CT10 NNLO and CT12 NNLO parton distribution functions

Pavel Nadolsky

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

in collaboration with
M. Guzzi, J. Gao, J. Huston, H.-L. Lai, Z. Li,
Z. Liang, J. Pumplin, D. Soper, D. Stump, C.-P. Yuan (CTEQ)

March 27, 2012

Two sets of CT NNLO error PDFs
1. CT10W NNLO eigenvector set

To be sent to LHAPDF this week

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

- Includes only "pre-LHC" CT10 data, can be used to predict LHC cross sections based on pre-LHC experimental inputs
- Same input parameters and parametrization forms as in CT10 NLO PDFs
  - $\alpha_s(M_Z) = 0.118 \pm 0.002$, $m_c^{pole} = 1.3$ GeV, $m_b^{pole} = 4.75$ GeV
  - $\bar{u}(x)/\bar{d}(x) \to 1$ as $x \to 0$
- Validation of heavy-quark S-ACOT-χ scheme at $O(\alpha_s^2)$ *(based on Guzzi, P.N., Lai, Yuan, arXiv:1108.5112 (hep-ph))*
- New $N_f = 3$ and 4 NLO sets with $\alpha_s(m_\tau) = 0.321$ will complement CT10F3 an CT10F4 sets with $\alpha_s(M_Z) = 0.118$

Two sets of CT NNLO error PDFs
1. CT12 NLO and NNLO eigenvector sets

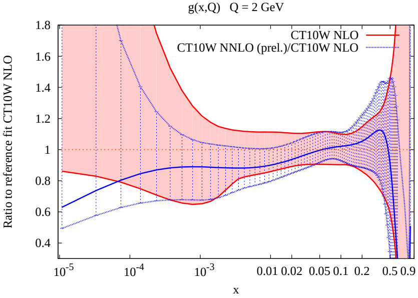
To be released within 1-2 months

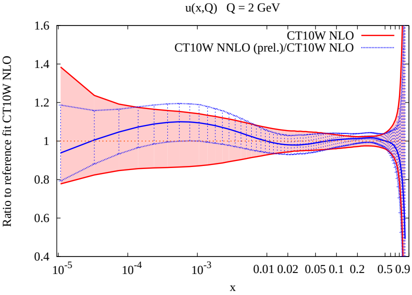
- Include LHC W and Z rapidity data, ATLAS and CMS jet data, HERA'2011 F_L data
- Only inclusive p_T bins of D0 electron and muon charged asymmetry data
- Updated α_s, m_c, m_b values
- Flexible $\bar{d}/\bar{u}$ ratio at $x \rightarrow 1$, updated $(s+\bar{s})/(\bar{u}+\bar{d})$ at $x \lesssim 10^{-2}$
  - Constrained by the LHC W/Z rapidity distributions

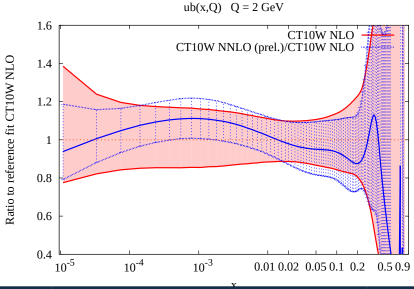
NNLO error PDFs

- NNLO fits have been examined for about 1 year
- Several benchmarking/validation studies were carried out to have better estimates of PDF uncertainties
- CT10W NNLO and NLO PDFs produce about the same $\chi^2/N_{pt} \approx 1.05 - 1.10$ for $N_{pt} = 2700$ data points
- Shapes of the NNLO PDFs have noticeably evolved compared to NLO as a result of $\mathcal{O}(\alpha_s^2)$ contributions, updated electroweak contributions, and revised statistical procedures

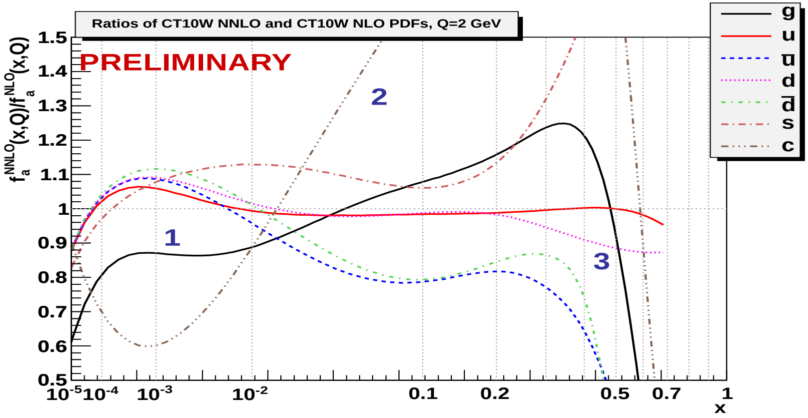
CT10W NNLO error PDFs (compared to CT10W NLO)





