CT NNLO PDFs, PDF benchmarking, understanding the gluon PDF

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November 14, 2012

1. CT NNLO error PDFs

Two sets of CT NNLO error PDFs

1. CT10 NNLO eigenvector set

Available at http://hep.pa.msu.edu/cteq/public/ct10_2012.html and in LHAPDF 5.8.6; arXiv:1206.3321, long paper on the way

Complements the CT10/CT10W NLO PDF sets *(Lai et al., PRD82, 074024 (2010))*

- Based on the NNLO implementation of NC DIS with massive quarks published in *Guzzi et al., arXiv:1108.5112*
- **Includes only "pre-LHC" CT10 data.** Can be used to predict LHC cross sections based on pre-LHC experimental inputs
- Same input parameters, functional forms for input PDFs as in the CT10 NLO PDFs
  - $\alpha_s(M_Z) = 0.118 \pm 0.002$, $m_c^{pole} = 1.3$ GeV, $m_b^{pole} = 4.75$ GeV
  - Simpler assumptions about the PDF flavor composition at $\mu_0 = m_c^{pole} = 1.3$ GeV, *e.g.*, $\bar{u}(x)/\bar{d}(x) \to 1$ as $x \to 0$
- Updated $N_f = 3$ and 4 NLO sets.

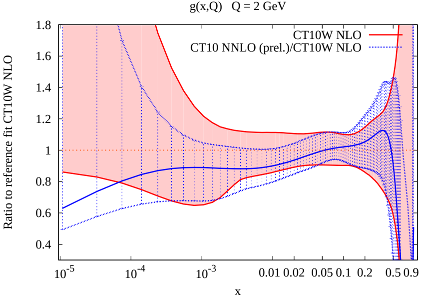
Two sets of CT NNLO error PDFs

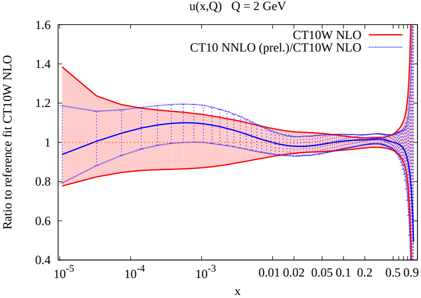
2. CT12 NLO and NNLO eigenvector sets

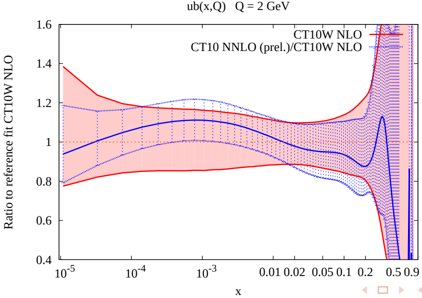
Is under development

- Include LHC W and Z rapidity data, ATLAS and CMS jet data, HERA'2011 F_L data
- Updated α_s, m_c, m_b values
- Flexible $\bar{d}/\bar{u}$ ratio at $x \to 1$, updated $(s+\bar{s})/(\bar{u}+\bar{d})$ at $x \lesssim 10^{-2}$
  - Constrained by the LHC W/Z rapidity distributions

CT10 NNLO error PDFs (compared to CT10W NLO)







CT10 PDF sets: the naming conventions

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

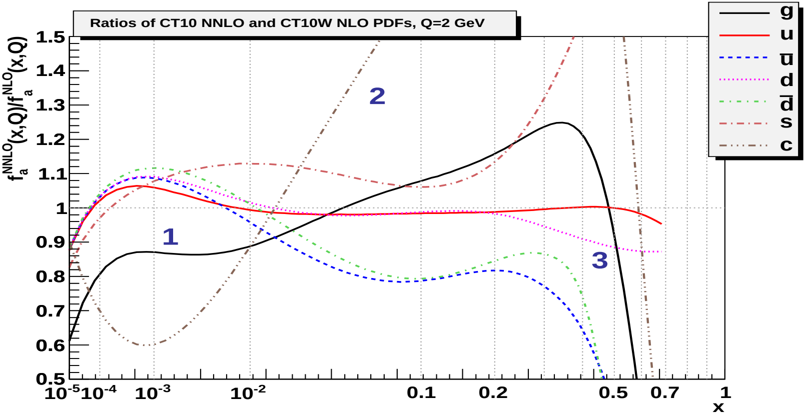
CT10 NLO does not include
CT10W NLO includes
4 $p_{T\ell}$ bins of D0 Run-2 A_ℓ data

$\Rightarrow$ 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

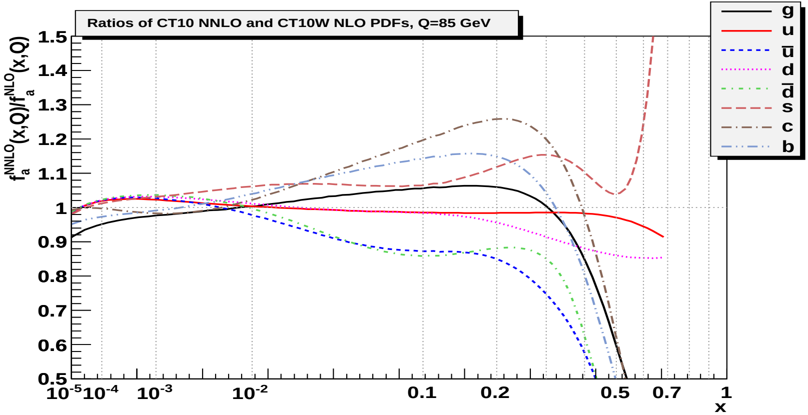
- **The NNLO set is a counterpart of both CT10 NLO and CT10W NLO. It uses only a part of the A_ℓ data sample that distinguishes between CT10 NLO and CT10W NLO.**

