Global analyses of nuclear PDFs with HQ and ν data

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for the nCTEQ collaboration

GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

Nuclear structure at high energies

Important current research topic:

- Understand fundamental q, g dynamics of p, n bound in nuclei
- Determine initial conditions in creation of new state of matter: Color-glass condensate (CGC) $\rightarrow$ Quark-gluon plasma (QGP)

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Knowns and (known) unknowns:

- Evolution of PDFs $f_{q,g}(x, Q^2)$ with squared energy Q^2: Calculable at NLO and beyond through DGLAP equations
- Dependence on longitudinal momentum fraction x: QCD factorization theorem $\rightarrow$ global fits to experimental data
- Fundamental dynamics of nuclear modifications: Parametrized, but remain to be fully understood

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nPDFs: nCTEQ, DSSZ, EPPS, HKN, KSASG, nNNPDF, TUJU

(Perturbative) Quantum Chromodynamics

Nuclear structure function(s) in deep-inelastic scattering (DIS):

$$F_2^A(x, Q^2) \;\; = \;\; \sum_i f_i^{(A,Z)}(x, Q^2) \otimes C_{2,i}(x, Q^2)$$

QCD factorization theorem, Wilson coefficients $C_{2,i}$ at NLO

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$$f_i^{(A,Z)}(x, Q^2) \;=\; \frac{Z}{A} f_i^{p/A}(x, Q^2) + \frac{A-Z}{A} f_i^{n/A}(x, Q^2)$$

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DGLAP evolution equations:

$$\frac{\partial f_i(x,Q^2)}{\partial \log Q^2} \;=\; \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(Q^2)\right) f_j(z,Q^2)$$

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Sum rules, but also isospin symmetry:

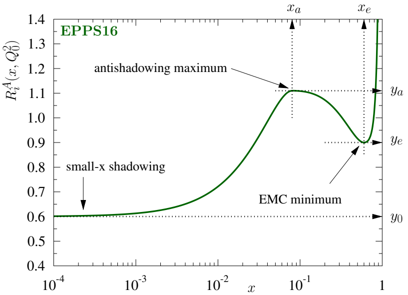
$$f_{d,u}^{n/A}(x, Q^2) = f_{u,d}^{p/A}(x, Q^2)$$

Nuclear modification factor

M. Arneodo, Phys. Rep. 240 (1994) 301; S. Malace, D. Gaskell, D. Higinbotham, Int. J. Mod. Phys. E23 (2014) 1430013

Definition:

$$f_i^{p/A}(x, Q^2) = R_i^A(x, Q^2) f_i^p(x, Q)$$



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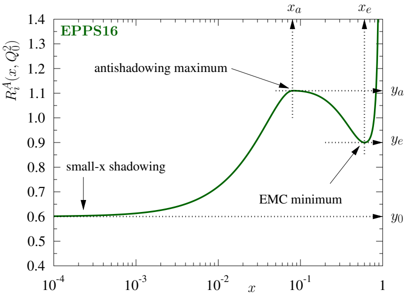

Regions:

- Shadowing: Surface nucleons absorb $q\bar{q}$ dipole, cast shadow
- Antishadowing: Imposed by momentum sum rule
- EMC effect: q_v suppression due to nuclear binding, pions, quark clusters, Nachtmann scaling, short-range correlations, ...
- Fermi motion: Nucleons move, $F_2^A = \int_x^A dz\ f_N(z)\ F_2^N(\frac{x}{z})$

nCTEQ15 parametrization, evolution and global fit

K. Kovarik et al., Phys. Rev. D 93 (2016) 085037

Parametrization:

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\begin{aligned}
xf_i^{p/A}(x, Q_0) &= c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5} \\
c_k &\rightarrow c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}})
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Proton baseline: $\sim$ CTEQ6.1 (w/o nuclear data)