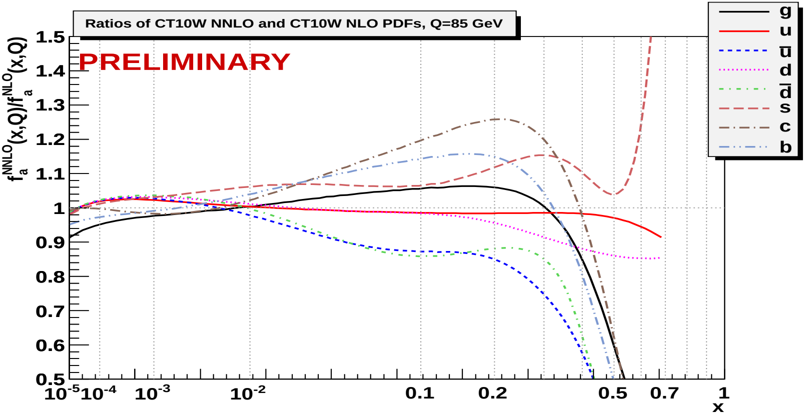


CT10W NNLO central PDFs, as ratios to NLO, Q=2 GeV



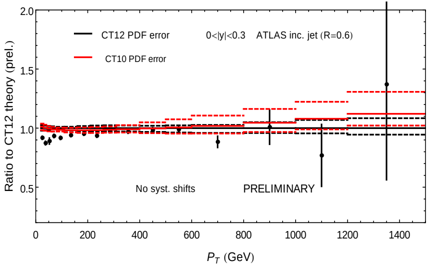
1. At $x < 10^{-2}$, $\mathcal{O}(\alpha_s^2)$ evolution suppresses $g(x,Q)$, increases $q(x,Q)$
2. $c(x,Q)$ and $b(x,Q)$ change as a result of the $\mathcal{O}(\alpha_s^2)$ GM VFN scheme
3. At $x > 0.1$, $g(x,Q)$ and $d(x,Q)$ are reduced by revised EW couplings, alternative treatment of correlated systematic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

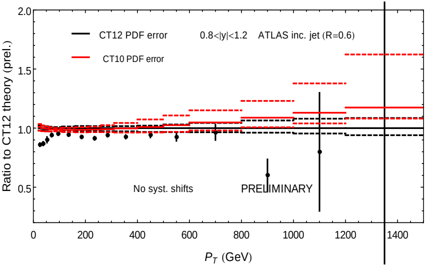
CT10W NNLO central PDFs, as ratios to NLO, Q=85 GeV

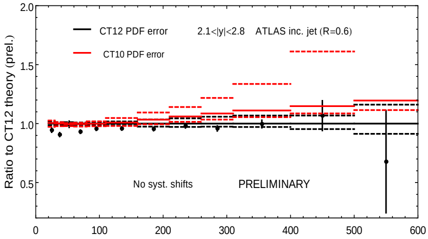


CT12 NLO predictions for LHC jet production

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)

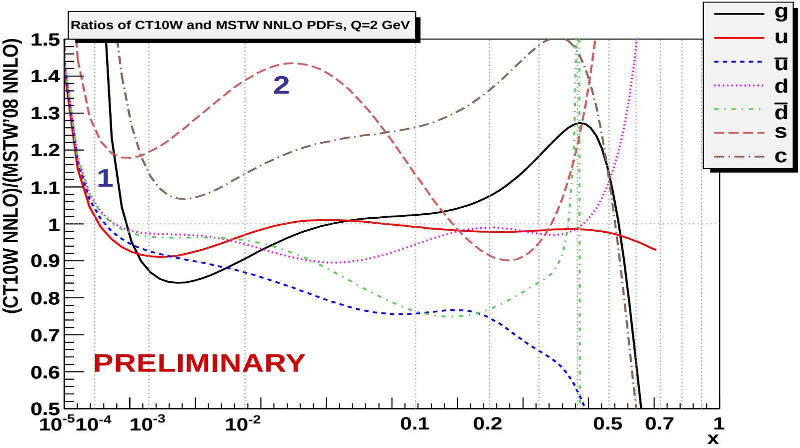






CT10 NNLO and CT12 PDFs (black lines) predict smaller jet cross sections at large p_T, as a result of reduced $g(x,Q)$ at $x > 0.1$

