WWU MÜNSTER

isoQuant SFB1225

nCTEQ
nuclear parton distribution functions

nCTEQ global analysis of nuclear PDFs

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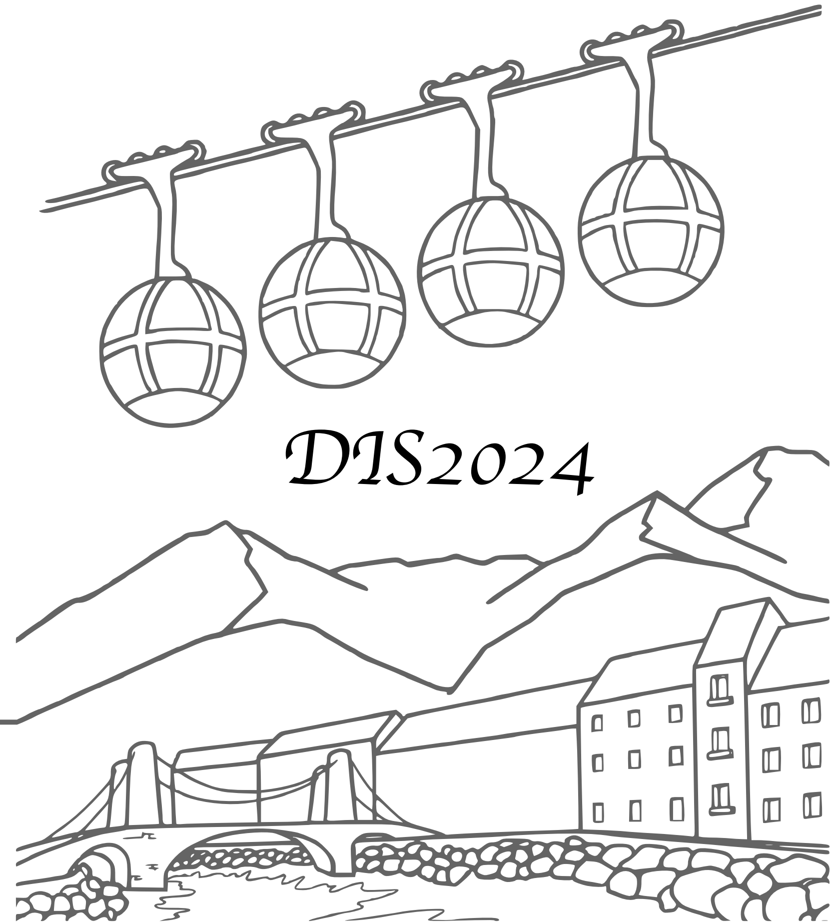
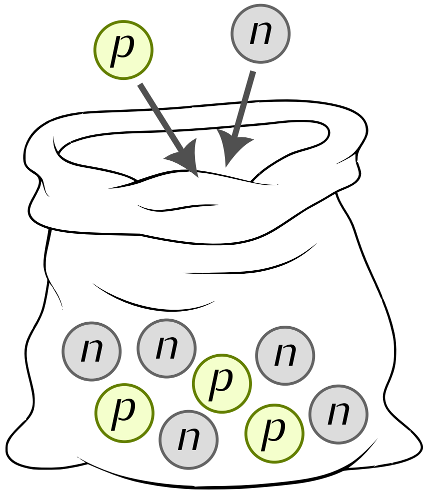


Structure of nuclei

- Nuclei made up of protons and neutrons ...

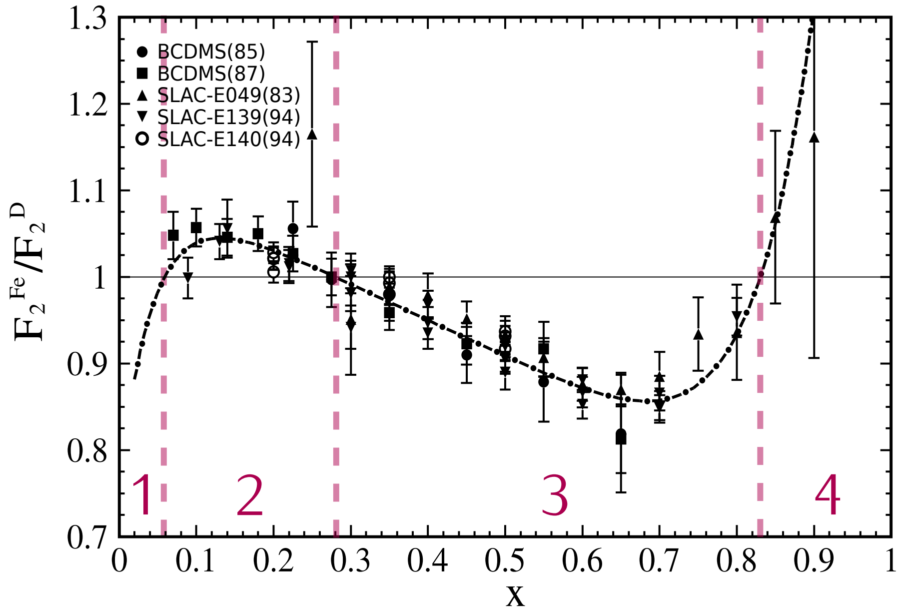


- Free nucleon approximation

$$Af^A \approx Zf^p + Nf^n$$

Structure of nuclei

- Nuclear modification:



- ▸ 1 shadowing
- ▸ 2 anti-shadowing
- ▸ 3 EMC effect
- ▸ 4 Fermi motion

- ▸ Underlying dynamics still to be fully theoretically understood
- ▸ Can be parametrized and incorporated into nuclear structure determinations