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



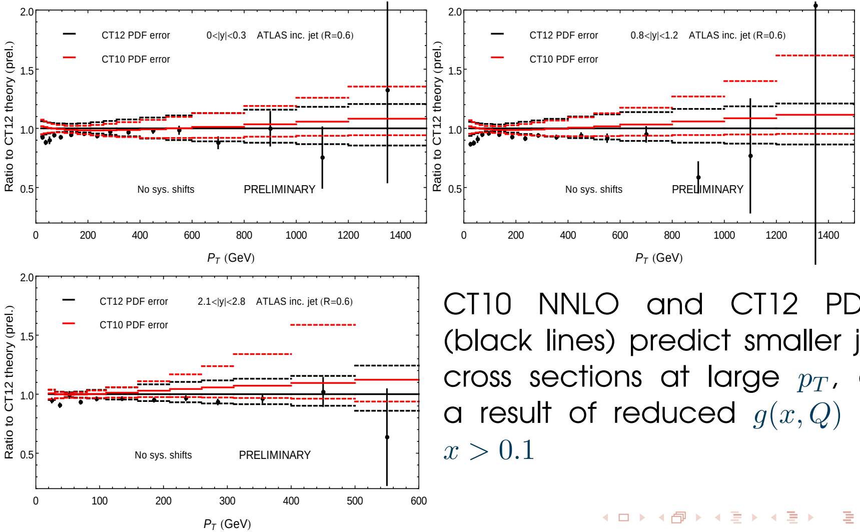
1. At $x < 10^{-2}$, $\mathcal{O}(\alpha_s^2)$ evolution suppresses $g(x,Q)$, increases $q(x,Q)$
2. $c(x,Q)$ and $b(x,Q)$ change as a result of the $\mathcal{O}(\alpha_s^2)$ GM VFN scheme
3. At $x > 0.1$, $g(x,Q)$ and $d(x,Q)$ are reduced by revised EW couplings, alternative treatment of correlated systematic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

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



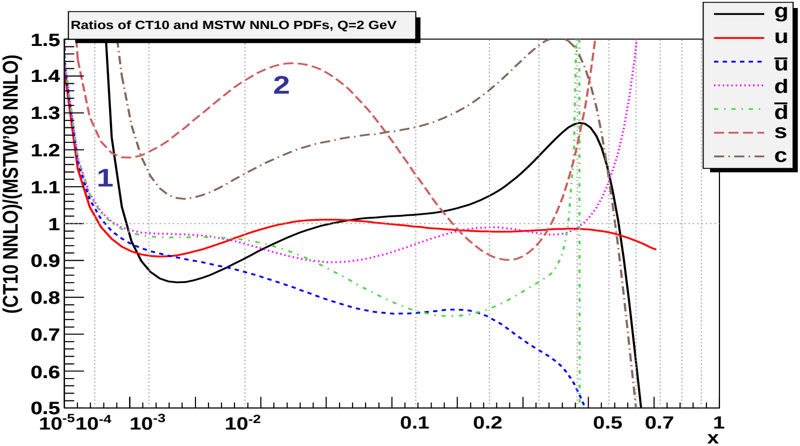
CT12 NLO predictions for LHC jet production

ATLAS single-inclusive jet production *(arXiv:1112.6297)*; FastNLO 2; R=0.6;
$\chi^2/N_{d.o.f} = 0.72\,(0.98)$ for CT12 NLO (CT10 NLO)



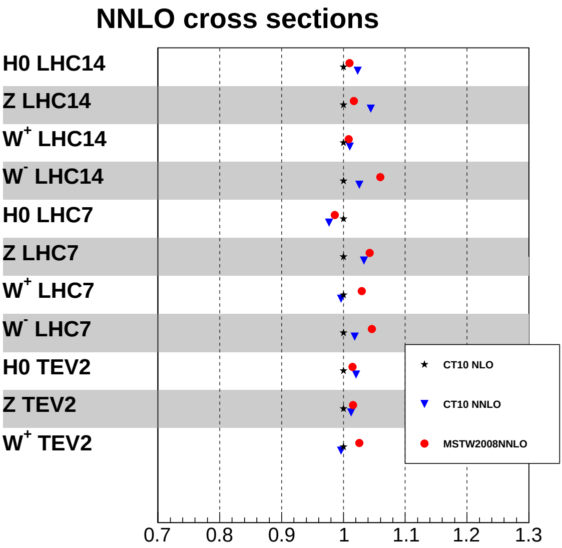
CT10 NNLO and CT12 PDFs (black lines) predict smaller jet cross sections at large p_T, as a result of reduced $g(x,Q)$ at $x > 0.1$

CT10 NNLO PDFs compared to MSTW NNLO



1. CT10 gluon and quarks are harder than MSTW at $x \to 0$; $g(x, Q_0) > 0$ at $10^{-5} \leq x \leq 1$
2. The CT10 strange PDF is larger at $x \sim 10^{-3}$

Predictions for production of electroweak bosons



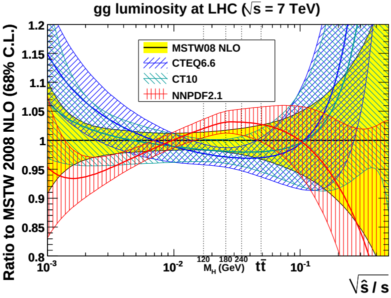
2. 2012 benchmark comparisons of NNLO PDFs

