Nuclear parton distribution functions

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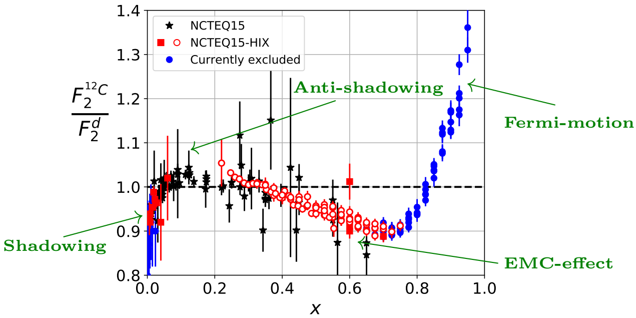
- Cross-sections in nuclear collisions are modified

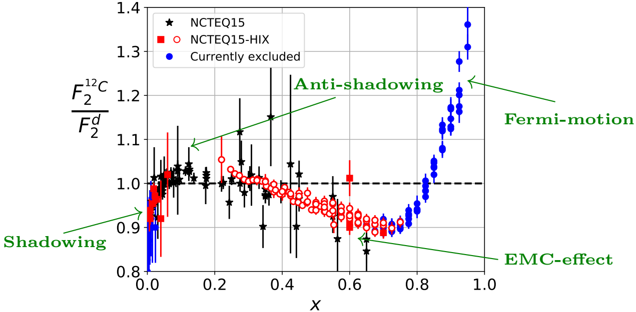
$$F_2^A(x) \neq Z F_2^p(x) + N F_2^n(x)$$



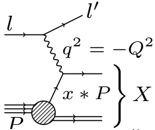
Introduction

- Cross-sections in nuclear collisions are modified

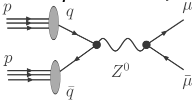
$$F_2^A(x) \neq Z F_2^p(x) + N F_2^n(x)$$



- Can we translate this modifications into ***universal*** **nuclear PDFs**?



$$\frac{d^2\sigma}{dx dQ^2} = \sum_{i=q,\bar{q},g} \int_x^1 \frac{dz}{z} f_i(z,\mu) d\hat{\sigma}_{il\to l'X}\left(\frac{x}{z}, \frac{Q}{\mu}\right) + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}^2}{Q^2}\right)$$



$$\sigma_{pp\to l\bar{l}X} = \sum_{i,j=q,\bar{q},g} \int_{x_1}^1 dz_1 \int_{x_2}^1 dz_2 f_i(z_1,\mu) f_j(z_2,\mu) \hat{\sigma}_{ij\to l\bar{l}X} + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}^2}{Q^2}\right)$$

Comparison of available nPDFs

	KSASG20 PRD 104, 034010	TUJU21 PRD 105, 094031	EPPS21 EPJC 82, 413	nNNPDF3.0 EPJC 82, 507	nCTEQ15HQ PRD 105, 114043
lA NC DIS	✓	✓	✓	✓	✓
νA CC DIS	✓	✓	✓	✓	
pA Drell-Yan	✓		✓	✓	✓
πA Drell-Yan			✓		
RHIC dAu π			✓		✓
LHC pPb π, K					✓
LHC pPb W/Z		✓	✓	✓	✓
LHC pPb dijet			✓	✓	
LHC pPb HQ			✓ GMVFNS	✓ FO+PS(rew)	✓ ME fit
LHC quarkonium					✓ ME fit
LHC pPb γ				✓	
Kinematic cuts	$Q > 1.3$ GeV	$Q > 1.87$ GeV $W > 3.5$ GeV	$Q > 1.3$ GeV $W > 1.8$ GeV $p_T^{HQ} > 3$ GeV	$Q > 1.87$ GeV $W > 3.5$ GeV	$Q > 2$GeV $W > 3.5$GeV $p_T^{HQ(SIH)} > 3$ GeV
No data points	4335	2410	2077	2188	1496
No free param.	9	16	24	256 (NN)	19
χ^2/dof	1.06(1.05)	0.94(0.84)	1.00	1.10	0.86
Error analysis	Hessian	Hessian	Hessian	Monte Carlo	Hessian
$\Delta\chi^2$ tol.	20 (68% CL)	50	35	N/A	35
Proton baseline	CT18	custom	CT18A	~NNPDF4.0	~CTEQ6.1
Q_0 ini. scale	1.3 GeV	1.3 GeV	1.3 GeV	1.0 GeV	1.3 GeV
No flavours	3	4	6	6	5
Deuteron treat.	fitted	fitted	free	fitted	free
QCD order	**NLO & NNLO**	**NLO & NNLO**	**NLO**	**NLO**	**NLO**
HQ scheme	FONLL	FONLL	S-ACOT	FONLL	S-ACOT