Theoretical framework: collinear factorization

- We rely on collinear factorization

$$d\sigma_{pp\to c} = \sum_{a,b} f_{p\to a}(x_a,\mu)\otimes f_{p\to b}(x_b,\mu)\otimes d\hat{\sigma}_{ab\to c}(\mu)$$
$$\mu \gtrsim 1\ \text{GeV}, x\in(0,1)$$

- With μ: factorization scale, x: fraction of parton $a(b)$ momentum in proton p

- Hard cross section $d\hat{\sigma}_{ab\to c}(\mu)$
  - Process specific
  - Calculable in perturbative QCD (pQCD)

- Parton Distribution Functions (PDFs) $f_{p\to a}(x,\mu)$
  - Universal
  - Not calculable from first principles (not yet)

- Similarly for lp, νp and one-particle inclusive[a] processes

[a]May involve second factorization scale and convolution with fragmentation functions.

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Theoretical framework: PDFs

- We rely on collinear factorization
- PDF x dependence not calculable in pQCD
  - Constrained through *number*...

$$\int_0^1 dx[\underbrace{f_u(x) - f_{\bar{u}}(x)}_{u-\text{valence distr.}}] = 2 \qquad \int_0^1 dx[\underbrace{f_d(x) - f_{\bar{d}}(x)}_{d-\text{valence distr.}}] = 1$$

$$\int_0^1 dx[f_s(x) - f_{\bar{s}}(x)] = \int_0^1 dx[f_c(x) - f_{\bar{c}}(x)] = 0$$

  - ...and *momentum* sum rules

$$\sum_{i=q,\bar{q},g} \int_0^1 dx\, x f_i(x) = 1$$

Theoretical framework: PDFs

- We rely on collinear factorization
- PDF x dependence not calculable in pQCD
- PDF μ dependence governed by DGLAP evolution equations

$$\frac{\mathrm{d}}{\mathrm{d}\log\mu^2} f_q(x,\mu^2) \sim (P_{qq}\otimes f_q)(x,\mu^2) + (P_{qg}\otimes f_g)(x,\mu^2)$$
$$\frac{\mathrm{d}}{\mathrm{d}\log\mu^2} f_g(x,\mu^2) \sim (P_{gg}\otimes f_g)(x,\mu^2) + (P_{gq}\otimes f_q)(x,\mu^2)$$

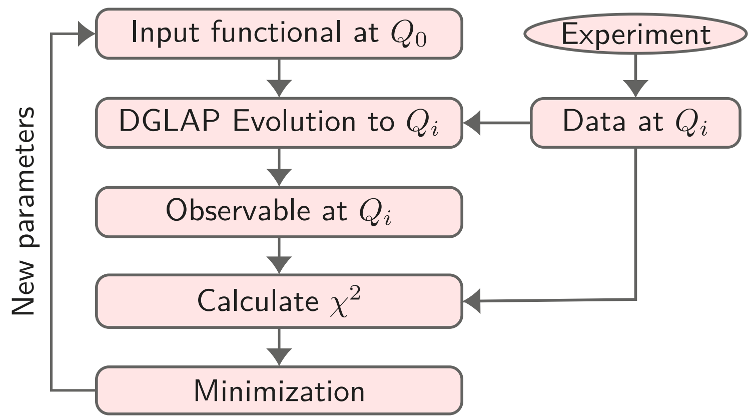
  - Describe violations of Bjorken x scaling
  - Flavours mix: set of $(2n_f+1)$ coupled integro-differential equations.

Theoretical framework: PDFs

- PDF x dependence extracted from data[a]
  - assume parametrization[b] in x at a chosen input scale Q_0:

$$xf_i(x, Q_0) = N(1-x)^{p_{i,1}} x^{p_{i,2}} P(x, p_{i,3}, \dots)$$

  - set $p_{i,j}$, calculate theoretical predictions, compare to data, iterate:



$$\chi^2 = \sum_{ij}^{N} (D_i - T_i)(C^{-1})_{ij}(D_j - T_j)$$

[a] Calculable in lattice QCD in near future?

[b] NNPDF collaboration use NN to avoid parametrization bias.

Theoretical framework: nuclear PDFs

- Nuclear modification can be incorporated into PDF determinations
  - Introduce the notion of bound PDF for flavour i: $f_i^{p/A}(x,\mu,A)$, with A-dependent x parametrization at Q_0
  - $x \in (0,A)$, but $x > 1$ region typically negligible
  - $f_i^{p/A}$ fulfils the usual evolution equations and sum rules
  - $f_i^{n/A}$ from isospin symmetry, i.e. $f_{d,u}^{n/A} = f_{u,d}^{p/A}$