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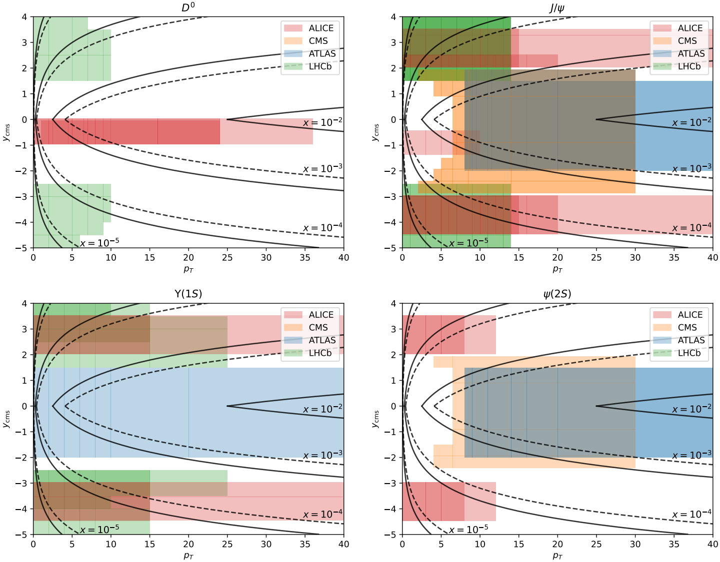
Global fit:

- Fixed target data: DIS A/D, A/A'; DY pA/pA'
- Collider data: PHENIX/STAR π^0; LHC data? ν data?

Heavy quark and quarkonium data from the LHC

P. Duwentäster, MK et al. [nCTEQ Coll.], Phys. Rev. D 105 (2022) 114043 [2204.09982]



Methodology for heavy quark/quarkonium production

P. Duwentäster, MK et al. [nCTEQ Coll.], Phys. Rev. D 105 (2022) 114043 [2204.09982]

Data-driven approach (Crystal Ball function):

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

- Originally proposed for J/Ψ pairs and double parton scattering

  [C.H. Kom, A. Kulesza, J. Stirling, PRL 107 (2011) 082002]
- Impact on nPDFs demonstrated with reweighting studies

  [A. Kusina, J.P. Lansberg, I. Schienbein, H.S. Shao, PRL 121 (2018) 052004 and PRD 104 (2021) 014010]
- New rapidity dependence allows to cover also LHCb data

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Choice of proton PDF (nCTEQ15) and factorization scales:

	D^0	J/ψ	$B\to J/\psi$	$\Upsilon(1S)$	$\psi(2S)$	$B\to\psi(2S)$
μ_0^2	$4M_D^2+p_{T,D}^2$	$M_{J/\psi}^2+p_{T,J/\psi}^2$	$4M_B^2+\frac{M_B^2}{M_{J/\psi}^2}p_{T,J/\psi}^2$	$M_{\Upsilon(1S)}^2+p_{T,\Upsilon(1S)}^2$	$M_{\psi(2S)}^2+p_{T,\psi(2S)}^2$	$4M_B^2+\frac{M_B^2}{M_{\psi(2S)}^2}p_{T,\psi(2S)}^2$

Fit to *pp* data and validation with NLO predictions

P. Duwentäster, MK et al. [nCTEQ Coll.], Phys. Rev. D 105 (2022) 114043 [2204.09982]

Crystal Ball fit parameters: Cut data with $p_T < 3$ GeV and $|y| > 4$

	D^0	J/ψ	$B \to J/\psi$	$\Upsilon(1S)$	$\psi(2S)$	$B \to \psi(2S)$
κ	0.33457	0.47892	0.15488	0.94524	0.21589	0.45273
λ	1.82596	0.30379	0.12137	0.06562	0.07528	0.13852
$\langle p_T \rangle$	2.40097	5.29310	-7.65026	8.63780	8.98819	7.80526
n	2.00076	2.17366	1.55538	1.93239	1.07203	1.64797
a	-0.03295	0.02816	-0.08083	0.22389	-0.10614	0.06179
N_{points}	34	501		375	55	
χ^2/N_{dof}	0.25	0.88		0.92	0.77	