J. Rojo, S. Carrazza, J. Gao, R. Ball, L. Del Debbio, S. Forte, N. Hartland, J. Huston, P. Nadolsky, D. Stump, R. Thorne, C.-P. Yuan

arXiv:1211.xxxx – submitted today

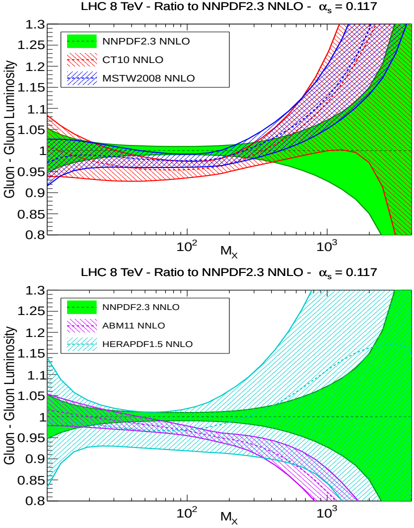
PDF benchmarks: gg luminosities

2010 NLO

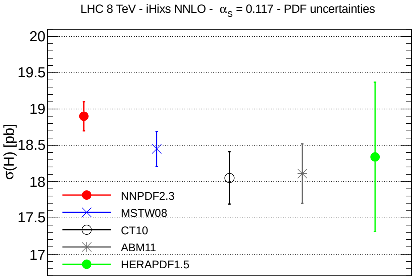


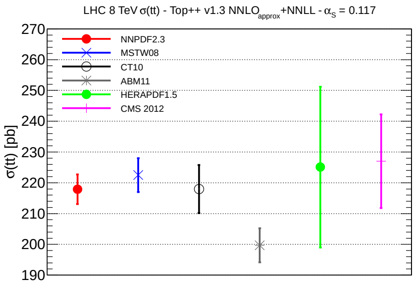
Thorne, Watt, arXiv:1106.5789 (hep-ph)

2012 NNLO



PDF benchmarks: SM Higgs and $t\bar{t}$ cross sections

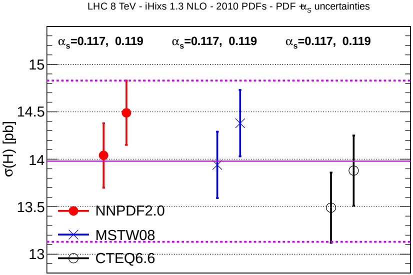




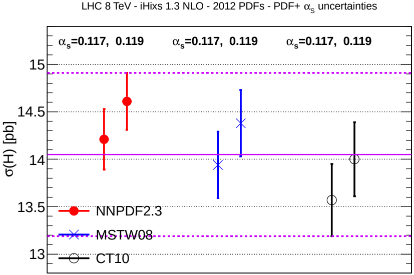
J. Rojo et al., arXiv:1211.xxxx – submitted today

PDF benchmarks, PDF+α_s uncertainty

2010 NLO



2012 NLO



$\sigma_H^{NLO}(2010) =$
13.98 ± 0.85 pb (6.1%)

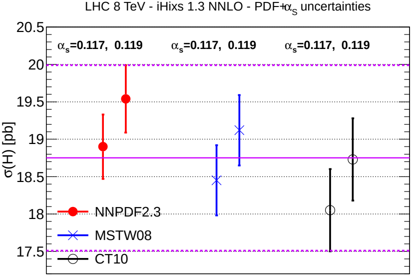
$\sigma_H^{NLO}(2012) =$
14.05 ± 0.86 pb (6.1%)

The PDF+α_s errors are computed by the “envelope” method

No significant change in NLO cross sections

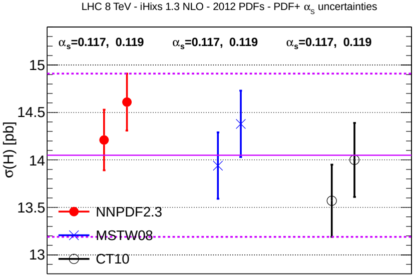
PDF benchmarks, PDF+α_s uncertainty

2012 NNLO



$\sigma_H^{NLO}(2010) =$
$18.75 \pm 1.24 \text{ pb } (6.6\%)$

2012 NLO



$\sigma_H^{NLO}(2012) =$
$14.05 \pm 0.86 \text{ pb } (6.1\%)$

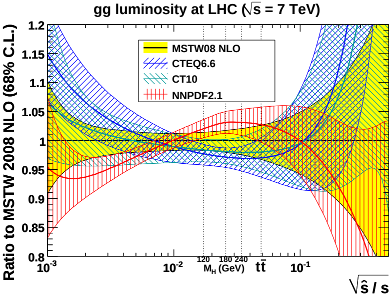
The PDF+α_s errors are computed by the "envelope" method **both** for NLO and NNLO

The NLO and NNLO **relative** PDF errors are about the same

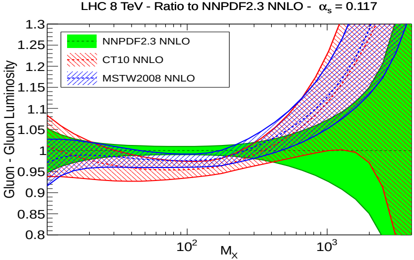
3. The puzzle of the gluon PDF

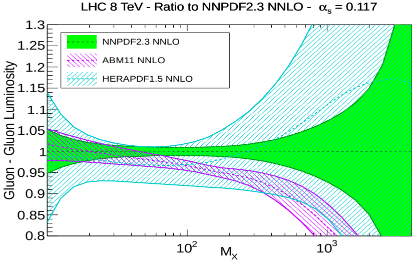
What drives remaining differences in gluon PDFs/luminosities?