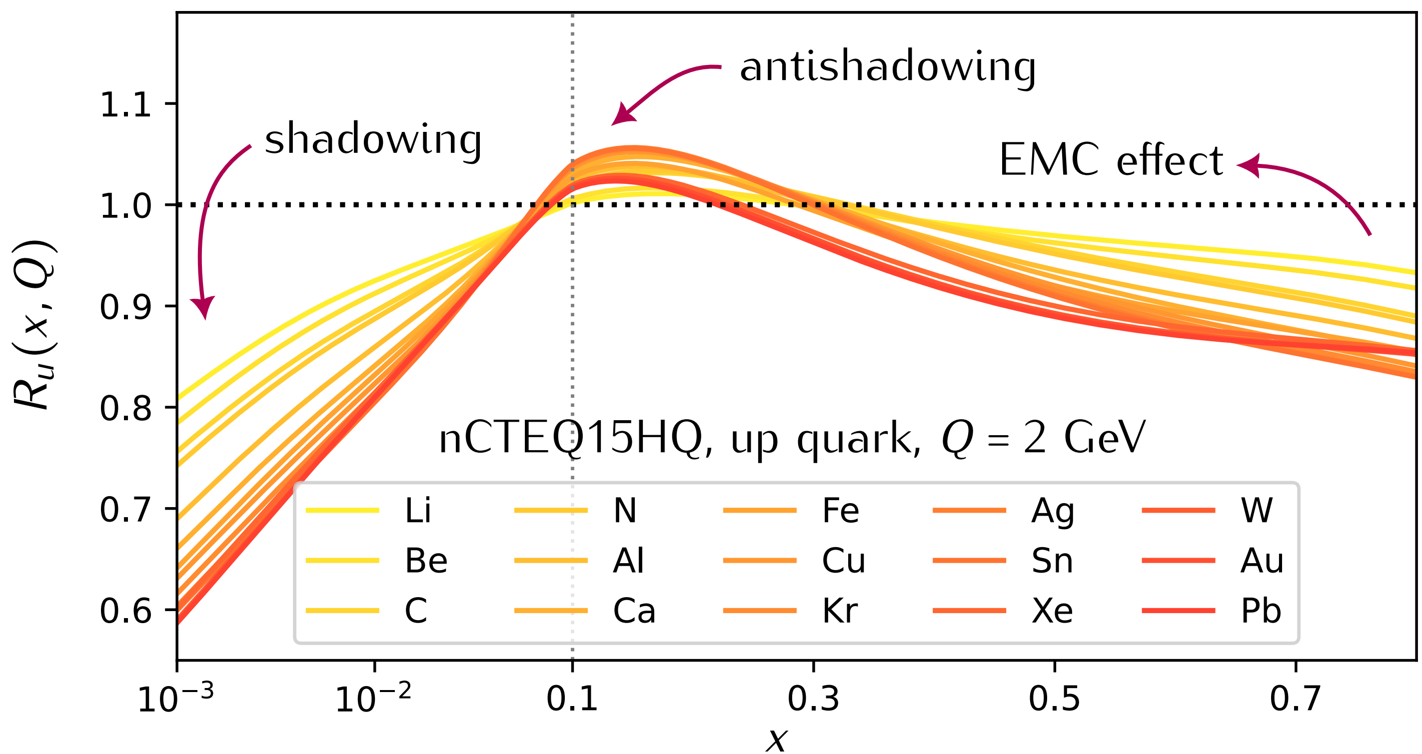
$$f_i^{(A,Z)}(x,\mu) = \frac{Z}{A} f_i^{p/A}(x,\mu,A) + \frac{A-Z}{A} f_i^{n/A}(x,\mu,A)$$

  - $f_i^{(A,Z)}$ replaces f_i^p in the factorization formula[a]

[a] Proof of factorization for collisions of nuclei not yet available.