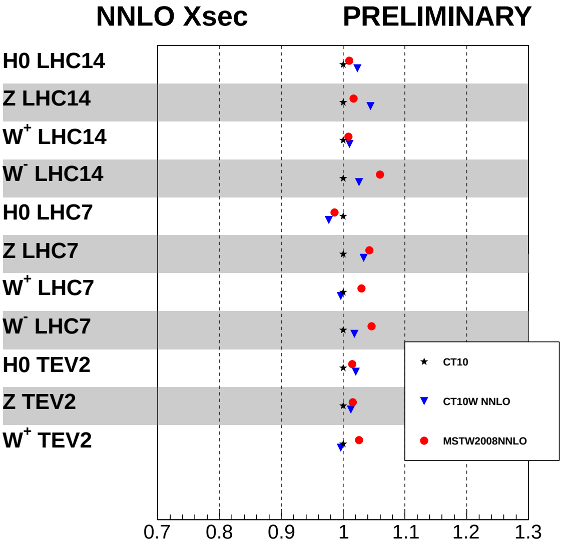
CT10W NNLO PDFs compared to MSTW NNLO



1. CT10 gluon and quarks are harder 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

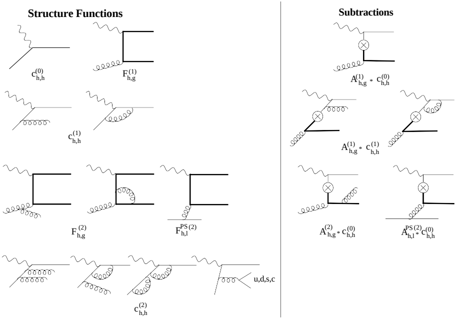


Neutral-current DIS in S-ACOT-χ scheme at NNLO

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

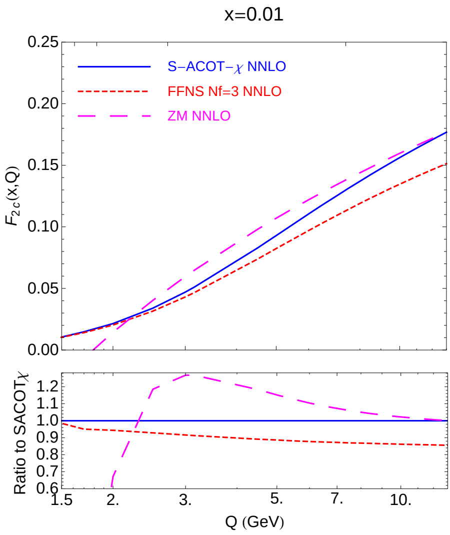
Objectives

- elucidate fundamental principles that a viable GM scheme must satisfy
- modify the QCD factorization theorem for DIS with massive quarks *(Collins, 1998)* to satisfy momentum conservation in all heavy-quark scattering channels
- provide algorithmic implementation of NNLO massive contributions, in close analogy to the ZM scheme



NNLO scattering contributions

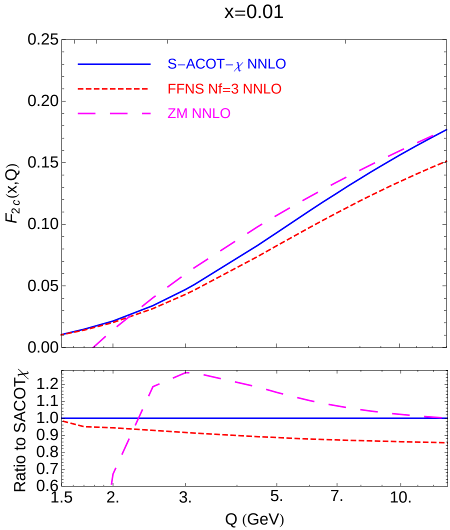
S-ACOT-χ scheme: merging FFN and ZM



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

S-ACOT-χ scheme: merging FFN and ZM



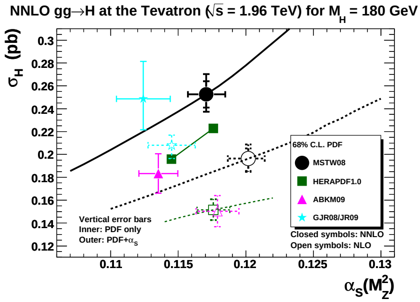
$\mathcal{O}(\alpha_s^2)$ flavor-creation contributions with $m_c \neq 0$ are included exactly *(based on the calculation by Riemersma, Smith, van Neerven, PL B347, 143 (1995))*

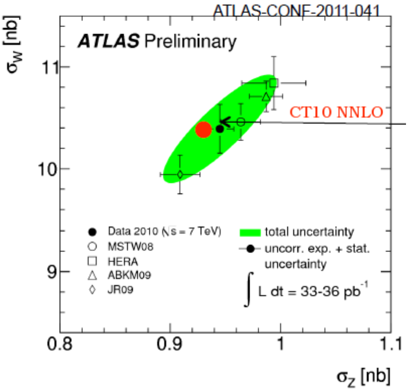
The implementation will be made available in HERA FITTER

A complementary calculation (a "hybrid mass scheme"; exact $\mathcal{O}(\alpha_s)$ massive ACOT terms + approximate $\mathcal{O}(\alpha_s^2)$ and $\mathcal{O}(\alpha_s^3)$ massive terms) has been published by *Stavreva, Olness, Schienbein, et al., arXiv:1203.0282*

Control of uncertainties in NNLO PDF sets

Agreement between the existing NNLO PDF sets is not automatically better than at NLO. Differences are comparable to experimental errors





Thorne, Watt, arXiv:1106.5789

We performed several validation studies to identify the uncertainties that compete with NNLO corrections

Benchmarking comparisons of the fitting codes

1. Benchmarks for inclusive DIS cross sections (with S. Alekhin, A. Glazov, A. Guffanti, J. Rojo)

2. Benchmarks for NLO jet production calculations (J. Gao, Z. Liang at SMU + J. Rojo representing ApplGrid)

The benchmarking studies already provided valuable insights. Thank you to all participants!