2010 NLO



2012 NNLO





(N)NNLO corrections are not the main source of uncertainty in the PDFs. Other sources were identified or eliminated in the past year

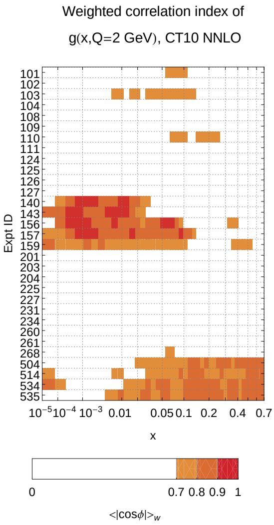
Differences between gluon PDFs from various groups

Origins of some differences are well-known; other differences (in bold) are still under investigation

Source	Example
Selection of fitted data	Are the Tevatron Run-1 jet data included in the fit?
Heavy-quark schemes	Fixed-flavor number (ABM); General-mass VFN (all other groups)
(NLO) EW contributions in DIS	
(In)compatible NLO programs for jet production	**EKS (CT10 NLO); NLOJet++ and interfaces (other groups)**
Scale choices	**Which QCD scales are used in incl. jet production?**
Treatment of correlated systematic effects	**How are correlated errors included in χ^2?**

Correlation index $\langle|\cos\varphi|\rangle_W$ measures sensitivity of experiments to $g(x,Q)$

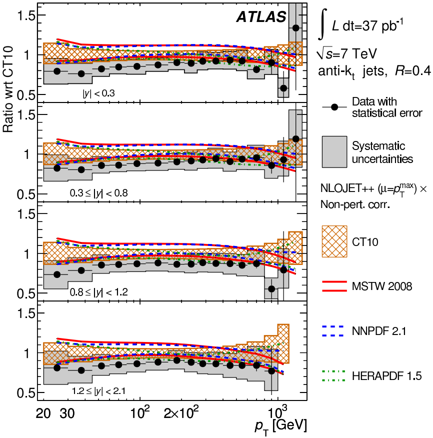
101	**BCDMS** F_2^p
102	BCDMS F_2^d
103	**NMC** F_2^p
104	NMC F_2^d/F_2^p
108	CDHSW F_2^p
109	CDHSW F_3^p
110	**CCFR** F_2^p
111	CCFR xF_3^p
124	NuTeV neutrino dimuon SIDIS
125	NuTeV antineutrino dimuon SIDIS
126	CCFR neutrino dimuon SIDIS
127	CCFR antineutrino dimuon SIDIS
140	**H1** F_2^c
143	**H1** σ_r^c **for** $c\bar{c}$
156	**ZEUS** $F_2^c(67)$
157	**ZEUS** $F_2^c(80)$
159	**Combined HERA1 NC and CC DIS**
201	E605 Drell-Yan process, $\sigma(pA)$
203	E866 Drell-Yan process, $\sigma(pd)/(2\sigma(pp))$
204	E866 Drell-Yan process, $\sigma(pp)$
225	CDF Run-1 W charge asymmetry
227	CDF Run-2 W charge asymmetry
231-234	D0 Run-2 W charge asymmetry
260	D0 Run-2 Z rapidity distribution
261	CDF Run-2 Z rapidity distribution
268	ATLAS combined W Z data
504	**CDF Run-2 inclusive jet production**
514	**D0 Run-2 inclusive jet production**
534	**ATLAS inclusive jet (R=0.4)**
535	**ATLAS inclusive jet (R=0.6)**



J. Gao, in preparation

A dark color indicates sensitivity to $g(x,Q)$ at x values on the horizontal axis

Measured single-inclusive jet and dijet cross sections are unfolded and corrected to be compared to PQCD theory directly at the parton level.



NLO theoretical predictions: EKS

(PRL69, 1496), NLOJET++ *(PRL88, 122003)*, FASTNLO *(hep-ph/0609285)*, APPLgrid *(EPJC66, 503)*, POWHEG *(JHEP04081)*, Z.Bern et. al. *(1112.3940)*;...

Resummed results: N. Kidonakis

(PRD63, 054019), POWHEG

NNLO predictions are anticipated soon and will make the difference

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).

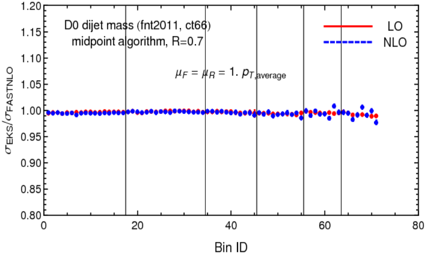
- Non-negligible differences between these codes were identified in the past year.
- We developed a modernized EKS program (MEKS) that provides an alternative to the NLOJET++ program in precision calculations for the Tevatron/LHC.
  - The old EKS required tuning for each jet observable, was not parallelizable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

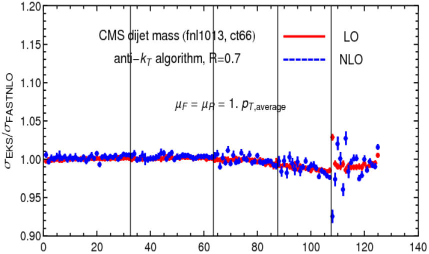
Main features of MEKS

- Can be downloaded from HEPFORGE
- **Double differential output** for single-inclusive jet and dijet production at NLO.
- Fortran 77; linked to CUBA (Monte-Carlo integration) and LHAPDF (PDF parametrizations)
- **Monte-Carlo integration is optimized for steeply falling jet cross sections**
- **Parallelization:** Events from independent parallel computations can be easily combined during offline analysis.
- A Monte-Carlo integration error of $\sim 1\%$ in each typical experimental bin is achieved within about 1 day on 10 CPU's at NLO.

