Nuclear PDFs with νDIS data: A compatibility analysis from nCTEQ

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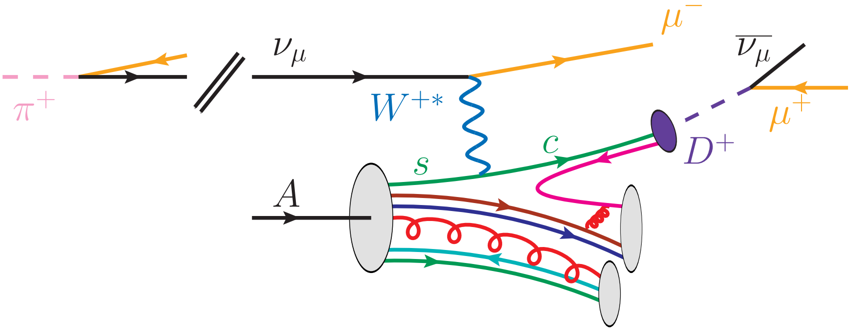
[1] w/ Muzakka, Kovařík, et al (nCTEQ Collaboration) [2204.13157]

Thank you for the invitation!

motivation for neutrino deeply inelastic scattering (νDIS)

Motivation (1/2)

νDIS probes flavor composition of sea (anti)quarks in hadrons and valence quarks through F_3



e.g., charm dimuon $\nu A \to \mu D + X \to \mu\mu + X'$

Motivation (2/2)

νDIS probes parity violation in hadronic structure functions

$$W^{A}_{\mu\nu}(p_A, q) = \frac{1}{4\pi}\int d^4z\ e^{iq\cdot z}\ \langle A|J^{\dagger}_{\mu}(z)\ J_{\nu}(0)|A\rangle$$

$$= -g_{\mu\nu}\ F_1 + \frac{p_{A\mu}p_{A\nu}}{Q^2}\ 2x_A\ F_2 - \boxed{i\epsilon_{\mu\nu\rho\sigma}\frac{p_A^{\rho}q^{\sigma}}{M_A^2}\ x_A F_3}$$

$$+ \frac{q_\mu q_\nu}{Q^2}\ 2F_4 + \frac{p_{A\mu}q_\nu + p_{A\nu}q_\mu}{Q^2}\ 2x_A\ F_5 + \frac{p_{A\mu}q_\nu - p_{A\nu}q_\mu}{Q^2}\ 2x_A\ F_6\ .$$

F_3 term nonzero when parity is violated, i.e., the weak force

(νDIS not dominated by γ exchange)

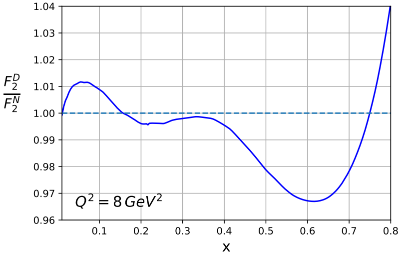
the part no one likes to talk about

ν scattering experiments are hard

· ν only interact through the weak force:
intense ν beams require even more intense beams of unstable particles

Plotted: $\frac{F_2^{\text{deuteron}}}{F_2^{\text{proton}}+F_2^{\text{neutron}}}$ for ℓ-DIS

· ν only interact through the weak force:
targets must be bigger ($\mathcal{O}(10)$tons), denser (Pb,Fe) $\implies$ more nuclear



· fact of life:
dynamic nuclear structure impacts sensitivity to hadronic structure $\implies$

[2204.13157]

For non-expert, QED (γ) contribution to F_2: $F_2(\xi) \approx \sum_{i\in\{q,\overline{q},g\}} Q_i^2\ \xi\ f_i^A(\xi)$, Q_i=electric charge of i

what exactly did the nCTEQ collaboration do?