Updates from nCTEQ

Recent nCTEQ results

- Last full nPDF release: **nCTEQ15** [PRD 93, 085037 (2016)]
  - DIS NC data
  - fixed-target DY data
  - pion data from RHIC

- Updates on the way to new release
  - **nCTEQ15WZ** [EPJC 80, 968 (2020)]
    - LHC W/Z data
    - constraints on *gluon* and *strange* nPDFs
  - **nCTEQ15HIX** [PRD 103, 114015 (2021)]
    - JLAB DIS data
    - constraints at high-x
    - theoretical corrections: TMC, HT, deuteron
  - **nCTEQ15SIH** [PRD 104 (2021) 9, 094005]
    - LHC & RHIC SIH data
    - constraints on *gluon* nPDF
  - **nCTEQ15neutrino** [PRD 106 (2022) 7, 074004]
    - DIS neutrino data (NuTeV, CHORUS, CDHSW, dimuons)
    - compatibility of NC & CC DIS
    - flavour separation
  - **nCTEQ15HQ** [PRL 121, 052004 (2018); PRD 105 (2022) 11, 114043]
    - LHC & RHIC HF data
    - constraints on low-x *gluon* nPDF
    - currently in form of PDF-reweighting

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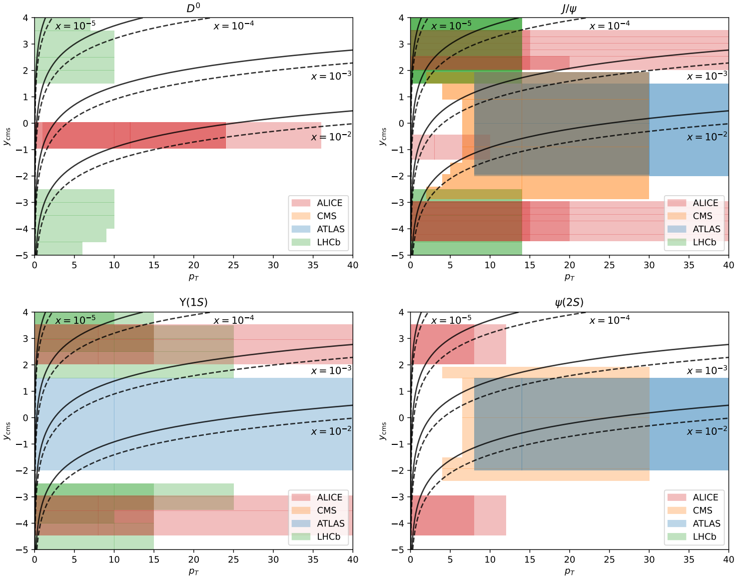
nCTEQ15HQ [PRD 105 (2022) 11, 114043]

- New data compared to nCTEQ15WZ+SIH ($p_T > 3$ GeV):
  D, J/ψ, $B \to J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \to \psi(2S)$



Heavy Quarks (HQ) - Theoretical approaches

Schemes for the calculation of **Open Heavy Quark** production (D, B mesons):

- **FFNS**: HQ present only in final state. Valid for small p_T.
- **ZM-VFNS**: HQ treated as massless, but included in PDFs. Valid at large p_T.
- Schemes interpolating between the two:
  - **FONLL**: $d\sigma_{\text{FONLL}} = d\sigma_{\text{FFNS}} + (d\sigma_{\text{ZMVFNS}} - d\sigma_{\text{FFNS},0}) \times G(m_Q, p_T)$,
  - **GM-VFNS**: Massive heavy quarks included in the PDFs for $\mu_f > \mu_T$.