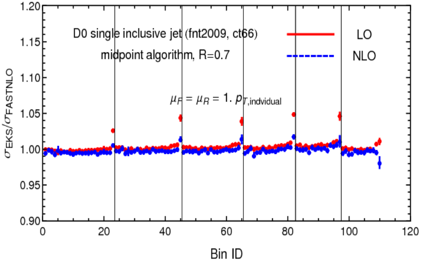
Comparison of MEKS and FastNLO 1.0

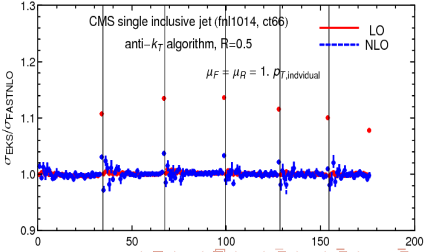
Dijet production: excellent agreement at both the Tevatron and LHC



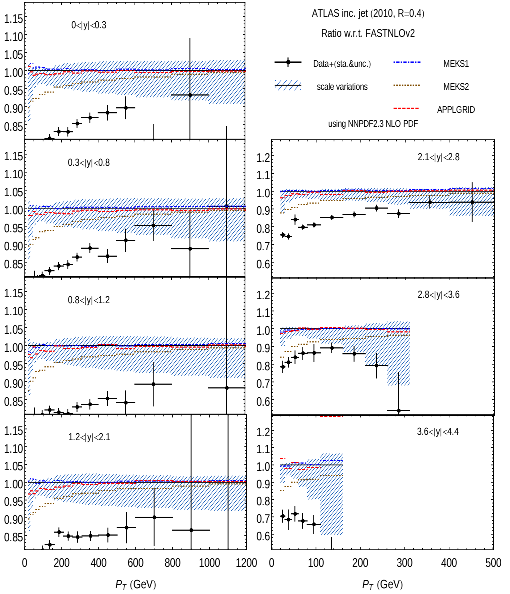


Single-inclusive jet production: discrepancies of 3-10% exist at large p_T, possibly due to different definitions of the "jet p_T" used as the QCD scale.





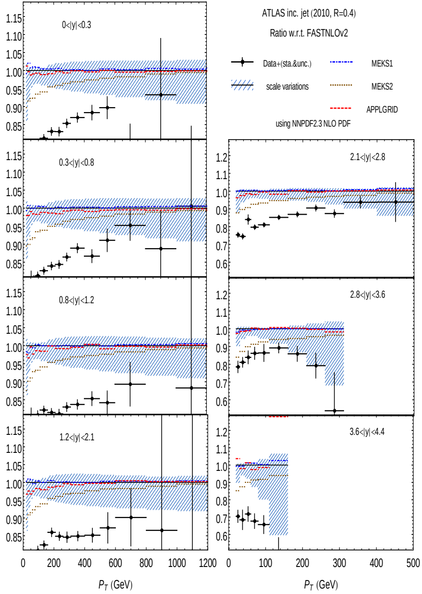
Benchmark comparison of NLO programs

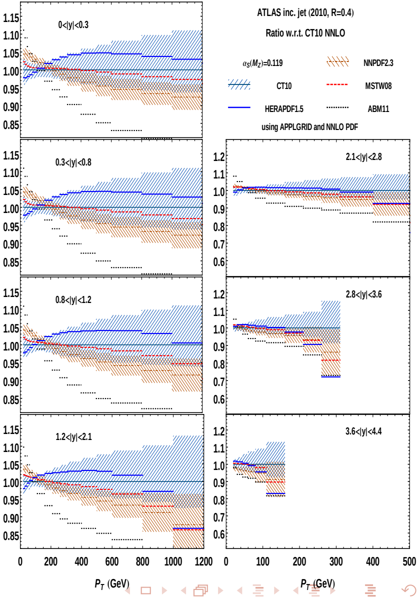


- "QCD scale: p_T of jet"
- FASTNLOv1: average p_T of each bin
- FASTNLOv2: individual jet p_T
- APPLGRID: hardest jet p_T in each rapidity bin
- MEKS1: individual jet p_T
- MEKS2: hardest jet p_T

Experim. syst. errors are not included

Scale variations (left) vs. PDF uncertainty (right)



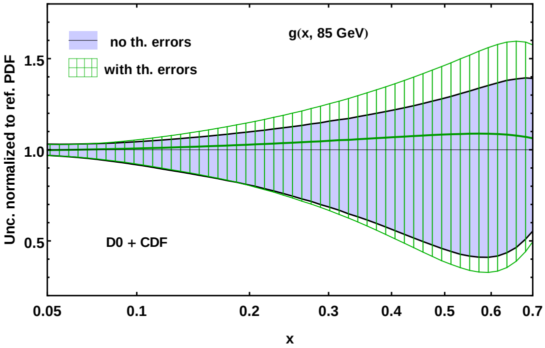


Observations from benchmark comparisons of NLO jet cross sections

- The NLO scale uncertainty of jet cross sections is appreciable. No optimal scale exists that would assuredly suppress NNLO corrections at all p_T and y.
- It is possible to estimate the impact of this NLO uncertainty on the current "NNLO fits" (cf. the next slide).
- The benchmarking of NLO codes prepares the stage for the NNLO calculation for jet production that is very desirable.