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revisited the role of νDIS data in nPDF fits

the setup

nPDF Fitting Framework (the big picture)

1. For nucleus (A, Z), parametrize nuclear PDF $f_i^A(x,\mu)$ as combination of effective "bound-nucleon" PDFs (≈free+nuclear corrections)

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

2. Invoke isospin symmetry

$$f_i^{p/A}(x,\mu) \leftrightarrow f_j^{n/A}(x,\mu)$$

3. Parameterize (again) and fit to data:

$$x f_i^{p/A}(x,Q_0) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}\left(1+e^{c_4}x\right)^{c_5}$$

$$\frac{\bar{d}(x,Q_0)}{\bar{u}(x,Q_0)} = c_0 x^{c_1}(1-x)^{c_2} + (1+c_3)(1-x)^{c_4}$$

where the flavor index i runs over $i = u_v, d_v, g, \bar{u}+\bar{d}, s+\bar{s}, s-\bar{s}$

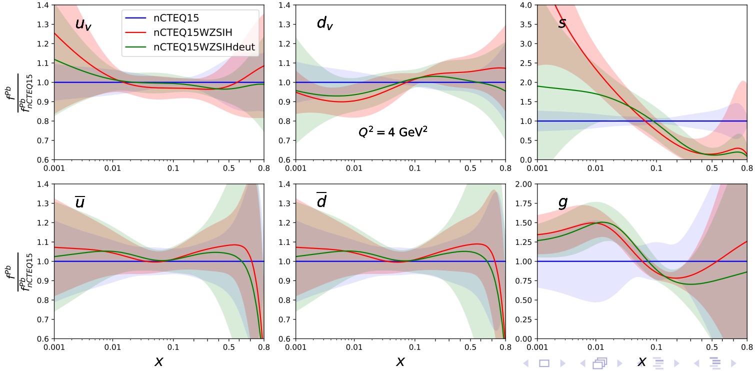
$$c_i(A,Z) = p_i + a_i(1-A^{-b_i})$$

Parametrization follows nCTEQ15 [1509.00792] and "free proton" part p_i fixed by proton PDF [hep-ph/0702159]

nPDF baseline

To quantify impact of νDIS data, introduce **nCTEQ15WZSIHdeut** PDF

- Start w/ **nCTEQ15WZSIH** (ℓ-DIS, LHC W/Z, LHC/RHIC single-inclusive hadron) [2105.09873]
- Remove $F_2^{\rm deuteron} \approx (F_2^{\rm proton} + F_2^{\rm neutron})$ corrections used for high-x fitting in **nCTEQ15HIX** [2012.11566]
- Add $F_2^{\rm deuteron}/(F_2^{\rm proton} + F_2^{\rm neutron})$ corrections



νDIS data sets

Inclusive DIS

✓ CDHSW – Fe [Z.Phys.C 49 (1991) 187-224]

✓ CCFR – Fe [hep-ex/0009041; U-K Yang (Thesis'01)]

✓ NuTeV – Fe [hep-ex/0509010]

✓ Chorus – Pb [Phys.Lett.B 632 (2006) 65-75]

× IceCube – Earth (x too small) [1711.08119]

× Minerva – many things (Q^2 too small) [1601.06313]

× NOMAD – many things (full data set never published ☹) [hep-ex/0602022; hep-ex/0602022]

Dimuon $\nu A \to \mu D + X \to \mu\mu + X'$

✓ CCFR/NuTeV [hep-ex/0102049]

☺ NOMAD [1308.4750]

☺ CDHS [Z.Phys.C 15 (1982) 19]

Kinematic cuts:

– $Q^2 > 4$ GeV^2

– $W^2 = m_p^2 + Q^2\frac{(1-x)}{x} > 12.25$ Gev^2

qualitative picture[2]

[2] see paper for hard numbers and in-depth quantitative assessment

First fit: DimuNeu (1/3) – only νDIS vs w/o νDIS

DimuNeu = **only** inclusive and semi-inclusive νDIS (bands = PDF uncertainties)