Theoretical framework: nuclear PDFs

- Dependence on A



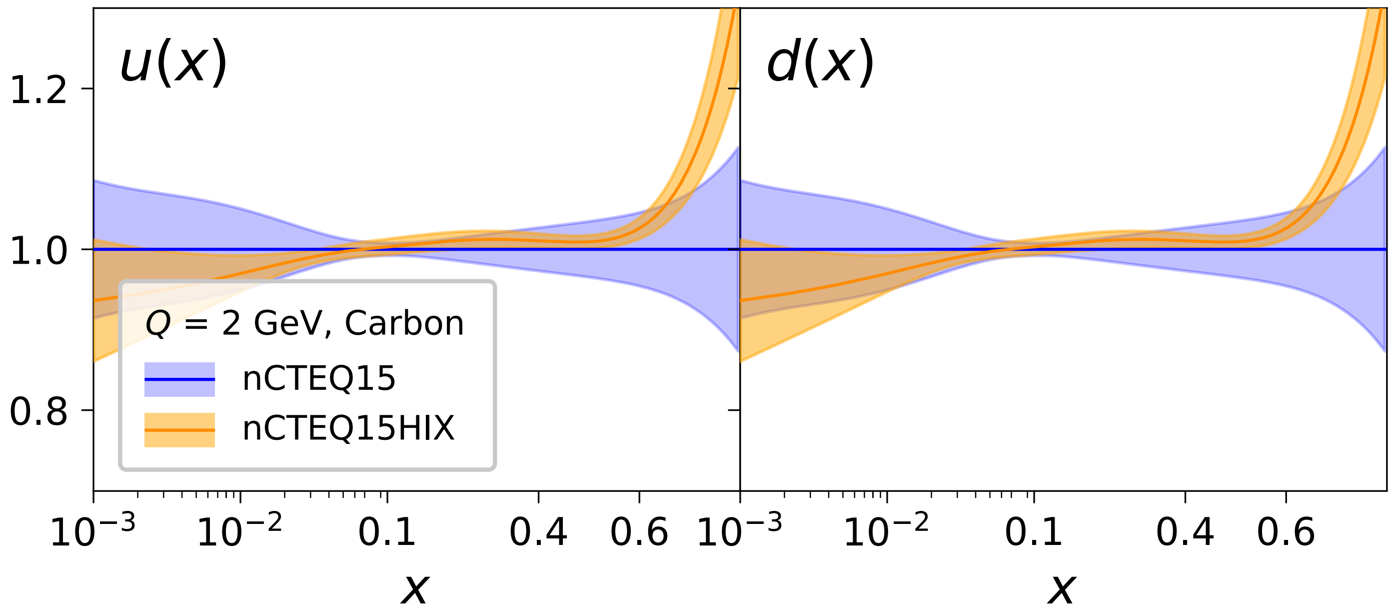
From nCTEQ15 onwards

- nCTEQ15
  - mostly NC DIS, some FT DY, a handfull of SIH (740 pts)
- nCTEQ15 upgrades
  - nCTEQ15WZ ('20): + LHC W/Z data (+120 pts)
  - nCTEQ15HIX ('20): + JLAB NC DIS data (+336 pts) + relaxed cuts
  - nCTEQ15WZSIH ('21): + LHC W/Z and SIH data (+120+112 pts)
  - nCTEQ15HQ ('22): + LHC W/Z + HQ data (+120+548 pts)
  - nCTEQ15NU[a] ('22): + LHC W/Z + SIH data + CC DIS (+120+112+974 pts)
- upcoming nCTEQ global analysis
  - combines upgrades above
  - LHC W/Z, JLAB NC DIS, SIH, HQ, CC DIS (over 3000 pts)
  - relaxed kinematic cuts, TMCs ('23), deuteron corrections, ...

[a] BaseDimuChorus

Valence

- nCTEQ15HIX includes very precise JLAB Class and Hall-C data
  - and explores impact of TMCs, HT, deuteron correction, high-x rescaling



[2012.11566]

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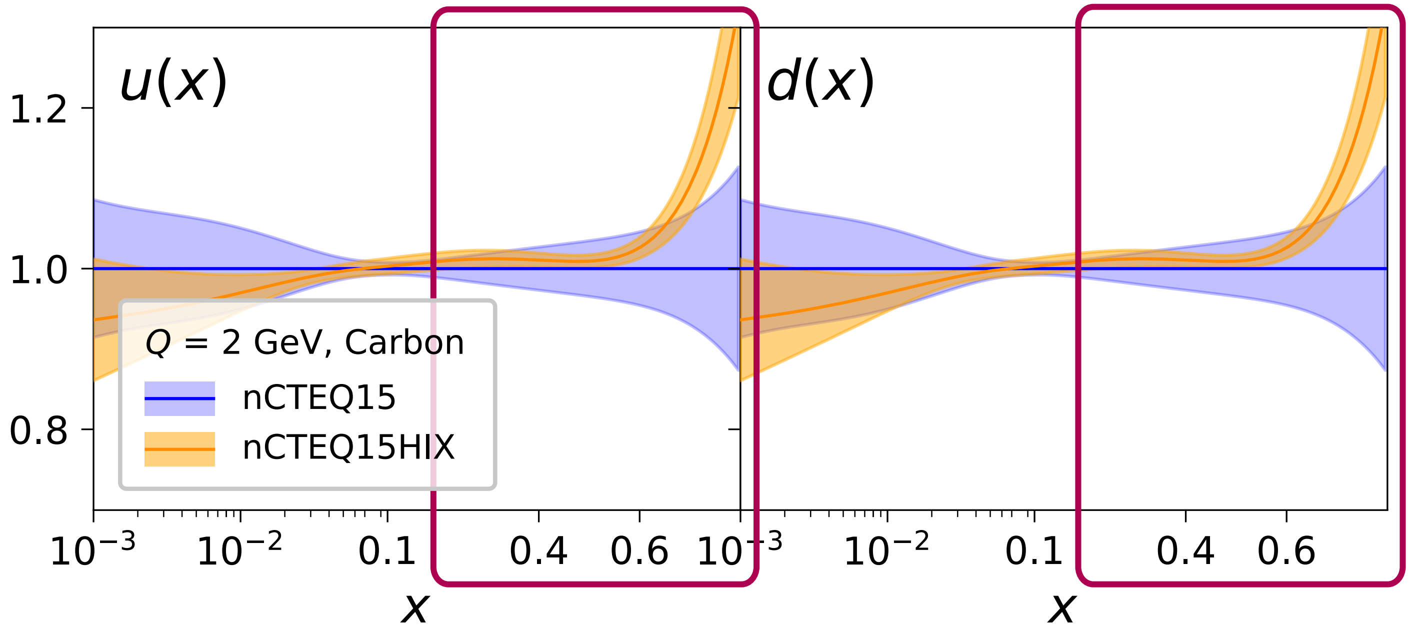
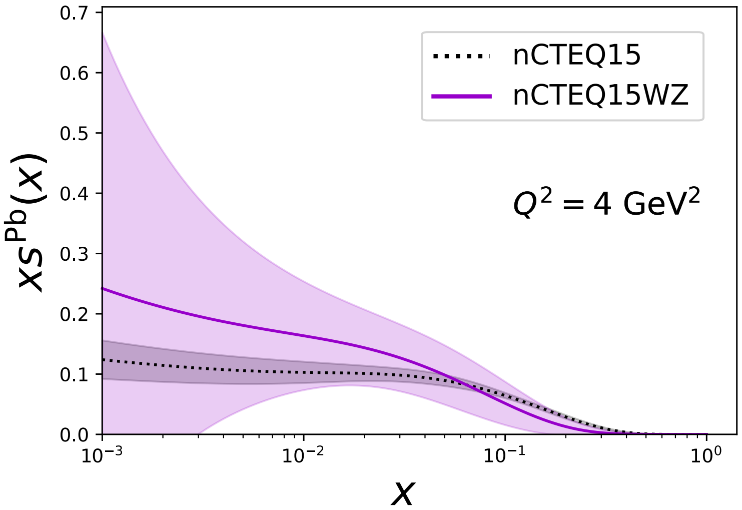


[2012.11566]