1.1. Validation: benchmarking of NC DIS cross sections

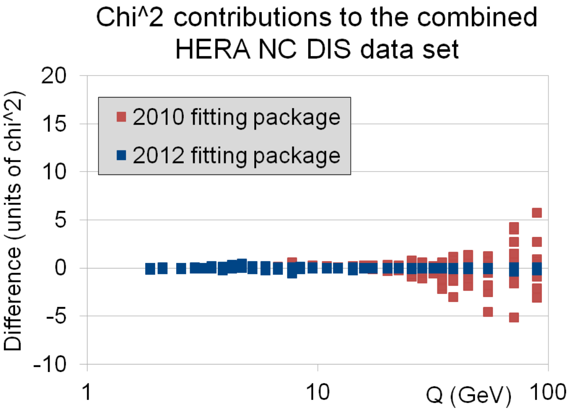
As a part of the DIS benchmarking study, we updated the treatment of the $\gamma^* Z$ interference in NC DIS reduced cross sections in the CTEQ fitting package to fully conform with the formulas in the combined HERA analysis *(arXiv:0911.0884)*.

CTEQ implementation of the $\gamma^* Z$ terms is based on the helicity formalism worked out in *Aivazis, Olness, Tung, Phys.Rev. D50 (1994) 3085* and shared definitions of EW couplings with vector boson production; did not change for 5+ years

The CTEQ code was compared against an alternative DIS calculation at ZM LO provided by Alberto Guffanti

With the latest updates in the Z coupling terms of the CTEQ package, the two codes are in excellent agreement *(cf. the next slide)*.

1.2. Validation: benchmarking of NC DIS cross sections

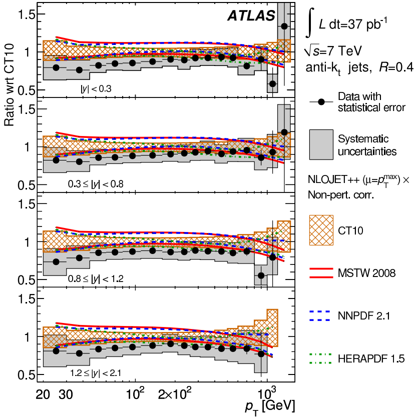


Point-by-point contributions to χ^2 for the combined HERA NC DIS set at ZM LO. Some differences between two codes were observed at large Q, in the (x, Q) region where experimental errors also increase. Differences become practically zero after the benchmarking. $\Rightarrow$ Reduction in $\bar{q}(x, Q), g(x, Q)$ at $x > 0.1$.

2.1 Benchmark comparison of NLO jet cross sections

J. Gao, Z. Liang, P. N., in 2011 Les Houches Proceedings; in collaboration with D. E. Soper, H.-L. Lai, C.-P. Yuan

Benchmarking of NLO cross sections for inclusive jet and dijet production at hadron colliders is important for understanding the theoretical uncertainties in the measurement of PDFs. It also serves as a preparation for NNLO calculation.



Modified EKS program *(publicly available)*

An early NLO calculation for single inclusive (di)jet and dijet production was done by S. D. **E**llis, Z. **K**unszt, and D. E. **S**oper*, PRL 69, 1496 (1992))*. CTEQ fits have been using the EKS program.

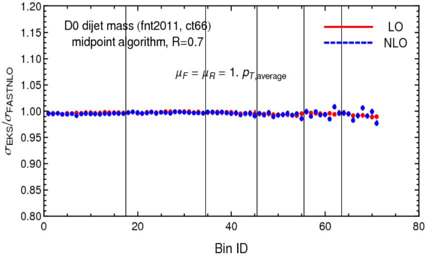
We modified the EKS code to calculate NLO jet cross sections more efficiently, with flexible input and output formats, and provide them in "almost differential" finely binned tables.

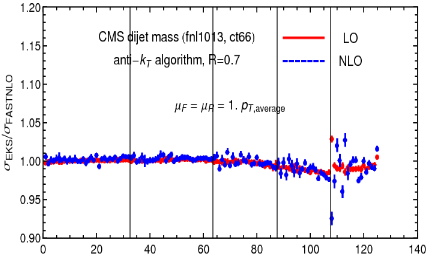
Other available programs include NLOJET++ *(Z. Nagy, PRL 88, 122003 (2002))* , FastNLO *(Kluge et. al., hep-ph/0609285)*, POWHEG *(Alioli et. al., JHEP 04081 (2011))*, APPLGRID *(EPJC66, 503 (2010))*

We identified specific conditions needed to reconcile MEKS and FastNLO outputs. For very specific settings of the jet algorithm, recombination scheme, jet trigger, QCD scale choices, MEKS and FastNLO show excellent agreement at most y^{jet}, p_T^{jet}, and M^{jj}.