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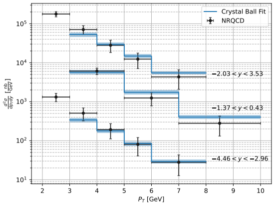
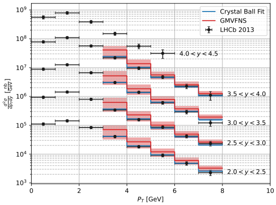
Heavy quarkonia in NRQCD:

[M. Butenschön, B. Kniehl, PRL 106 (2011) 022003]



Open heavy quarks in GM-VFNS:

[B. Kniehl et al., PRD 71 (2005) 014018]



Impact of heavy quark and quarkonium data

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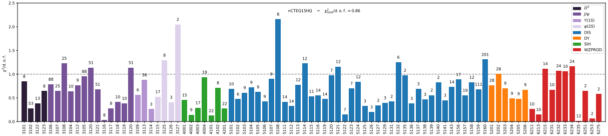
Cut D^0 data with $p_T > 15$ GeV (no p), 2 high-p_T LHCb Υ points



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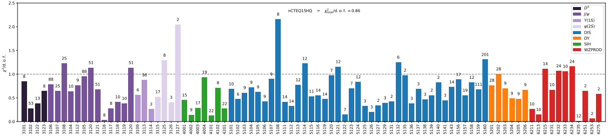
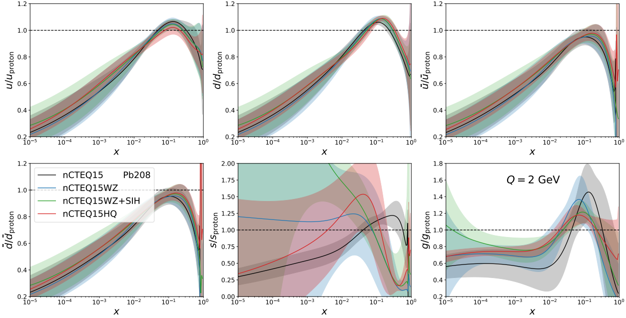


Impact on lead PDFs: [nCTEQ15 (χ^2/dof=1.23), WZ (0.90), WZ+SIH (0.92), HQ (0.86)]



Compatibility of neutrino DIS data

K.F. Muzakka, MK et al. [nCTEQ Coll.], submitted to Phys. Rev. D [2204.13157]

Are CC DIS data compatible with NC DIS and DY data?

- No (in particular high-precision NuTeV data)

  [K. Kovarik, I. Schienbein et al., PRD 77 (2008) 054013, PRL 106 (2011) 122301; also prel. HKN]

- Yes (if taken without correlations, normalized)

  [H. Paukkunen, C.A. Salgado, JHEP 07 (2010) 032, PRL 110 (2013) 212301; also DSSZ]

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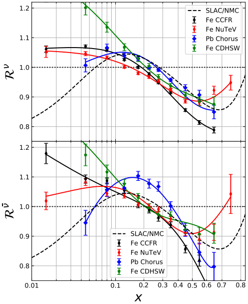
Neutrino data sets:

Data set	Nucleus	$E_{\nu/\bar{\nu}}$(GeV)	#pts	Corr.sys.
CDHSW ν	Fe	23 - 188	465	No
CDHSW $\bar{\nu}$			464	
CCFR ν	Fe	35 - 340	1109	No
CCFR $\bar{\nu}$			1098	
NuTeV ν	Fe	35 - 340	1170	Yes
NuTeV $\bar{\nu}$			966	
Chorus ν	Pb	25 - 170	412	Yes
Chorus $\bar{\nu}$			412	
CCFR dimuon ν	Fe	110 - 333	40	No
CCFR dimuon $\bar{\nu}$		87 - 266	38	
NuTeV dimuon ν	Fe	90 - 245	38	No
NuTeV dimuon $\bar{\nu}$		79 - 222	34	

Internal consistency:



New baseline nCTEQ15WZSIHdeut

K.F. Muzakka, MK et al. [nCTEQ Coll.], submitted to Phys. Rev. D [2204.13157]