Strange

- nCTEQ15WZ includes LHC W/Z data
  - first realistic uncertainties
- nCTEQ15NU[a] also adds CC DIS data
  - neutrino data provides further constraints down to low-x



[2007.09100]

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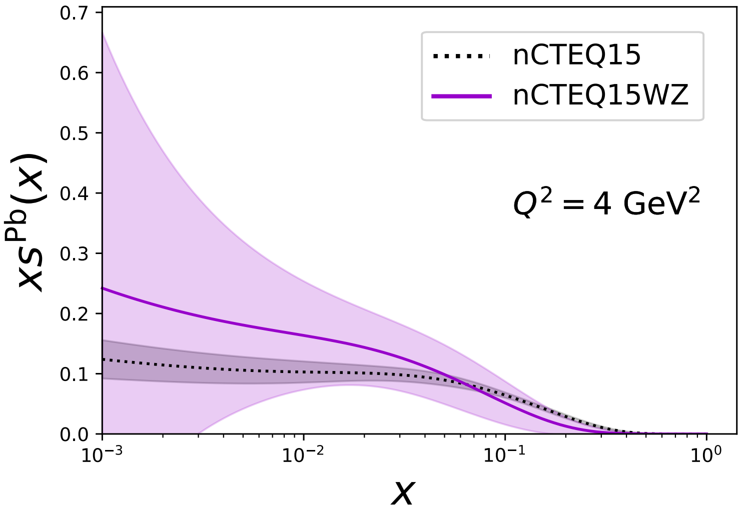
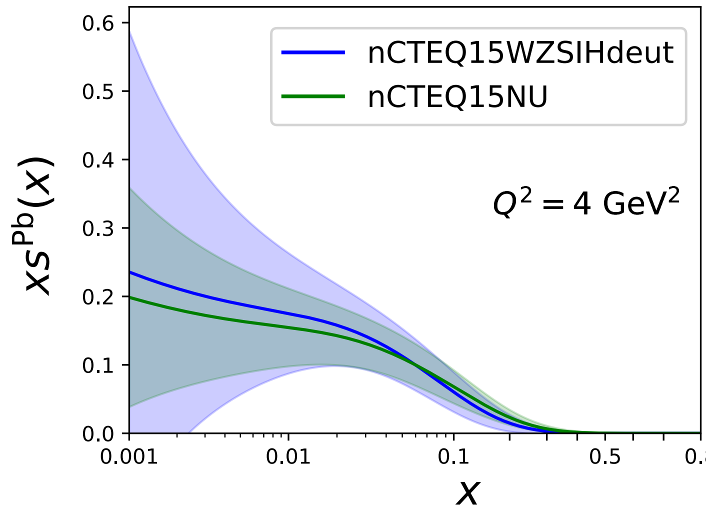


[2007.09100]

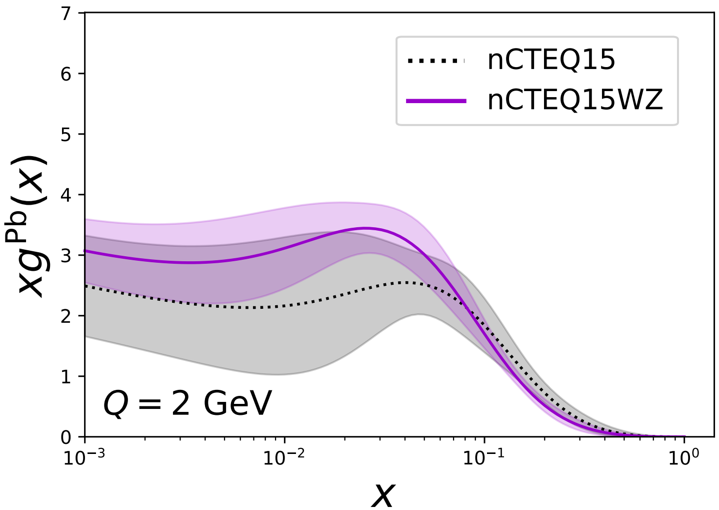


[2204.13157]

[a] BaseDimuChorus

Gluon

- nCTEQ15WZ includes LHC W/Z data
  - also constrain gluon
- nCTEQ15HQ also adds quarkonium and open HQ data
  - unprecedentend low-x reach



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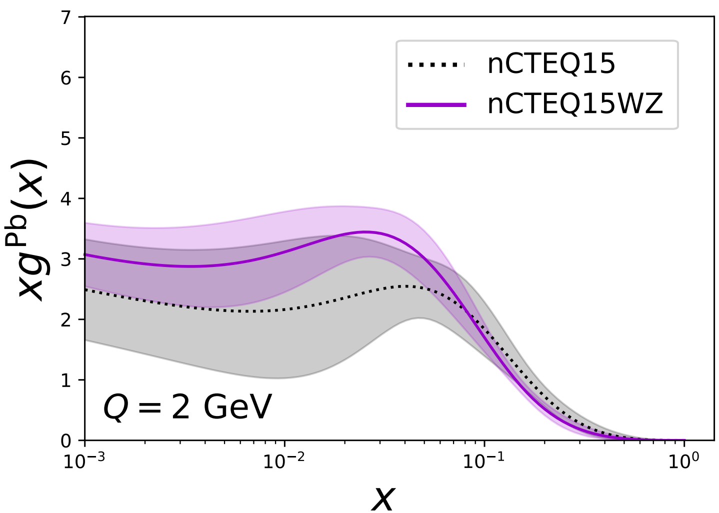
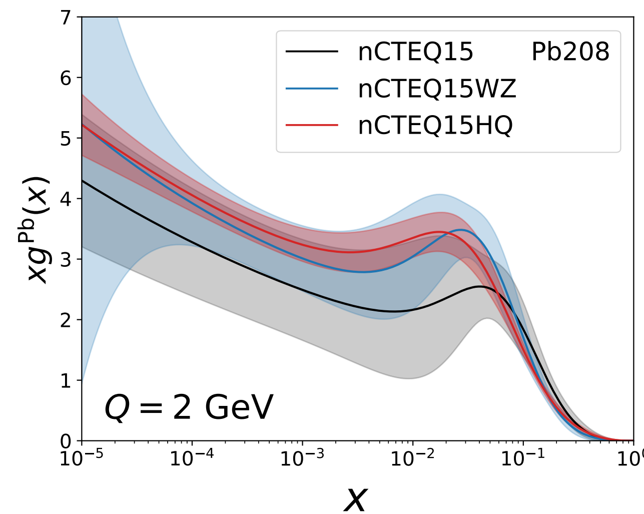