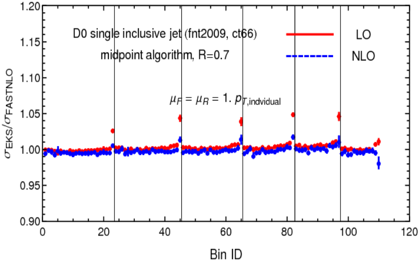
Comparison of MEKS and FastNLO 1.0

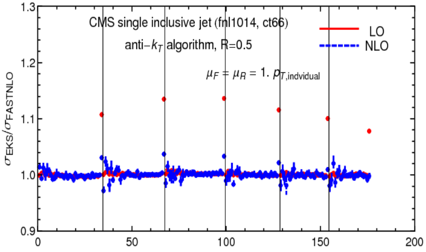
Dijet production: excellent agreement at both the Tevatron and LHC





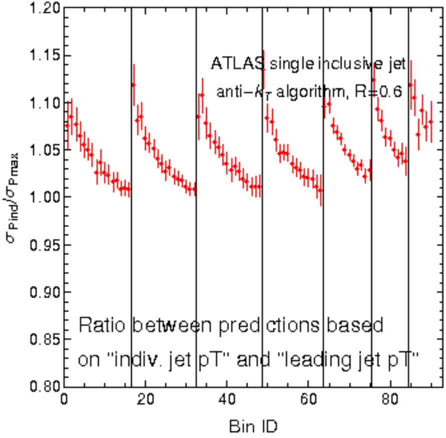
Single-inclusive jet production: discrepancies of 3-10% exist at large p_T, possibly due to different definitions of the "jet p_T" used as the QCD scale.





The choice of scale in jet production cross sections

The *"jet p_T"* may refer to the *"p_T of the leading jet in an event"*, *"p_T of each jet in each p_T bin"*, *"average p_T in each p_T bin (FastNLO 1)"*, or *"p_T of the leading jet in each bin (ATLAS)"*. Differences resulting from these definitions are comparable to NNLO/PDF uncertainties.



CT10 NNLO/CT12 PDFs use $\mu_F = \mu_R = \langle p_T \rangle_{bin}$ and FastNLO 2 (implemented as an alternative to the K-factor lookup tables based on the MEKS calculation).

$\Rightarrow$ Softer gluon than in CT10 NLO

2. Computation of correlated systematic errors

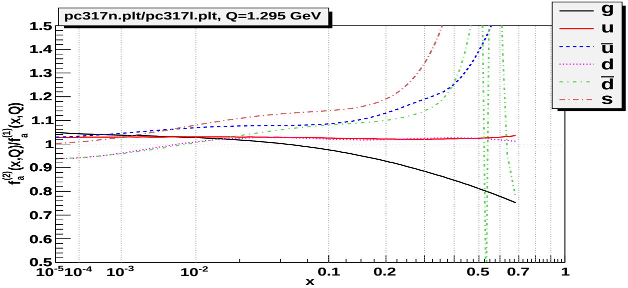
$$\chi^2 = \sum_{\{\text{exp.}\}} \left[\sum_{k=1}^{N_{pts}} \frac{1}{s_k^2} \left(D_k - T_k(\{a\}) - \sum_{\alpha=1}^{N_\lambda} \lambda_\alpha \beta_{k\alpha} \right)^2 + \sum_{\alpha=1}^{K_e} \lambda_\alpha^2 \right]$$

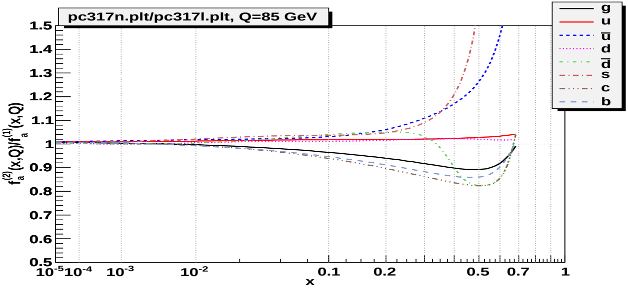
The experimental correlated systematic errors $\beta_{k\alpha}$ are often published as percentages. It can be taken to be a percentage of the theoretical prediction T_k ("truth") or the experimental datum D_k.

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.

