Neutrino data for nuclear parton distribution determinations

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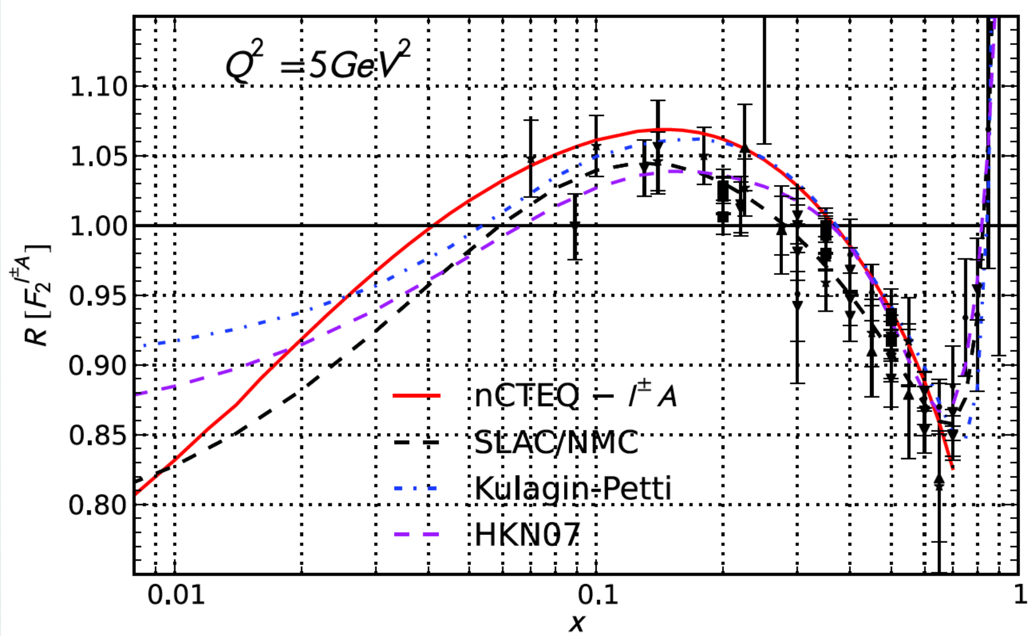
Introduction/Motivation

nPDFs and neutrino data

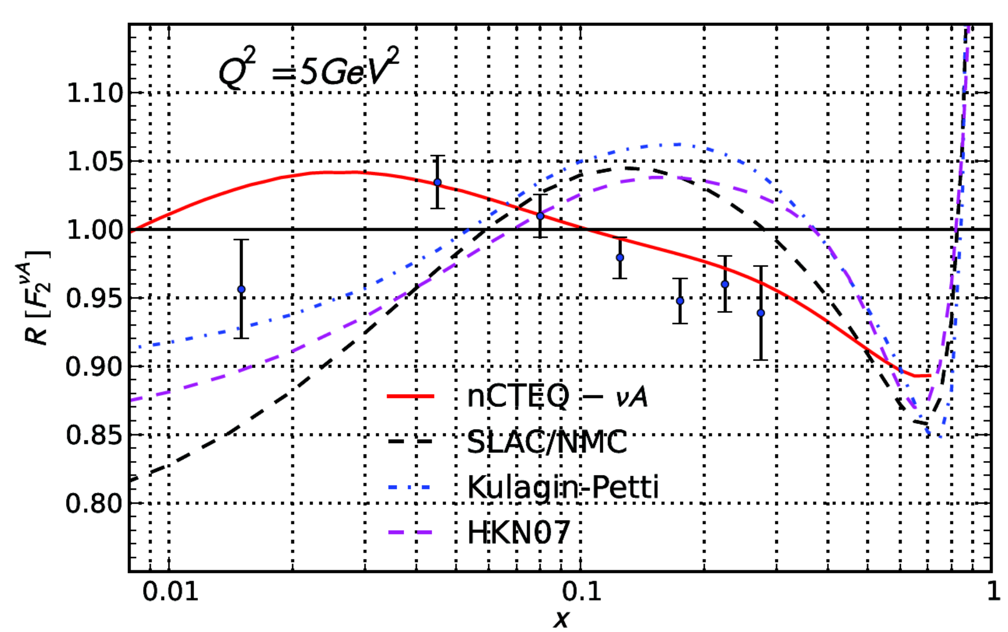
Neutrino deep inelastic scattering:

- Neutrino data important for many reasons: flavour separation of PDFs, ew precision physics, …
- Neutrino experiments use heavy nuclear targets: Pb, Fe, Ar, H_2O, C
- As discovered more than 30 years ago by the European Muon Collaboration, nucleon structure functions are modified by the nuclear medium (EMC effect)
- Studies of nucleon structure: need to correct for nuclear effects
- Are nuclear corrections in neutrino DIS the same as in charged lepton DIS?