Effects of scale uncertainties on the CT12 PDF set

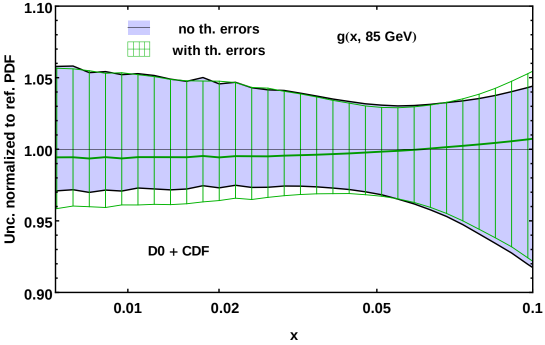
We included scale uncertainty of jet cross sections into the PDF uncertainty of a candidate CT12 set. The scale uncertainty is included with the same method as the experimental correlated uncertainty.



Gluon PDF uncertainties at 90% C.L. for the fits with and without theoretical errors. Scale dependence of jet cross sections increases the net gluon PDF uncertainty at $x > 0.1$ by about 20%

PRELIMINARY

Effects of scale uncertainties on the CT12 PDF set



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

PRELIMINARY

A basic estimate of missing higher-order corrections

See also Olness, Soper, arXiv:0907.5052; Cacciari, Houdeau, arXiv:1105.5152

For arbitrary $\mu_{R,F}$, the NLO cross sections in the experimental bins i can be written as

$$\sigma_{bin}^{NLO}(\mu_F,\,\mu_R,\,i) = \sigma_{bin}^{NLO}(\mu_F^{(0)},\,\mu_R^{(0)},\,i)\Big\{1 + \sum_{j=1}^{5} e_j(\mu_F^{(0)},\mu_R^{(0)},i)x_j + \mathcal{O}(\alpha_s^3(\mu_R^{(0)}))\Big\}$$

with

$$x_1 = \ln(\frac{\mu_F}{\mu_F^{(0)}}), \qquad x_2 = \ln(\frac{\mu_R}{\mu_R^{(0)}}), \qquad x_3 = \ln^2(\frac{\mu_F}{\mu_F^{(0)}}),$$
$$x_4 = \ln^2(\frac{\mu_R}{\mu_R^{(0)}}), \qquad x_5 = \ln(\frac{\mu_F}{\mu_F^{(0)}})\ln(\frac{\mu_R}{\mu_R^{(0)}}),$$

where $\mu_F^{(0)}$ and $\mu_R^{(0)}$ are the reference scales.

A basic estimate of missing higher-order corrections

See also Olness, Soper, arXiv:0907.5052; Cacciari, Houdeau, arXiv:1105.5152

For arbitrary $\mu_{R,F}$, the NLO cross sections in the experimental bins i can be written as

$$\sigma_{bin}^{NLO}(\mu_F,\,\mu_R,\,i) = \sigma_{bin}^{NLO}(\mu_F^{(0)},\,\mu_R^{(0)},\,i)\Big\{1+\sum_{j=1}^{5} e_j(\mu_F^{(0)},\mu_R^{(0)},i)x_j + \mathcal{O}(\alpha_s^3(\mu_R^{(0)}))\Big\}$$

Treat x_i as independent corr. sources with quasi-Gaussian distributions (plausible, but not necessarily true). Assign your favorite confidence level (68% c.l.) to the range $1/2 < \mu_{F,R}/\mu_{F,R}^{(0)} < 2$. Evaluate the variation of $\sigma_{bin}^{NLO}(\mu_F,\,\mu_R,\,i)$ in this scale range. Find $e_j(i)$ numerically and use them to construct the correlation matrix. Reduce the number of principal components to eliminate x_i combinations that have vanishing effect on theory cross sections.

Conclusions and prospects

– The CT10 NNLO PDF analysis (using pre-LHC data only) is released. It is based on a new NNLO implementation (S-ACOT-χ) of heavy-quark DIS contributions *(Guzzi et al., arXiv:1108.5112)*.

– The CT12 (N)NLO analysis (in progress) will include latest LHC data on W, Z, and jet production. Possible impact on $SU(3)$ properties of quark sea at $x < 10^{-3}$.

– The 2012 benchmarking study will update the recommendation for computing the NNLO PDF+α_s uncertainty for LHC measurements

– A code MEKS for full NLO inclusive (di)jet production was developed. MEKS is independent from NLOJET++, it is fast, and parallelizable. Its comparison against APPLgrid/FastNLO reveals significant impact of scale dependence in NLO jet cross sections on the NNLO PDFs.

– Near-future publications will discuss other issues affecting the gluon and other PDFs, such as the treatment of correlated syst. errors in jet production.