2.2. Impact on the best fit NLO PDFs



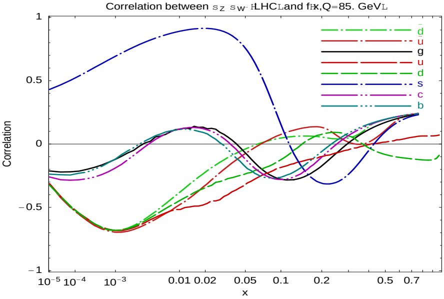


pc317l: CT12 NLO candidate obtained with method 1

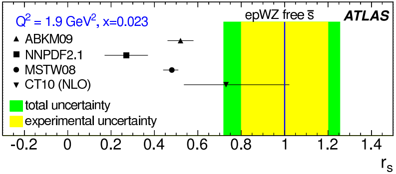
pc317n: CT12 NLO candidate obtained with method 2

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

Strangeness in CT12 PDFs and LHC W/Z cross sections



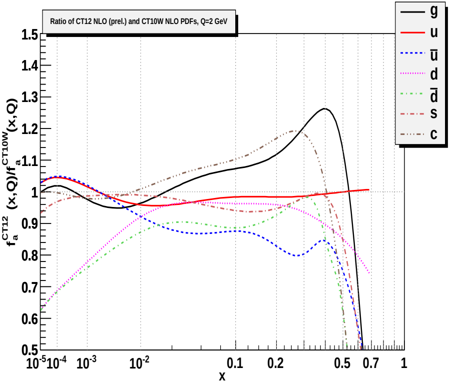
In 2008, our CTEQ6.6 PDF correlation analysis pointed out the sensitivity of ratios σ_W/σ_Z of LHC W & Z cross sections to strangeness PDF, with implications to EW precision measurements *(P.N., Lai, Cao, Huston, Pumplin, Tung, Yuan, PRD, 78 (2008) 013004)*.

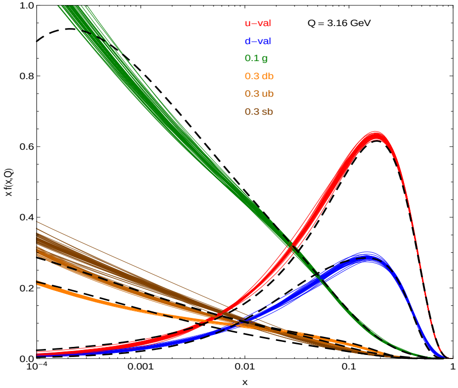


The ATLAS analysis (arXiv:1203.4051) of W and Z production suggests that $\bar{s}(x,Q)/\bar{d}(x,Q) = 1.00^{+0.25}_{-0.28}$ at $x = 0.023$ and $Q^2 = 1.9$ GeV^2

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.

Conclusions

- The CT10W NNLO PDF analysis (based on pre-LHC data only) will be released this week. It is based on a new streamlined implementation of heavy-quark DIS contributions at two loops *(Guzzi et al., arXiv:1108.5112).*

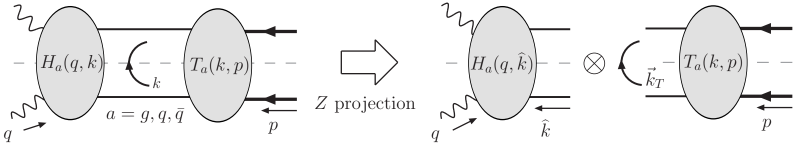
- The CT12 NLO and NNLO analysis (in progress) will include latest LHC data on W, Z, and jet production. Possible impact on $SU(3)$ properties of quark sea at $x < 10^{-3}$.

- Several factors that are comparable to NNLO contributions (treatment of percentage corr. syst. errors, choices of scales, electroweak radiative contributions, ...) have been thoroughly examined in this analysis

- We use a specific choice to evaluate these factors in the CT12 (N)NLO fits. The uncertainty associated with this choice need to be examined in the future

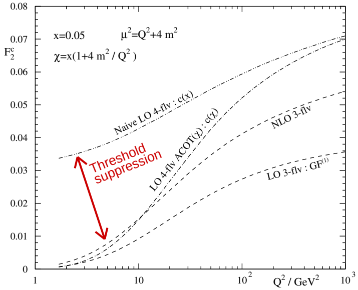
Backup slides

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



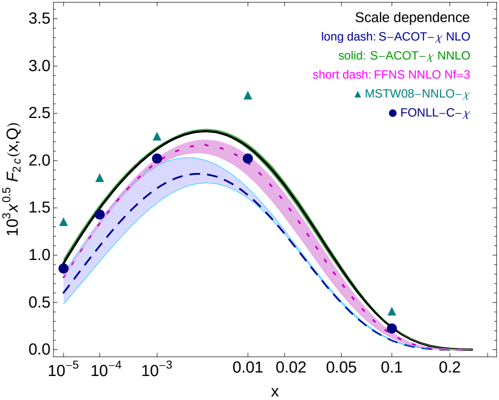
NNLO results for $F_2^{(c)}(x, Q^2)$

At NNLO and $Q \approx m_c$:

S-ACOT-$\chi\,(N_f = 4) \approx$ FFN $(N_f = 3)$
without tuning

- S-ACOT is numerically close to other NNLO schemes, especially the FONLL-C scheme

(Forte, Laenen, Nason, Rojo, arXiv:1001.2312).