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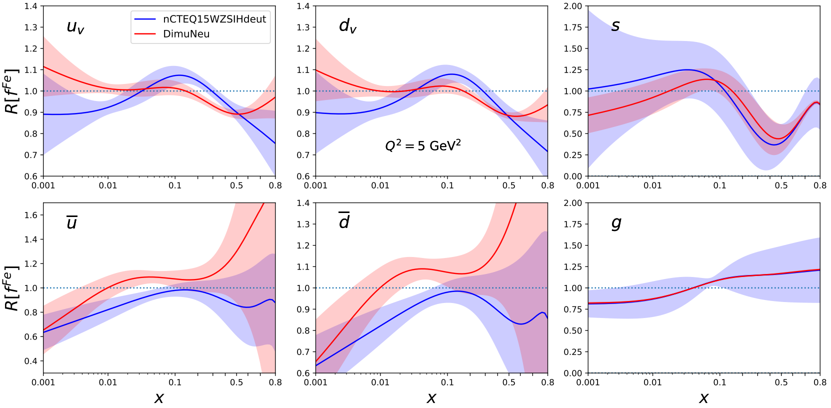
Plotted: ratio of bound-nucleon PDF to free-nucleon PDF on ^{56}Fe

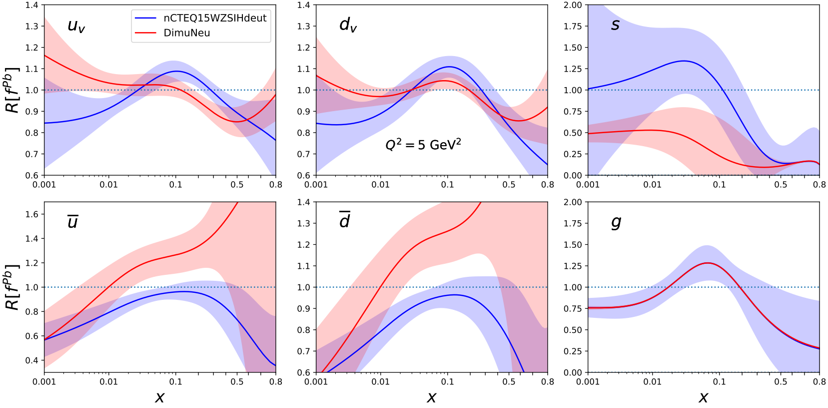


shape differences for valence and sea partons

First fit: DimuNeu (2/3)

DimuNeu = **only** inclusive and semi-inclusive νDIS

Plotted: ratio of bound-nucleon PDF to free-nucleon PDF on ^{208}Pb

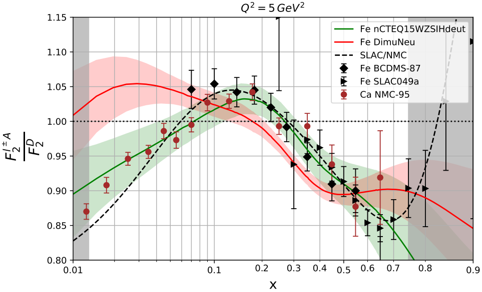


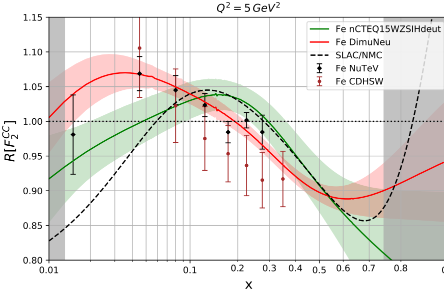
more differences

First fit: DimuNeu (3/3)

DimuNeu = **only** inclusive and semi-inclusive νDIS

Plotted: (L) $F_2^A/F_2^{\text{deuteron}}$ (neutral current ℓ-DIS) (R) F_2^A/F_2^{free} (charged current ℓ-DIS)





hints that fits differ at "low" x

Second fit: BaseDimuNeu (1/1) – w/ vs w/o νDIS

BaseDimuNeu = **DimuNeu** + **nCTEQ15WZSIHdeut** (bands = PDF unc.)