Different schemes for the calculation of **Quarkonium** production:

- **Color-evaporation model**: hard scattering creates $Q\bar{Q}$-pair, which radiates gluons until it hadronizes
- **Color-singlet model**: Intermediate state is a color neutral $Q\bar{Q}$-pair
- **Non-relativistic QCD**: separation of short and long distance physics through expansion in velocity

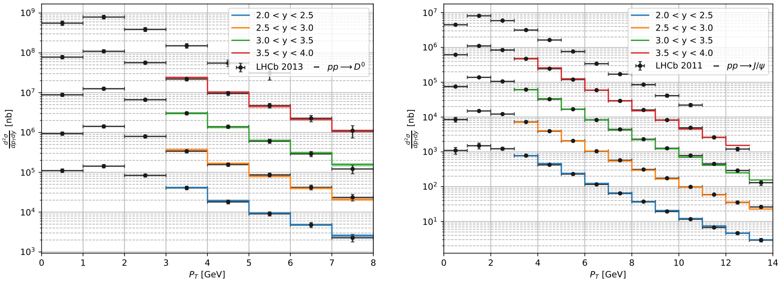
Heavy Quarks (HQ) - Data-driven Approach

$$\sigma(AB \to \mathcal{Q} + X) = \int \mathrm{d}x_1\ \mathrm{d}x_2 f_{1,g}(x_1)\, f_{2,g}(x_2)\, \frac{1}{2\hat{s}} \overline{\left|\mathcal{A}_{gg\to Q} + X\right|^2} \mathrm{dLIPS}$$

- Crystal-Ball parametrization extended to include rapidity dependence (a param.)

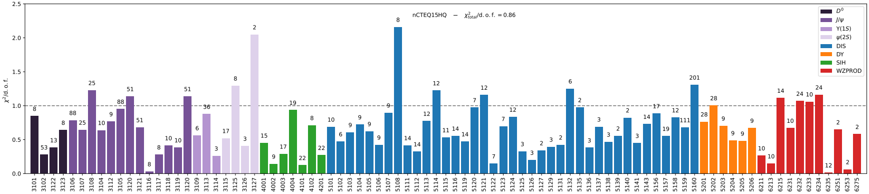
$$\overline{\left|\mathcal{A}_{gg\to Q+X}\right|^2} = \frac{\lambda^2 \kappa \hat{s}}{M_{\mathcal{Q}}^2} \begin{cases} e^{-\kappa \frac{p_T^2}{M_Q^2} + a|y|} & \text{if } p_T \leq \langle p_T \rangle \\ e^{-\kappa \frac{\langle p_T \rangle^2}{M_Q^2} + a|y|} \left(1 + \frac{\kappa}{n} \frac{p_T^2 - \langle p_T \rangle^2}{M_Q^2}\right)^{-n} & \text{if } p_T > \langle p_T \rangle \end{cases}$$

- Very good agreement between data and fitted theory

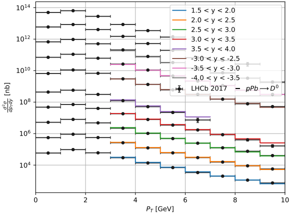


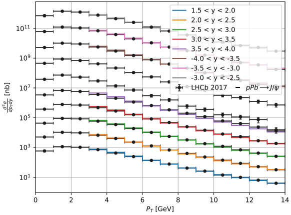
nCTEQ15HQ data description [PRD 105 (2022) 11, 114043]

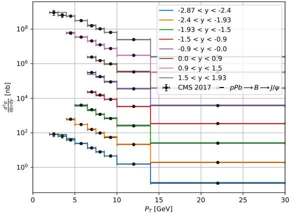
χ^2 for nCTEQ15HQ with 548 new HF data points:



Example pPb data description:

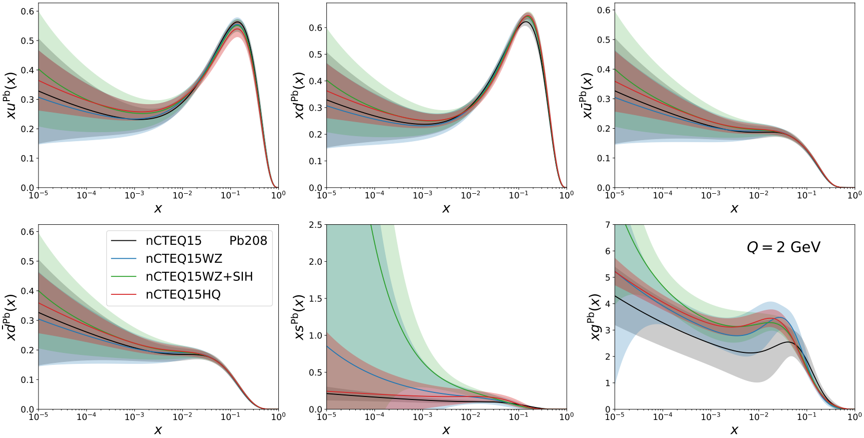






nCTEQ15HQ nPDFs [PRD 105 (2022) 11, 114043]

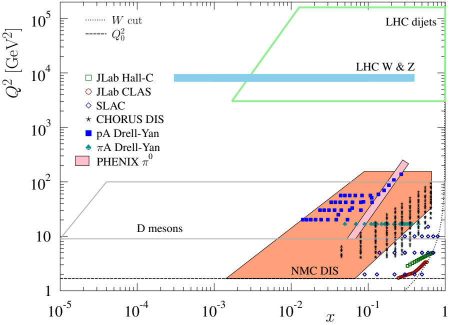
- New data compared to nCTEQ15WZ+SIH:
  D, J/ψ, $B \to J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \to \psi(2S)$
- Predictions for heavy quark(onium) data done with data-driven method [PRL 121 (2018) 052004; PRL107, 082002 (2011); EPJC77, 1 (2017)]



Updates from EPPS

EPPS21 vs. EPPS16

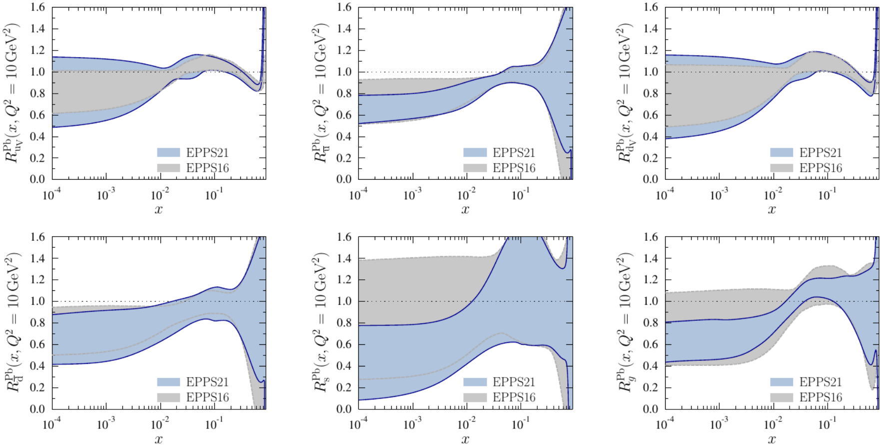
- New data compared to EPPS16:
  - LHC pPb D-meson data from LHCb (Run I)
  - LHC pPb $W^{\pm}$ data from CMS (Run II)
  - LHC pPb double-differential dijet data from CMS (Run I)
  - JLAB DIS data from Hall C and CLAS



- Methodological updates:
  - New parametrization (24 free parameters vs. 20)
  - Account for the uncertainties of the proton baseline
  - Tolerance criterion $\Delta\chi^2 \simeq 33$ (compared to 50)
  - Inclusion of $W > 1.8$ GeV cut for DIS data

EPPS21 vs. EPPS16 [EPJC 82 (2022) 5, 413]

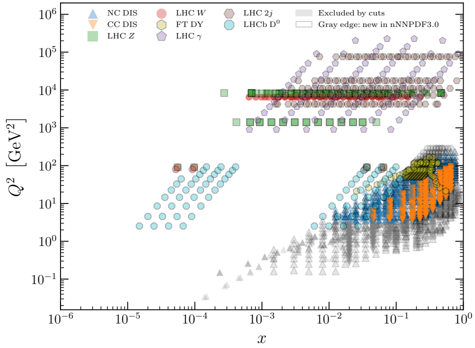
- New data compared to EPPS16:
  JLAB DIS, CMS W from pPb @8TeV, CMS dijet, LHCb D^0
- D meson data from LHCb at $\sqrt{s} = 5$ TeV [JHEP 1710 (2017) 090]
- Predictions for D meson (double differential in p_T and y) calculated in version of GM-VFNS scheme [JHEP 05 (2018) 196]