- The $\mathcal{O}(\alpha_s^2)$ S-ACOT-χ prediction is close to the FFN prediction at $Q \to m_c$ as a consequence of the kinematical rescaling introduced in the proof of factorization. Rescaling improves perturbative convergence of S-ACOT-χ predictions near the threshold.

Main features of the S-ACOT-χ scheme

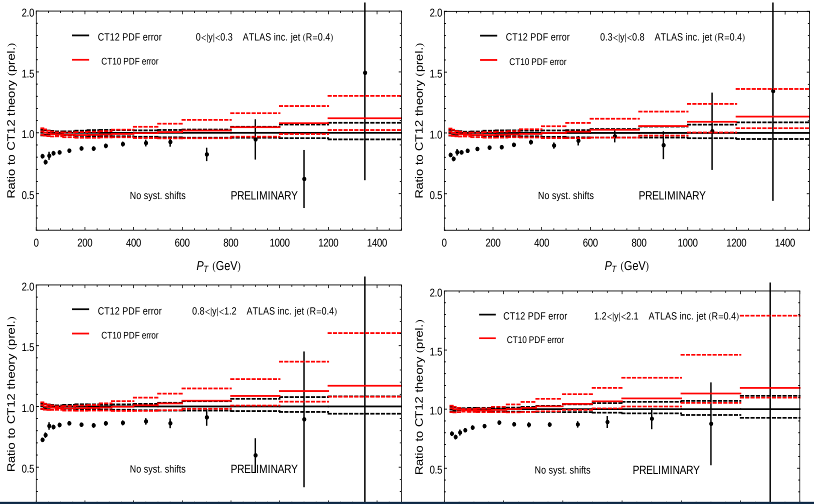
- It is proved to all orders by the QCD factorization theorem for DIS *(Collins, 1998)*
- It is relatively simple
  - One value of N_f (and one PDF set) in each Q range
  - sets $m_h = 0$ in ME with incoming $h = c$ or b
  - matching to FFN is **implemented as a part of the QCD factorization theorem**
- **Universal** PDFs
- 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

Details of the NNLO computation

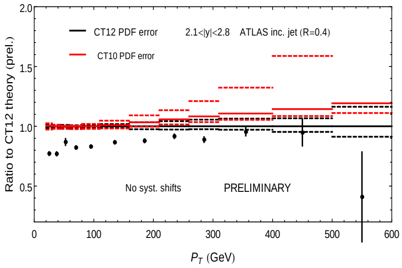
- NNLO evolution for α_s and PDFs (HOPPET)
  - matching coefficients relating the PDFs in N_f and N_{f+1} schemes *(Smith, van Neerven, et al.)*
- NNLO Wilson coefficient functions for $F_2(x, Q)$, $F_L(x, Q)$
- Pole quark masses or $\overline{MS}$ quark masses as an input
- CT10 NNLO: pole masses $m_c = 1.3$ GeV, $m_b = 4.75$ GeV (as in CT10)

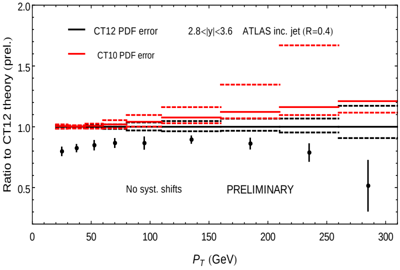
CT12 predictions for ATLAS jet production (2)

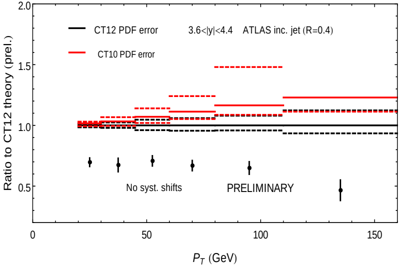
ATLAS single-inclusive jet production (arXiv:1112.6297); FastNLO 2; R=0.4;
$\chi^2/N_{d.o.f} = 0.76\,(0.95)$ for CT12 NLO (CT10 NLO)

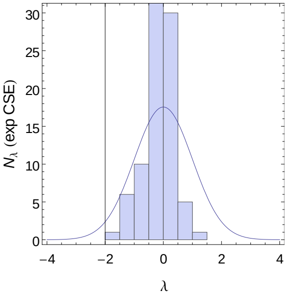


CT12 predictions for ATLAS jet production (3)









Factorization scale in NLO jet cross sections

NLO jet cross sections depend significantly on renorm. and fact. scales, μ_F and μ_R

CT10 fit assumed the default scale $\mu_F^0 = \mu_R^0 = p_T/2$; other groups and experimentalists often use $\mu_F^0 = \mu_R^0 = p_T$