Fit to $l^{\pm}A$ DIS and DY data
$\chi^2/\text{dof} = 0.89$



Fit to νA DIS data only
$\chi^2/\text{dof} = 1.33$



nPDFs and neutrino data

Neutrino deep inelastic scattering:

- Several studies have been performed:
  - "iron PDFs: PRD77(2008)054013
  - nCTEQ analysis of nuA+lA+DY data: PRL106(2011)122301
  - Differences independent of the proton baseline: Kalantarians, Keppel, PRC96(2017)032201
  - Ultimate analysis: "Compatibility of Neutrino DIS data and its Impact on Nuclear Parton Distribution Functions", **arXiv:2204.13157 [This talk]**

Fit to $l^{\pm}A$ DIS and DY data

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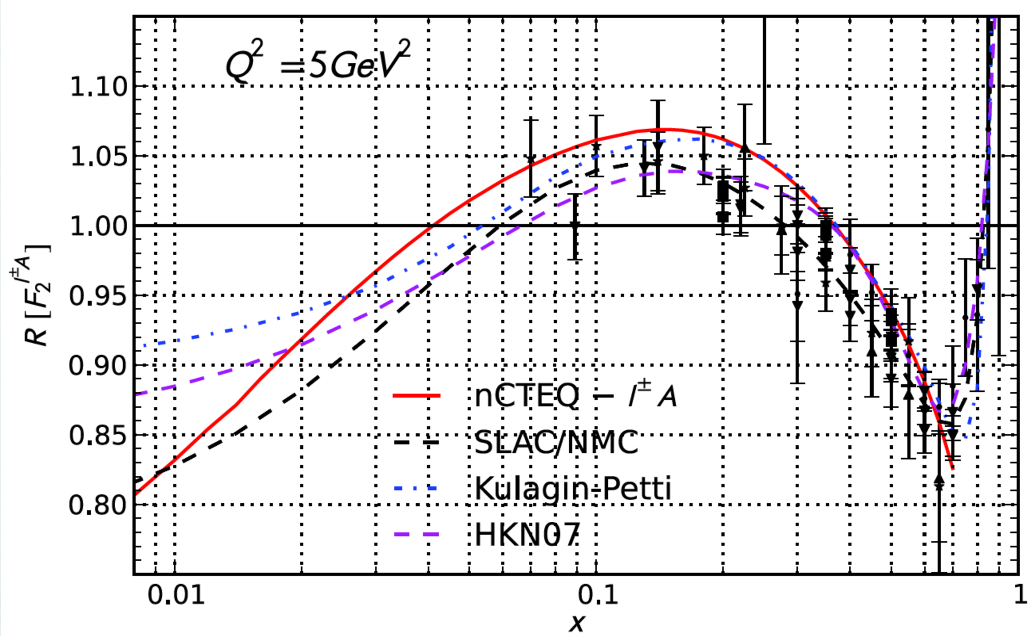

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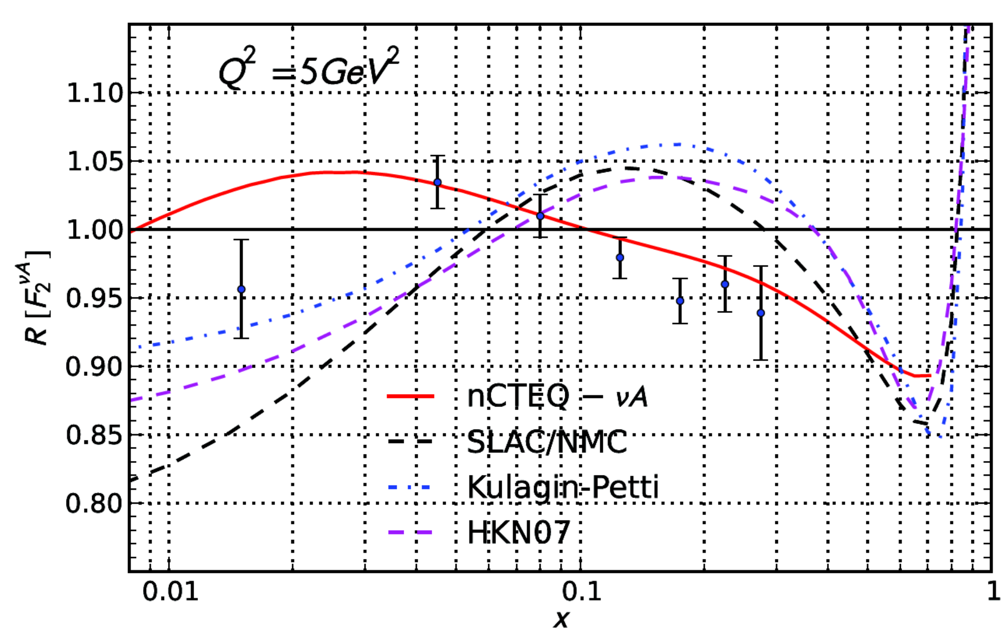


