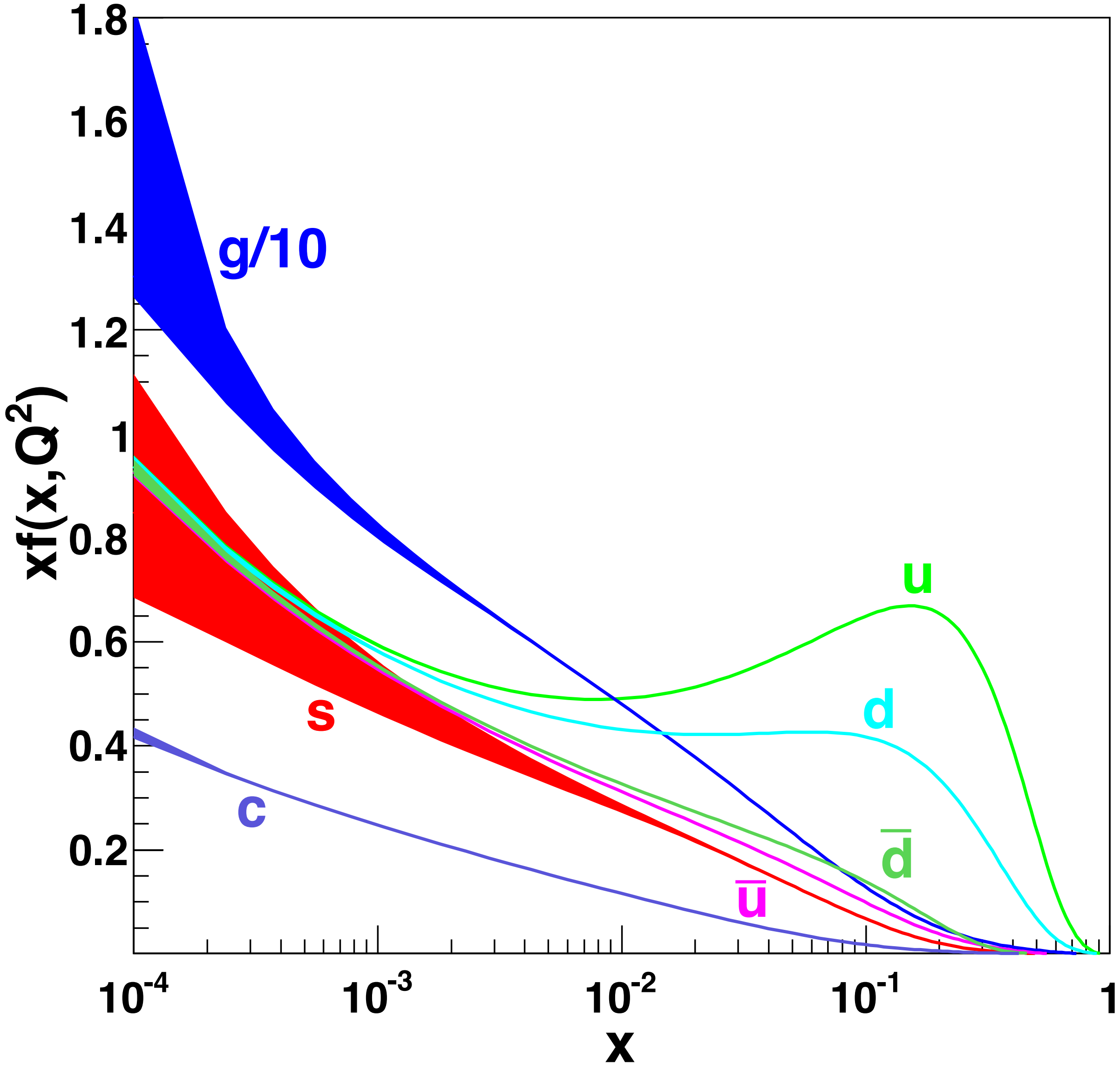


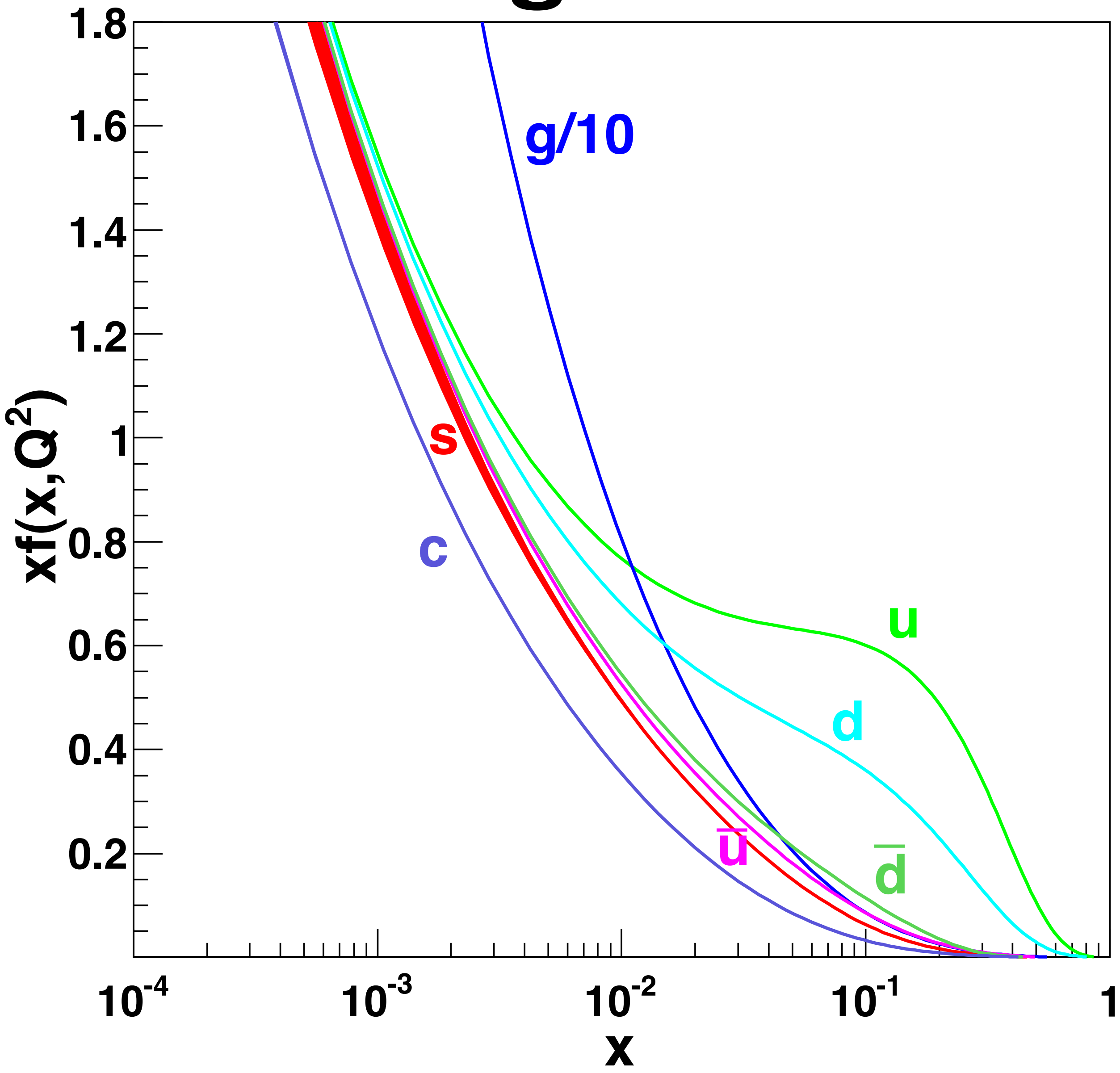
Figure 3: CT10-NNLO parton distribution functions. These figures show the *alternate fits* for the CT10-NNLO analysis. Each graph shows $x\,u_{\text{valence}} = x(u - \overline{u}), x\,d_{\text{valence}} = x(d - \overline{d}), 0.10\,x\,g$ and $0.10\,x\,\overline{q}$sea as functions of x for a fixed value of Q. The values of Q are $2, 3.16, 8, 85$ GeV. Sea $= 2(\overline{d} + \overline{u} + \overline{s})$. The dashed curves are the central NLO fit, CT10.