[2007.09100]



[2204.09982]

Combined global analysis

- We[a] combine all our past efforts into a global analysis
  - Include all data considered so far + bonus W/Z and HQ data
    - NC & CC DIS, FT DY, LHC W/Z, SIH, HQ
  - Extend the Q and W cuts from (2,3.5) GeV to (1.3,1.7) GeV (over 3000 pts)
  - Upgrade our proton baseline to CJ22
  - Synchronize our input scale parametrization with CJ22
    - with finetuned A-dependence

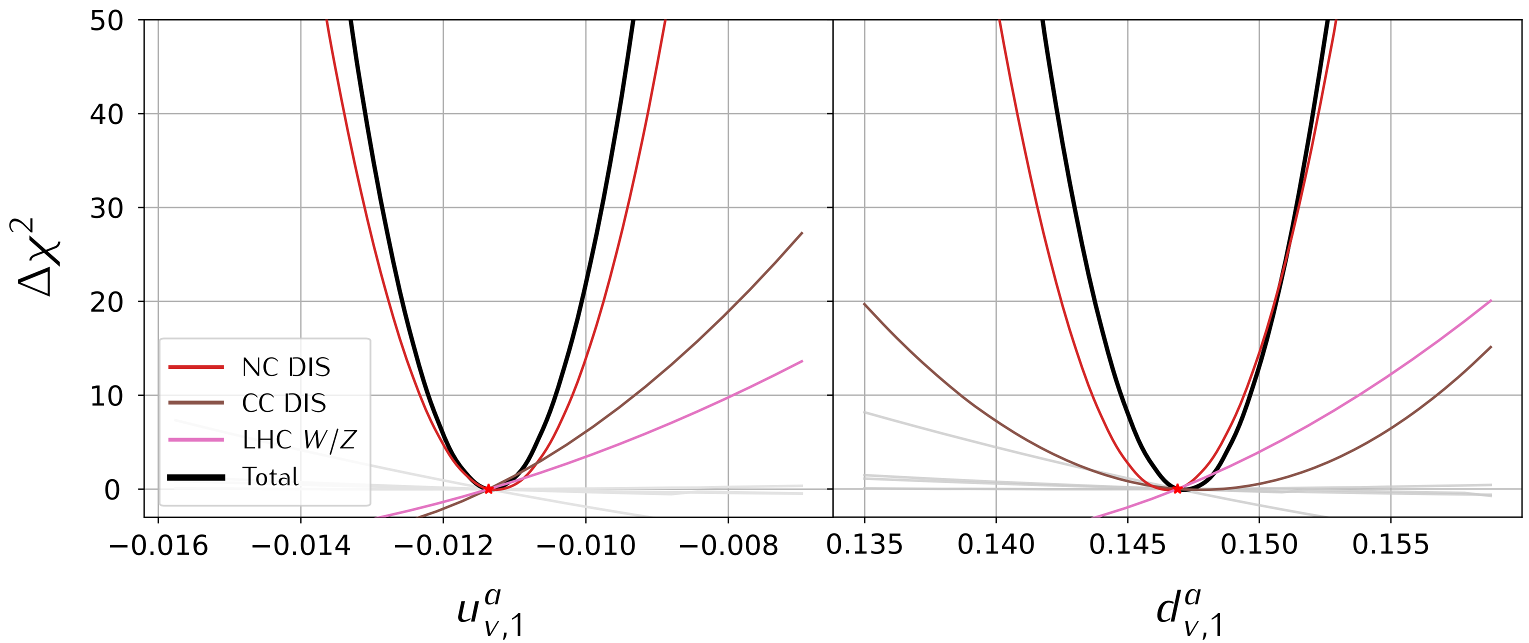
$$c_j(A) = p_j + a_j(1 - A^{-b_j}) \quad \Rightarrow \quad c_j(A) = p_j + a_j \ln A + b_j \ln^2 A$$

  - Further setup
    - NLO QCD, SACOT-χ, Open 31 parameters, Hessian with tolerance, deuteron correction & higher twist (CJ22), TMCs, ...