Backup slides

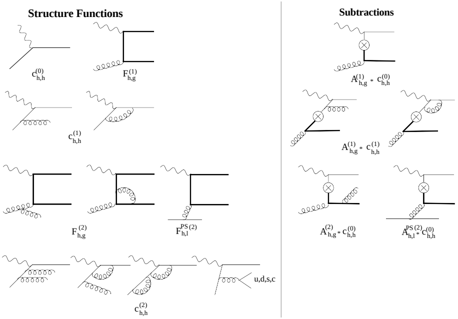
Neutral-current DIS in a general-mass scheme at NNLO

M. Guzzi, P.N., H.-L. Lai, C.-P. Yuan, arXiv:1108.5112 (hep-ph)

Objectives

- The CT10 fit computes c, b quark contributions to NC DIS in the S-ACOT-χ general-mass factorization scheme *(Aivasis, Collins, Olness, Tung, 1994; Collins, 1998; Kramer, Olness, Soper; Tung, Kretzer, Schmidt)*

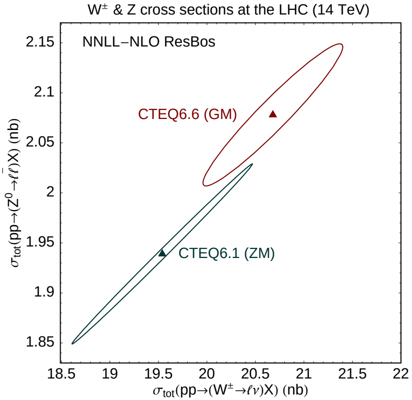
- We have realized this scheme at NNLO. We have also demonstrated how to derive this scheme (including kinematic rescaling of heavy-quark scattering terms at the mass threshold) from the QCD factorization theorem by Collins



NNLO scattering contributions

Massive quark contributions to neutral-current DIS...

...affect predictions for the LHC W and Z cross sections *(Tung et al., hep-ph/0611254)*



arXiv:0802.0007

Extensive recent work

Tung et al., hep-ph/0611254; Thorne, hep-ph/0601245; Tung, Thorne, arXiv:0809.0714; P.N., Tung, arXiv:0903.2667; Forte et al., arXiv:1001.2312; J. Rojo et al., arXiv:1003.1241;Alekhin, Moch, arXiv:1011.5790;...

Several heavy-quark factorization schemes

FFN, ACOT, BMSN, CSN, FONLL, TR'...

The NNLO realization of the S-ACOT-χ factorization scheme combines benefits of several approaches

Main features of the S-ACOT-χ scheme

- It is proved to all orders by the QCD factorization theorem for DIS *(Collins, 1998)*
- **Universal** PDFs
- It is relatively simple
  - One value of N_f (and one PDF set) in each Q range
  - sets $m_h = 0$ in ME with incoming $h = c$ or b
  - matching to FFN is **implemented at the level of the QCD factorization theorem**
- It reduces to the ZM $\overline{MS}$ scheme at $Q^2 \gg m_Q^2$, without additional renormalization
- It reduces to the FFN scheme at $Q^2 \approx m_Q^2$
  - has reduced dependence on tunable parameters at NNLO

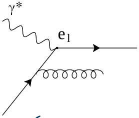
Components of inclusive $F_{2,L}(x,Q)$

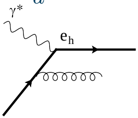
S-ACOT-χ NNLO expressions are reminiscent of the ZM scheme (e.g., in Moch, Vermaseren, Vogt, 2005), with all components available from literature

Components of inclusive $F_{2,L}(x,Q^2)$ are classified according to the quark couplings to the photon

$$F=\sum_{l=1}^{N_l} F_l + F_h \qquad (1)$$

$$F_l = e_l^2 \sum_a \left[C_{l,a}\otimes f_{a/p}\right](x,Q), \quad F_h = e_h^2 \sum_a \left[C_{h,a}\otimes f_{a/p}\right](x,Q). \qquad (2)$$



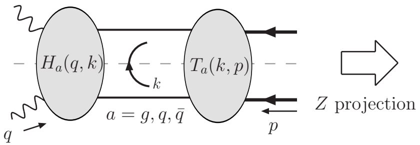


At $\mathcal{O}(\alpha_s^2)$:

$$F_h^{(2)} = e_h^2\left\{c_{h,h}^{NS,(2)}\otimes\left(f_{h/p}+f_{\bar h/p}\right) + C_{h,l}^{(2)}\otimes\Sigma + C_{h,g}^{(2)}\otimes f_{g/p}\right\}$$

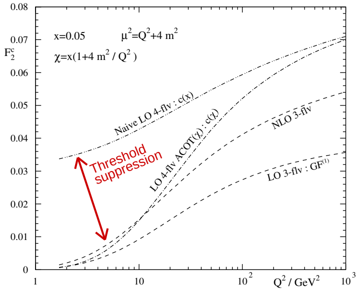
$$F_l^{(2)} = e_l^2\left\{C_{l,l}^{NS,(2)}\otimes\left(f_{l/p}+f_{\bar l/p}\right) + c^{PS,(2)}\otimes\Sigma + c_{l,g}^{(2)}\otimes f_{g/p}\right\}. \qquad (3)$$

Rescaling to all orders of α_s and the factorization theorem



We show that a minor modification of the QCD factorization theorem *(Collins, 1998)...*

- enables suppression of charm production at $Q^2 \to m^2_{c,b}$ in all channels and at each α_s order without extra smoothness conditions or damping factors
- preserves universality of heavy-quark PDFs