Updates from nNNPDF

nNNPDF3.0 vs. nNNPDF2.0

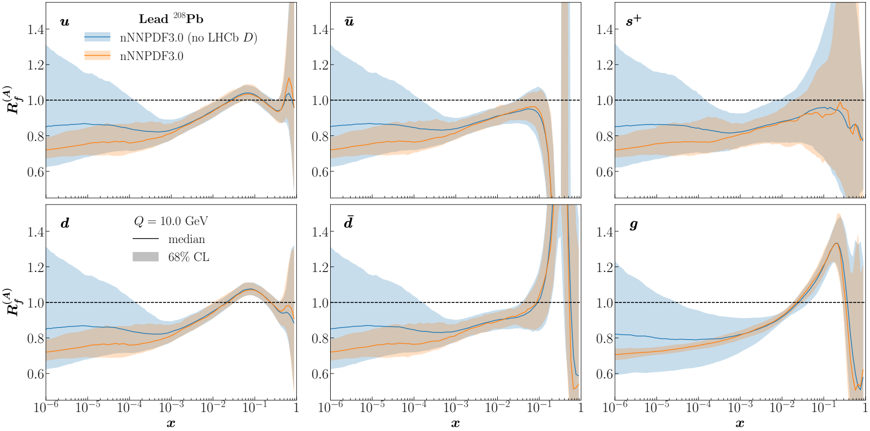
- New data compared to nNNPDF2.0:
  - LHC pPb D-meson data from LHCb (Run I)
  - LHC pPb prompt γ from ATLAS (Run II)
  - LHC pPb Z data from CMS (Run II), ALICE (Run I, Run II), LHCb (Run I)
  - LHC pPb $W^{\pm}$ data from ALICE (Run I)
  - LHC pPb dijet data from CMS (Run I)
  - NC DIS data for deuteron



- Methodological updates
  - Proton boundary condition imposed at $x = 10^{-6}$ (instead of $x = 10^{-6}$)
  - New proton baseline
  - Hyperparameter optimisation (NN architecture, etc.)

nNNPDF3.0 [EPJC 82 (2022) 6, 507]

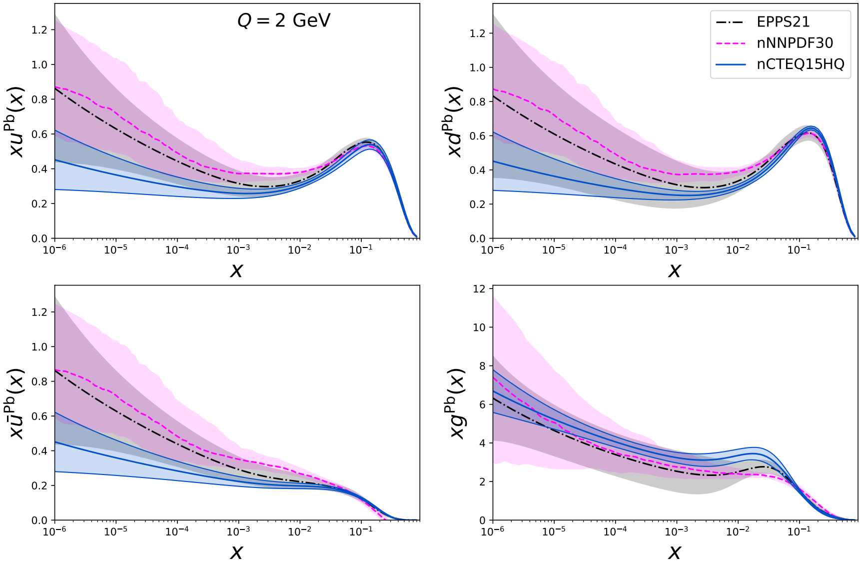
- New data compared to nNNPDF2.0:
  pPb data from LHC: ALICE W @5TeV, LHCb Z @5TeV, ALICE Z @8TeV, CMS Z @8TeV, CMS dijet, prompt photon ATLAS @8TeV, LHCb D^0
- D meson data from LHCb at $\sqrt{s} = 5$ TeV [JHEP 1710 (2017) 090]
- Predictions for D meson in FFNS done in POWHEG+PYTHIA included using **PDF reweighting**