[a] nCTEQ collaborators: Accardi, Derakhshanian, Duwentäster, Greve, **TJ**, Keppel, Klasen, Kovařík, Kusina, Leger, Morfín, Muzakka, Olness, Owens, Risse, Ruiz, Schienbein, Wissmann, Yu

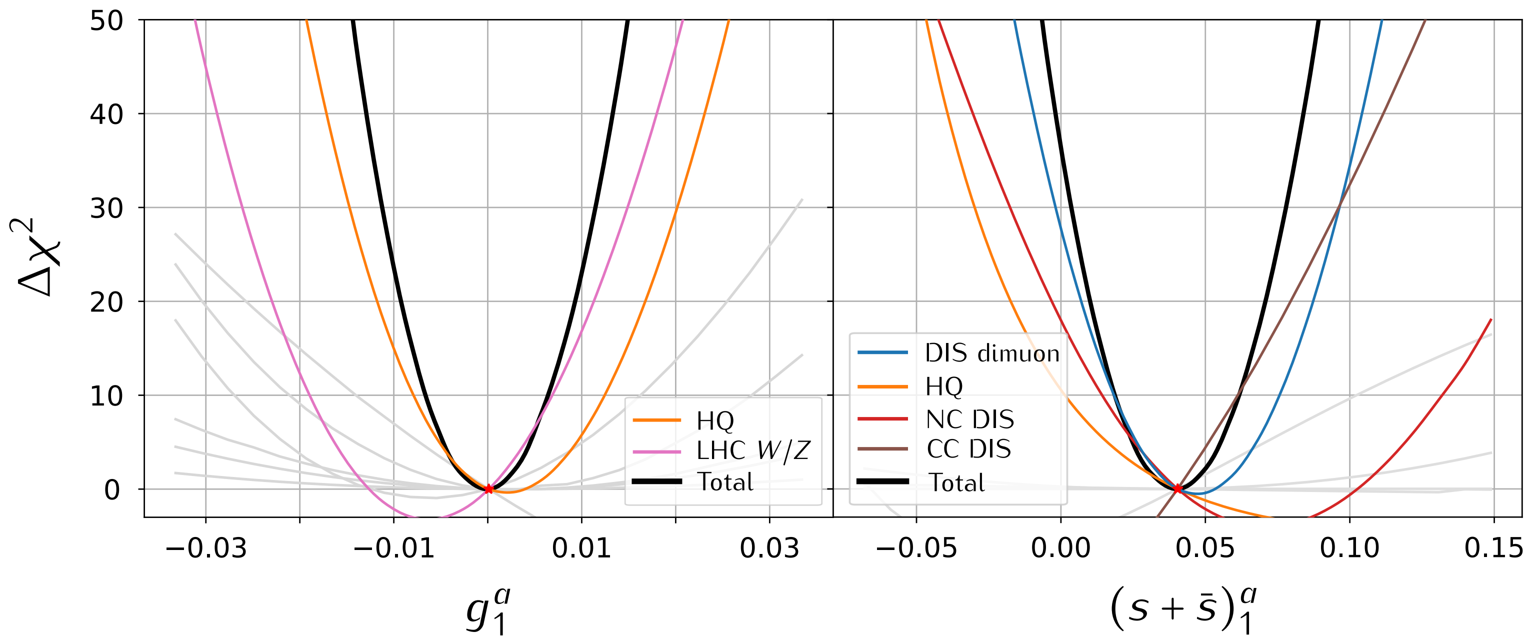
Data constraints

- Valence parameters constrained mostly by DIS



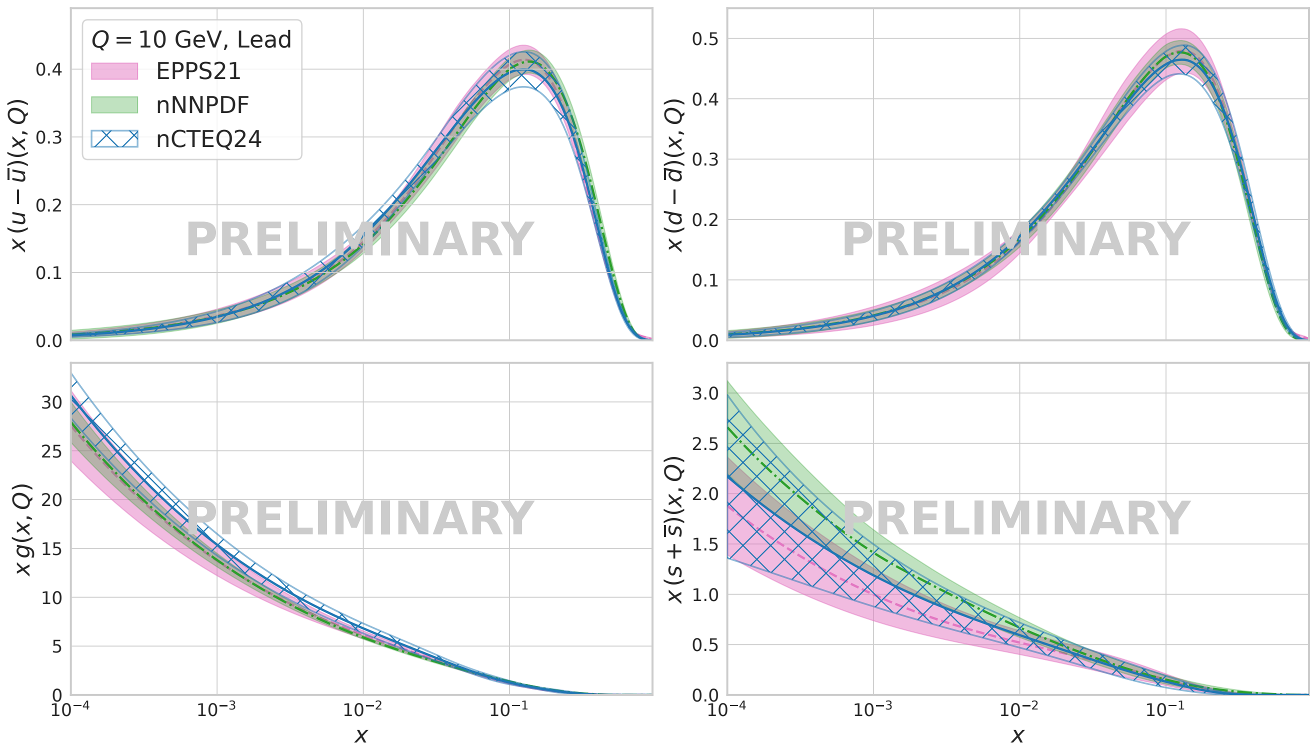
Data constraints

- Gluon constrained by HQ and W/Z production
- Strange is a compromise between DIS, DIS dimuon and HQ