Compatibility of neutrino DIS data and its Impact on NPDFs

arXiv:2204.13157

nCTEQ global analysis framework

- Twist-2 collinear factorisation based on QCD factorisation theorems
- Hard processes perturbatively calculable
- Universal nuclear PDFs
- Parameterization of NPDFs at the initial scale $Q_0 = 1.3$ GeV ($i = u_v, d_v, g, \bar{u}+\bar{d}, s+\bar{s}, s-\bar{s}$)
- Scale-dependence of NPDFs by DGLAP evolution
- Sum rules

DIS $F_2^A(x,Q^2) = \sum_i [f_i^A \otimes C_{2,i}](x,Q^2)$

DY $\sigma_{A+B\to\ell^+ +\ell^- +X} = \sum_{i,j} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j\to\ell^+ +\ell^+ X}$

SIH $\sigma_{A+B\to H+X} = \sum_{i,j,k} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j\to k+X} \otimes D_k^H$

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

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

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

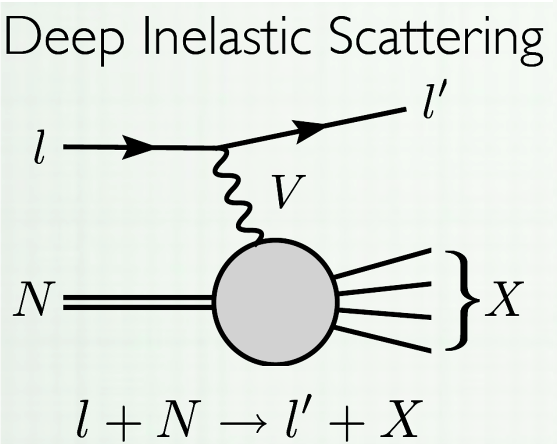
A-dependent coefficients:

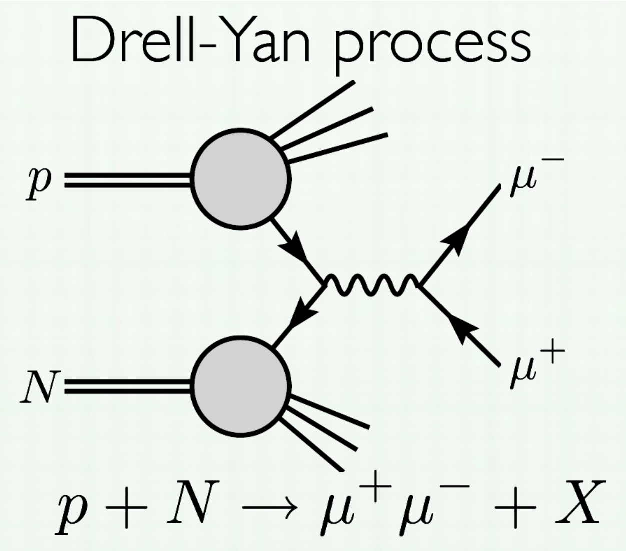
$$c_i(A,Z) = p_i + a_i(1-A^{-b_i})$$

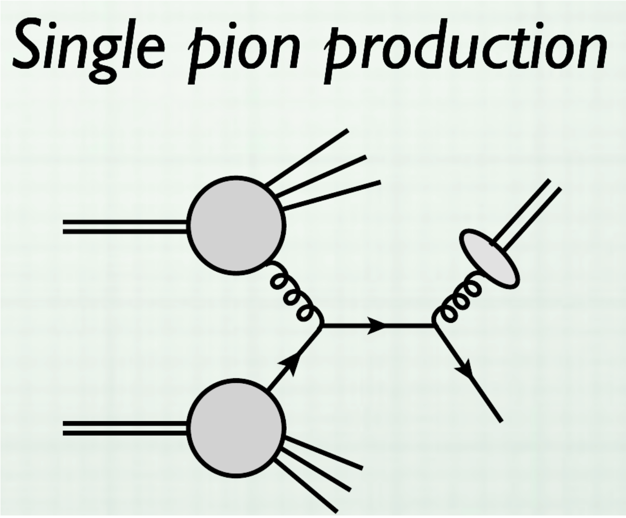
Free proton PDF parameters

Data sets used in nCTEQ

- **IA DIS:** backbone of all global analyses [**SLAC, NMC, EMC, BCDMS, FNAL, JLAB**]
- **pA DY:** disentangle valence and sea quarks [**E772, E866**]
- **SIH data**: gluon distribution (weaker impact compared to HQ and dijet data)
    - **RHIC** single hadron production:
    - **LHC** single hadron production:
- **LHC W, Z production:** gluon, strange distribution [**CMS, ATLAS (ALICE, LHCb) Run I (5 TeV), CMS Run II (8 TeV)**]







Reference fit without neutrino data

- ***nCTEQ15WZSIHdeut* (=Ref fit)**:
  IA DIS + DY + LHC W,Z + SIH data sets

- Improvements w.r.t. *nCTEQ15WZSIH*:

  - Corrections to deuteron structure function F_2^D (~1% at x<0.1, 3.5% at x=0.65)

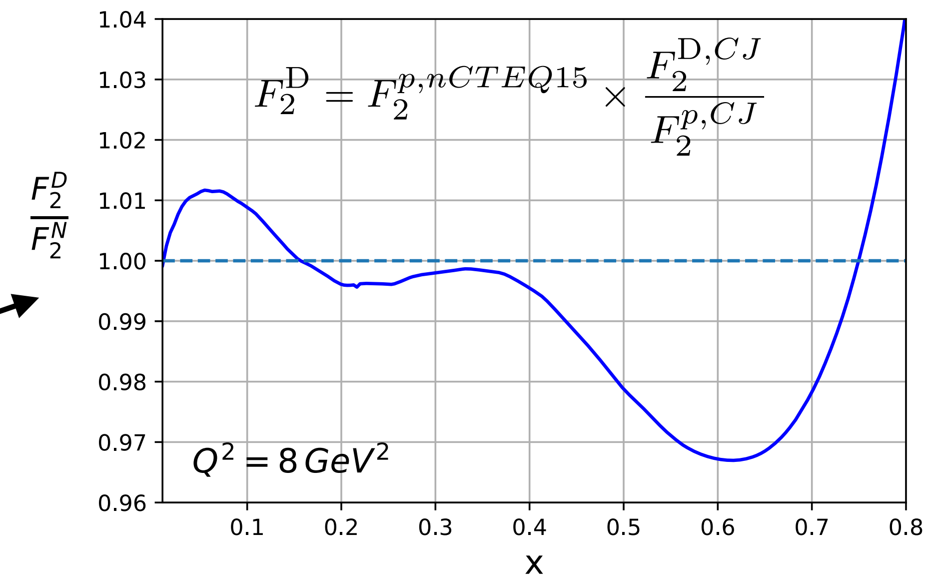
  - Isoscalar corrections to data removed