Available nPDFs including heavy quark(onium) data

	N_{data}	N_{params}	Observables
EPPS21	2029+48	24	(ν)DIS, DY, SIH, W/Z, dijet, D
nNNPDF3.0	2151+37	256	(ν)DIS, DY, W/Z, dijet, γ, D
nCTEQ15HQ	936+548	19	DIS, DY, SIH, W/Z D, J/ψ, $B \to J/\psi$, $\Upsilon(1S)$, $\psi(2S)$, $B \to \psi(2S)$

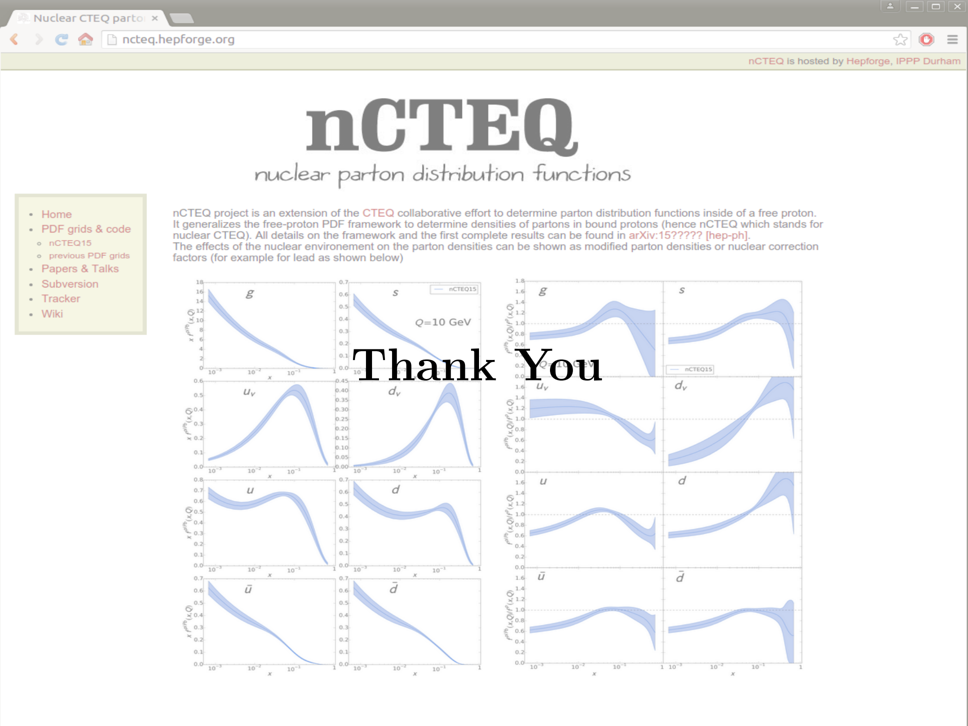
Comparison of nPDFs using HF data



Summary

- The pPb LHC data have provide crucial information about nPDFs
  - extending kinematic coverage down to $x \sim 10^{-5}$ (before $x \gtrsim 10^{-2}$)
  - gluon distribution (HQ(-onium), dijets, prompt photon, W/Z)
  - flavour separation (W/Z)
  - strange quark (W/Z)
- This is reflected in relatively good agreement of nPDFs from different groups (which wasn't the case in the past).
- The new release of nCTEQ PDFs including the presented updates is on the way:
  - new data (pPb LHC, JLAB, Neutrinos)
  - methodological updates
- Good starting point for EIC but
  - factorization in pA collisions is not proven
  - there can be other effects like energy loss [JHEP 01 (2022) 164]
- In the future EIC will allow to test what we learn at the LHC and should bring us to a new era of precision nPDFs.

Thank You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nCTEQ project is an extension of the CTEQ collaborative effort to determine parton distribution functions inside of a free proton. It generalizes the free-proton PDF framework to determine densities of partons in bound protons (hence nCTEQ which stands for nuclear CTEQ). All details on the framework and the first complete results can be found in arXiv:15????? [hep-ph].
The effects of the nuclear environement on the parton densities can be shown as modified parton densities or nuclear correction factors (for example for lead as shown below)
nCTEQ15
Q=10 GeV