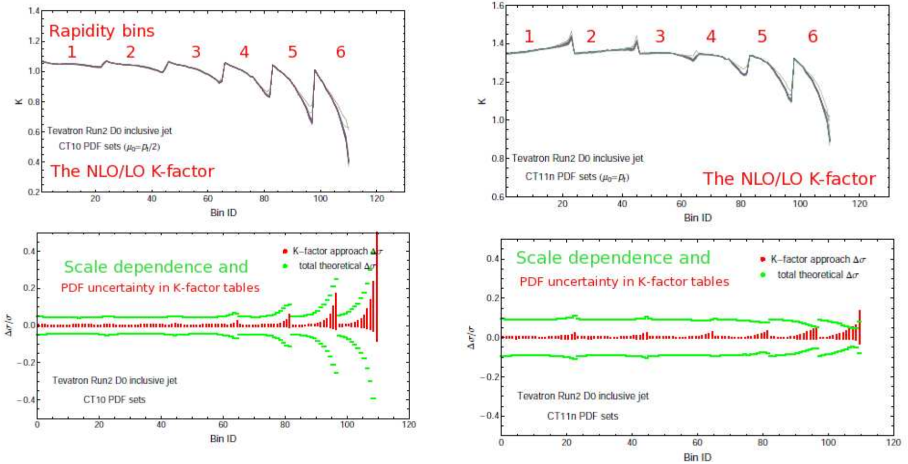
Trade-offs between the scale choices (see the next slide)

- $\mu_{F,R} = p_T/2$: $K \approx 1$ at small y_{jet}, large scale dependence at large y_{jet}
- $\mu_{F,R} = p_T$: $K \approx 1.4$ at small y_{jet}, smaller scale dependence at large y_{jet}

CT10 NNLO will provide a PDF set for $\mu_{F,R} = p_T$

NLO corrections for $\mu^0_{F,R} = p_T/2$ (left) and p_T (right)

Jun Gao, 2011



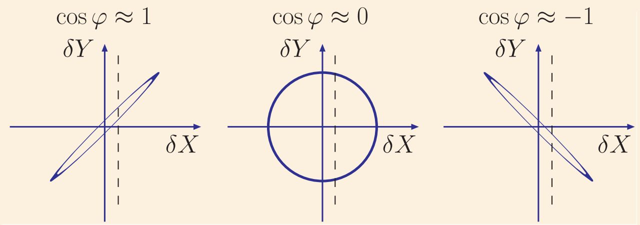
Scale dependence (green) corresponds to variations $1/2 \leq \mu_{F,R}/\mu^0_{F,R} \leq 2$. Red bands reflect the PDF uncertainty in the lookup tables for the NLO K-factors.

But which PDFs do the jet data exactly constrain?

Compute the PDF correlation cosine *(hep-ph/0101032; arXiv:0802.0007)*,

$$\cos\varphi \equiv \frac{1}{4\Delta X\,\Delta Y}\sum_{i=1}^{N_{PDF\,params}}\left(X_i^{(+)} - X_i^{(-)}\right)\left(Y_i^{(+)} - Y_i^{(-)}\right)$$

to establish which PDFs $X(x,Q)$ contribute most of the PDF uncertainty in the observable Y

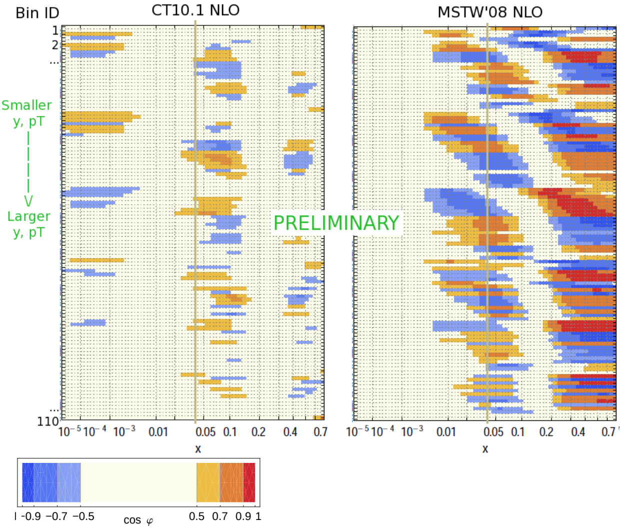


$\cos\varphi \approx \pm 1$: Measurement of Y imposes tight constraints on X

$\cos\varphi \approx 0$: Measurement of Y imposes loose constraints on X

Correlations between D0 Run-2 inc. jet data and gluon PDF

Z. Liang, P. Nadolsky, in 2011 Les Houches Proceedings



Correlation between $g(x, Q = 3.163 \text{ GeV})$ and χ_i^2 in jet p_T bins (with syst. shifts)...

...is more pronounced for the MSTW'08 sets (right) than for CT10 sets (left)