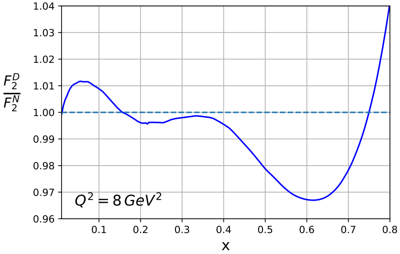
Improvements:

- Remove experimental isoscalar corrections $\rightarrow u/d$ separation

  [E.P. Segarra, MK et al., PRD 103 (2021) 114015]

- Deuteron correction from CJ15 $\rightarrow F_2^{\mathrm{D}} = F_2^{p,nCTEQ15} \times \frac{F_2^{\mathrm{D},CJ}}{F_2^{p,CJ}}$

  [A. Accardi et al., PRD 93 (2016) 114017]

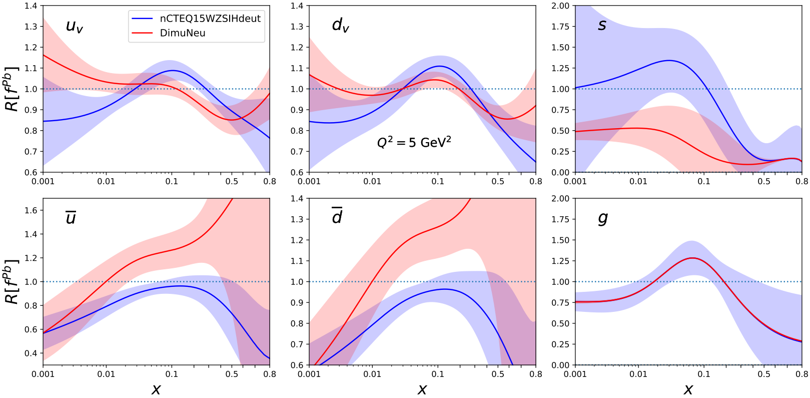


  Influences description of all NC DIS data (F_2^A/F_2^D).

- Repeat nCTEQ15WZ+SIH analysis (better χ^2/dof=0.782)

Comparison to all neutrino data fit

K.F. Muzakka, MK et al. [nCTEQ Coll.], submitted to Phys. Rev. D [2204.13157]



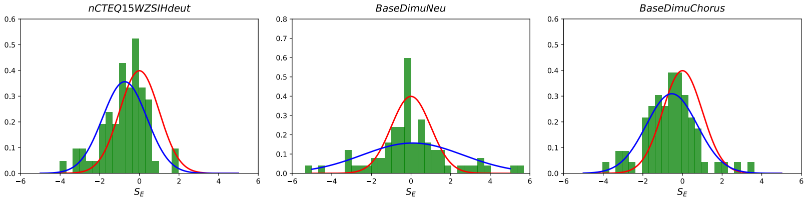
Normalization uncertainties: $\chi^2_r(a, r) = \sum_{i,j}(D_i - rT_i)C^{-1}_{ij}(D_j - rT_j) + \frac{(1-r)^2}{\sigma^2_{norm}}$

Correlations included, gluon parameters fixed.

Compatibility of neutrino DIS data (rev.)

K.F. Muzakka, MK et al. [nCTEQ Coll.], submitted to Phys. Rev. D [2204.13157]

For each experiment: $S_E(\chi^2_E(N_E), N_E) = \sqrt{2\chi^2_E(N_E)} - \sqrt{2N_E - 1}$



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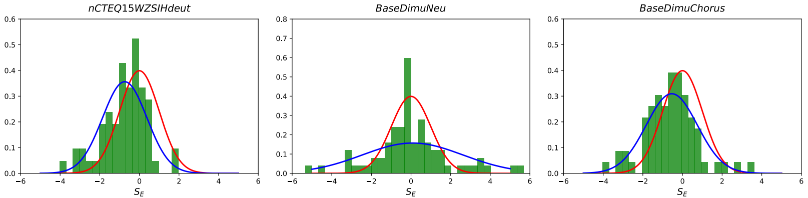

Compatibility assessment:

Analysis name	χ^2_S/N	χ^2_S/pt	$\chi^2_{\bar{S}}/N$	$\chi^2_{\bar{S}}/pt$	$\Delta\chi^2_S$	$\Delta\chi^2_{\bar{S}}$	$p_S/p_{\bar{S}}$
nCTEQ15WZSIHdeut	735/940	0.78	-	-	0	-	0.500 / -
DimuChorus	-	-	1059/974	1.09	-	0	- / 0.500
BaseChorus	737/940	0.78	969/824	1.18	2	-	0.530 / -
BaseCDHSW	778/940	0.83	584/929	0.63	43	-	0.895 / -
BaseCCFR	815/940	0.87	2119/2207	0.96	80	-	0.989 / -
BaseNuTeV	807/940	0.86	3049/2136	1.43	72	-	0.981 / -
BaseNuTeVU	787/940	0.84	1984/2136	0.93	52	-	0.933 / -
BaseDimuNeuU	861/940	0.92	5569/5689	0.98	126	-	0.99978 / -
BaseDimuNeuX	781/940	0.83	5032/4644	1.08	46	-	0.908 / -
BaseDimuChorus	740/940	0.79	1117/974	1.15	5	58	0.559 / 0.885

Consistent global fits with neutrino DIS data?

K.F. Muzakka, MK et al. [nCTEQ Coll.], submitted to Phys. Rev. D [2204.13157]

BaseDimuNeuU:

- Exclude NuTeV correlations
- Unpublished, may have underestimated systematic uncertainty
- Neutrino data better described, but tension with NC remains

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- Nuclear shadowing might be different in CC and NC
- Barely consistent with baseline ($\Delta\chi^2 = 46 > 45$)

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BaseDimuChorus:

- Include only dimuon and Chorus data
- All data well described

Impact of neutrino DIS data

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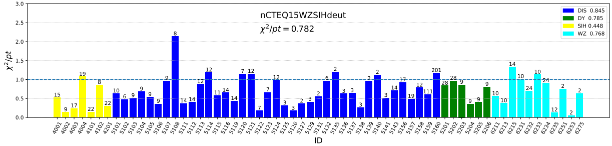
Baseline:



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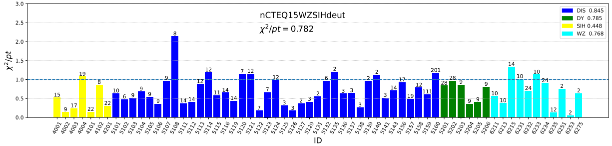
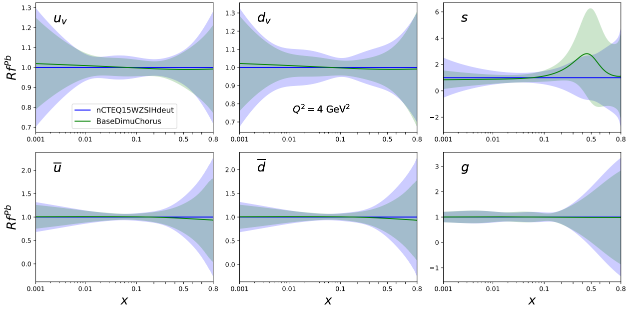


Impact on lead PDFs:



Conclusions and Outlook

Wealth of LHC heavy quark and quarkonium data:

- Well described by data-driven approach
- Validated with NLO NRQCD and GM-VFNS
- Constrain gluon down to $x = 10^{-5}$, very small uncertainty

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- Well described by data-driven approach
- Validated with NLO NRQCD and GM-VFNS
- Constrain gluon down to $x = 10^{-5}$, very small uncertainty

Wealth of fixed-target neutrino data (high statistics, older):

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- Reanalysis with improved baseline, three compatibility criteria
- Three proposed solutions, only one (DimuChorus) really works
- Neutrino data constrain in particular the strange quark

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Outlook:

- Many individual nCTEQ analyses (also HIX, more coming)
- Must and will be combined → nCTEQ22 release this year
- More LHC data (jets, photons), update proton, NNLO etc.