CT10 PDF plots

Low Scale



High Scale



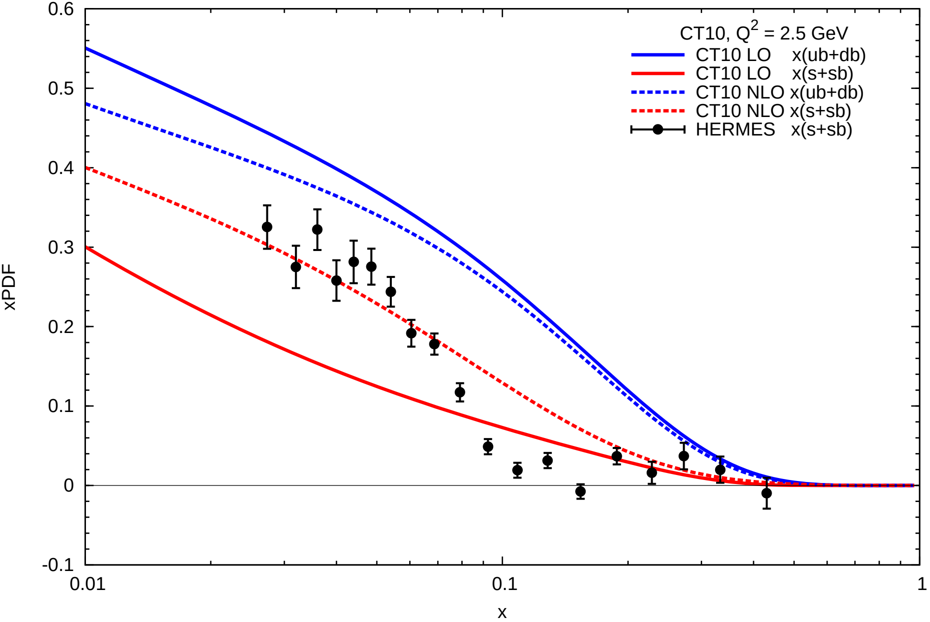
Interpretation of experimental data at LO, NLO and NNLO

- Factorization Theorem

⇒ Data depends on PDFs and Wilson coefficients

- Higher order calculation (including both PDFs and Wilson coefficients) yields better description of experimental data.

FIG. 3


CT10, Q2 = 2.5 GeV
CT10 LO x(ub+db)
CT10 LO x(s+sb)
CT10 NLO x(ub+db)
CT10 NLO x(s+sb)
HERMES x(s+sb)
xPDF
x
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0.01
0.1
1

No experimental evidence for asymmetric strangeness

- CTEQ 6.6 study concluded that there is no experimental evidence for asymmetric strangeness inside proton.

- NNPDF concluded a large uncertainty in the asymmetric strangeness, centering around zero. ⇨

No apparent anomaly in NuTeV data.

Strangeness asymmetry and NuTeV anomaly
M. Ubiali, NNPDF

Preliminary results from NNPDF:

Flexible parametrization for
$s_-(x) = (s(x) - \bar{s}(x))/2$

$$\int_0^1 x\, s_-(x)\, dx \approx 0 \pm \delta_{PDF},$$

where δ_{PDF} is **large** compared to CTEQ/MSTW

■ sufficient to **eliminate** NuTeV $\sin\theta_W$ anomaly

Strange valence ↓