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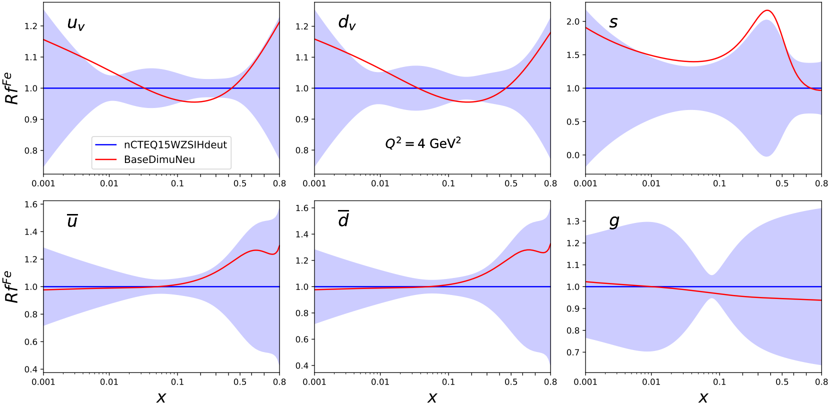
Plotted: ratio of **BaseDimuNeu** PDF to **nCTEQ15WZSIHdeut** on ^{56}Fe



tension largest for valence and strange content

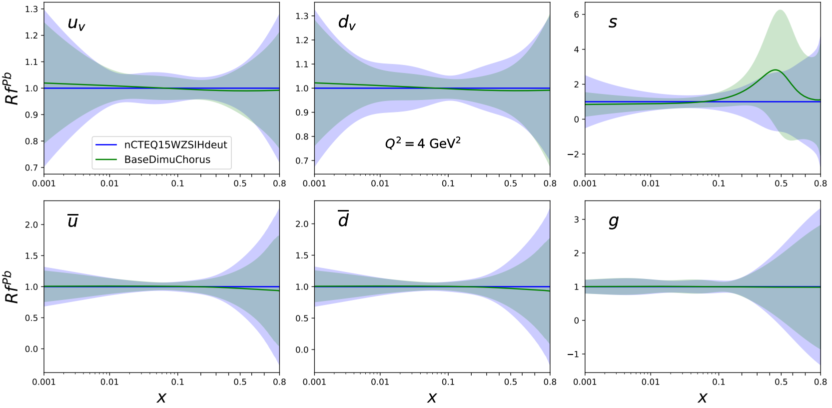
nth fit: BaseDimuChorus (1/1) – w/o vs w/ only νPb

BaseDimuChorus = **nCTEQ15WZSIHdeut** + Chorus

n^{th} fit: BaseDimuChorus (1/1) – w/o vs w/ only νPb

BaseDimuChorus = **nCTEQ15WZSIHdeut** + Chorus

Plotted: ratio of **BaseDimuChorus** PDF to **nCTEQ15WZSIHdeut**

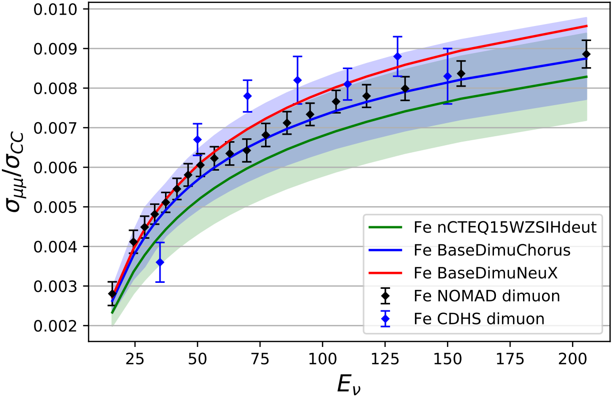


better agreement

outlook

NOMAD and CDHS data

Plotted: $\sigma_{\text{charm dimuon}} \,/\, \sigma_{\text{charged current}}$ ratio vs incoming E_ν



interesting agreement

summary

Summary and conclusion

The nCTEQ collaboration has revisited the role of νDIS data in nPDF fits

- **corroborate** previously reported tension in data and fits from different experiments / targets
- *many* different fits were **tried to explore compatibility**
- **find tension** w/ three Fe expts. but **compatibility** w/ one Pb expt.
- hope this work **guides future discussions**
- lots not covered (stats, more figures, more fits), so see the paper! [2204.13157]

Thank you!