Preliminary results

- Good agreement between EPPS, nNNPDF and nCTEQ
- nCTEQ: slightly different valence uncertainties and a higher gluon

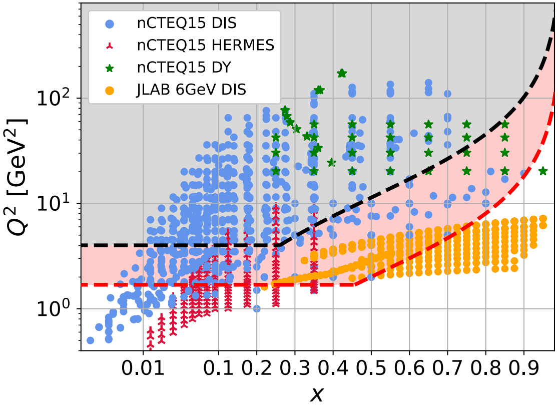


Summary

- Reviewed nCTEQ setup for nuclear PDF extractions
  - full PDF (nCTEQ) vs. nuclear modification ratio (EPPS)
  - fixed functional form + Hessian (nCTEQ) vs. NN + replicas (nNNPDF)
- Reviewed our recent efforts
  - nCTEQ15WZ ('20): first look at gluon and strange
  - nCTEQ15HIX ('20): high-x ($x > 0.1$) valence
  - nCTEQ15WZSIH ('21): improvements to gluon
  - nCTEQ15HQ ('22): gluon down to very low-x ($x \to 10^{-5}$)
  - nCTEQ15NU[a] ('22): realistic strange
- Outlined how the upgrades are being combined into a new global analysis with preliminary comparisons to EPPS and nNNPDF

[a] BaseDimuChorus

Cuts



- Old cuts: $Q = 2$ GeV/ $Q^2 = 4$ GeV^2 $W > 3.5$ GeV,
- new cuts: $Q = 1.3$ GeV / $Q^2 = 1.69$ GeV^2 $W > 1.7$ GeV

no. of data points nCTEQ15	no. of data points nCTEQ24
708	3371

credit K. Greve

Settings $\rightarrow$ Parameterization

Short reminder:
CJ22/nCTEQ24 [2]:

$$xf_k^{p/A} = c_0^k x^{c_1^k}(1-x)^{c_2^k}(1 + c_3^k\sqrt{x} + c_4^k x)$$

where $k = u_v,\ \bar{u}+\bar{d},\ \bar{u}-\bar{d},\ g,\ s+\bar{s}$

$$c_j(A) \rightarrow p_j + a_j \ln A + b_j \ln^2 A$$

Rescaling:

$(1-x)^{c_2^k} \rightarrow (1-x+\epsilon)^{c_2^k}$ with $\epsilon = cx^{\kappa} \ln A$

Special parameterization for d_v:

$$xd_v = c_0(x^{c_1}(1-x)^{c_2}(1 + c_3\sqrt{x} + c_4 x) + c_5 x^{c_6} x u_v)$$

And no strange asymmetry: $x(s-\bar{s}) = 0$

Compared to nCTEQ15[3]:

$$xf_k^{p/A} = c_0^k x^{c_1^k}(1-x)^{c_2^k} e^{c_3 x}(1 + e^{c_4^k} x)^{c_5^k}$$

where $k = u_v, d_v,\ \bar{u}+\bar{d},\ g,\ s+\bar{s},\ s-\bar{s}$

$$c_j(A) \rightarrow p_j + a_j(1 - A^{-b_j})$$

Rescaling:

– – –

Special parameterization for $\bar{d}/\bar{u}$:

$$\frac{\bar{d}}{\bar{u}} = c_0 x^{c_1}(1-x)^{c_2} + (1 + c_3 x)(1-x)^{c_4}$$

credit K. Greve

Settings → Parameterization

Open in the presented Fit:

xu_v : $a_1,\ a_2, a_3,\ a_4,\ b_1$

xd_v : $a_1,\ a_2, a_3,\ a_4,\ a_5, b_1,\ b_2$

$x(\bar{d}+\bar{u})$: $a_0,\ a_1, a_2,\ a_4, b_1,\ b_3,\ b_4$

$x(s+\bar{s})$: $a_1, a_2,\ a_4$ plus $\kappa : a_0$

xg : $a_1,\ a_2, a_3,\ a_4,\ b_1,\ b_2$

$x(\bar{d}-\bar{u})$: $a_1,\ a_2$

$\rightarrow \Sigma$ 31 Parameters

Open in nCTEQ15 [3]:

xu_v : $a_1,\ a_2, a_4,\ a_5$

xd_v : $a_1,\ a_2,\ a_4$

$x(\bar{d}+\bar{u})$: $a_1,\ a_5,$

xg : $a_1,\ a_4,\ a_5,\ b_0,\ b_1,\ b_4,\ b_5$

$x(\bar{d}/\bar{u})$: − − − −−

$x(s+\bar{s})$: − − − − − −

$\rightarrow \Sigma$ 15 Parameters

credit K. Greve