4. Computation of correlated systematic errors

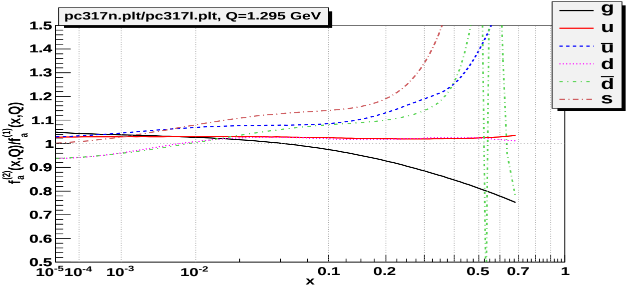
$$\chi^2 = \sum_{\{\text{exp.}\}} \left[\sum_{k=1}^{N_{pts}} \frac{1}{s_k^2} \left(D_k - T_k(\{a\}) - \sum_{\alpha=1}^{N_\lambda} \lambda_\alpha \beta_{k\alpha} \right)^2 + \sum_{\alpha=1}^{K_e} \lambda_\alpha^2 \right]$$

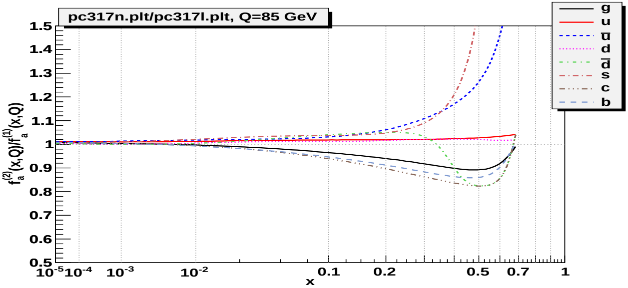
The experimental correlated systematic errors $\beta_{k\alpha}$ are often published as percentages. It can be taken to be a percentage of the theoretical prediction T_k ("truth") or the experimental datum D_k.

1. **Percentage of T_k:** results in smooth $\beta_{k\alpha}$:-); may depend on the theoretical model :-(
2. **Percentage of D_k:** $\beta_{k\alpha}$ is deduced from the measured data :-), but may not be smooth due to statistical fluctuations :-(

The methods are equivalent if T_k is close to D_k. In the actual CTXX fits to the Tevatron Run-2 jet data, **method 1** (used in pre-2012 CTEQ fits) results in a harder gluon at $x > 0.1$ than **in method 2**. We use **method 2** in the latest NNLO fits.

4.2. Impact on the best fit NLO PDFs



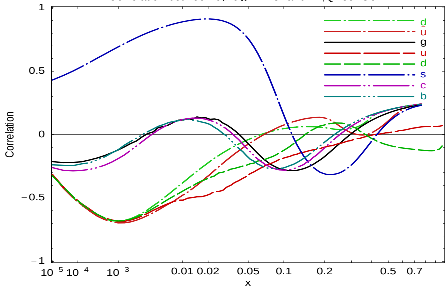


pc317l: CT12 NLO candidate obtained with method 1

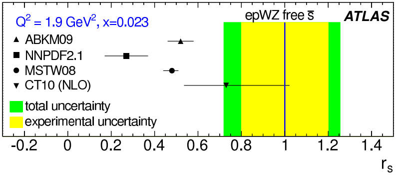
pc317n: CT12 NLO candidate obtained with method 2

Notice changes in $u(x,Q)$, $d(x,Q)$, $g(x,Q)$

Strangeness in CT12 PDFs and LHC W/Z cross sections



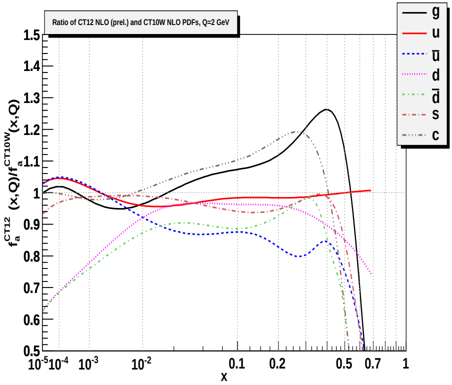
In 2008, our CTEQ6.6 PDF correlation analysis pointed out the sensitivity of ratios σ_W/σ_Z at the LHC to the strangeness PDF, with implications to EW precision measurements *(P.N., Lai, Cao, Huston, Pumplin, Tung, Yuan, PRD, 78 (2008) 013004)*.

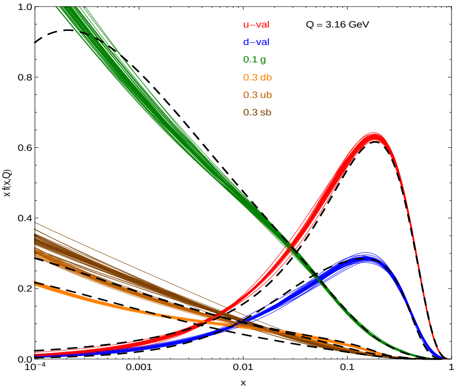


The ATLAS analysis (arXiv:1203.4051) of W and Z production suggests that $\bar{s}(x,Q)/\bar{d}(x,Q) = 1.00^{+0.25}_{-0.28}$ at $x = 0.023$ and $Q^2 = 1.9$ GeV^2

What is the impact of the new LHC W and Z data on the CT12 PDFs that will include them?

Small-x limits of $\bar{d}(x,Q)/\bar{u}(x,Q)$ and $\bar{s}(x,Q)/\bar{u}(x,Q)$ in the CT12 analysis (PRELIMINARY)





The CT12 analysis explores the possibility of $\lim_{x\to 0} \bar{d}/\bar{u} \neq 1$. Some "unbiased" CT12 candidate fits have $\bar{s}(x,Q)/\bar{u}(x,Q) > 1$ at $x < 10^{-3}$.

We would like to better understand the flavor decomposition at small x before releasing the CT12 PDFs.