- DIS cuts: Q>2 GeV, W>3.5 GeV

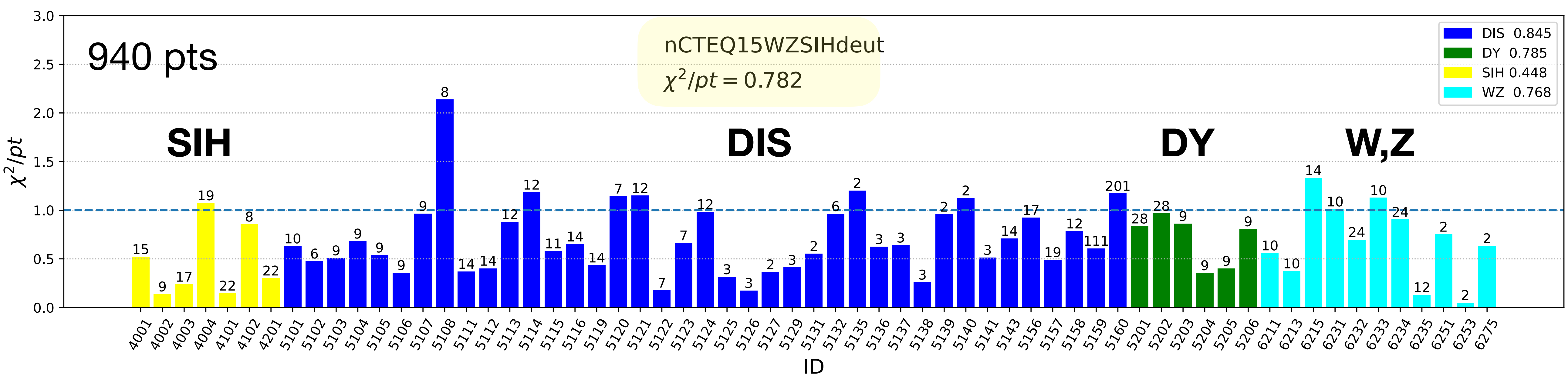
- SIH cut: $p_T > 3$ GeV

- 27 free parameters + 10 free normalisations

Deuteron corrections from CJ15 analysis



	DIS	DY	SIH	W,Z LHC	**Total**
nCTEQ15	0.91	0.73	(0.25)	(6.20)	**1.66**
nCTEQ15WZSIH	0.91	0.78	0.41	0.91	**0.83**
nCTEQ15WZSIHdeut	0.85	0.79	0.45	0.77	**0.78**



Neutrino data

Data set	Nucleus	$E_{\nu/\bar{\nu}}$(GeV)	#pts	Corr.sys.	Ref.
CDHSW ν	Fe	23 - 188	465	No	[48]
CDHSW $\bar{\nu}$			464		
CCFR ν	Fe	35 - 340	1109	No	[50]
CCFR $\bar{\nu}$			1098		
NuTeV ν	Fe	35 - 340	1170	Yes	[23]
NuTeV $\bar{\nu}$			966		
Chorus ν	Pb	25 - 170	412	Yes	[27]
Chorus $\bar{\nu}$			412		
CCFR dimuon ν	Fe	110 - 333	40	No	[19]
CCFR dimuon $\bar{\nu}$		87 - 266	38		
NuTeV dimuon ν	Fe	90 - 245	38	No	[19]
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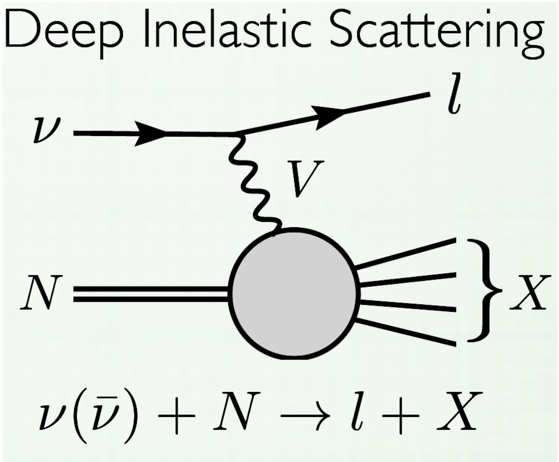
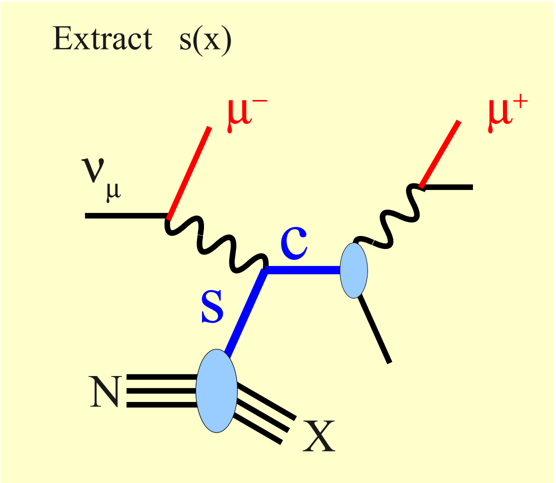




- Chorus, CCFR, NuTeV cross section data: ew corrections applied directly to data
- Chorus, NuTeV: point-to-point correlated systematic errors included in analysis
- Exclude all CCFR data with x>0.4 [see NuTeV collab., PRD74(2006)012008]
- Data from NOMAD (not publicly released), ICECUBE (small x~10^{-6}), Minerva (low Q): not considered
- Dimuon data from CCFR and NuTeV included in the analysis
  NOMAD data not included but compared to; older CDHS, CHORUS data not included

TABLE III. Relative experimental uncertainties (in percent) of various data sets at $E_\nu \sim 85$ GeV where all the data sets overlap.

Experiment	#pts	Relative Error(%)
CDHSW ν	59	8.36
CDHSW $\bar{\nu}$	59	10.75
CCFR ν	54	6.01
CCFR $\bar{\nu}$	54	16.90
NuTeV ν	55	5.88
NuTeV $\bar{\nu}$	54	10.29
Chorus ν	65	7.70
Chorus $\bar{\nu}$	65	18.32

DimuNeu fit with only neutrino data

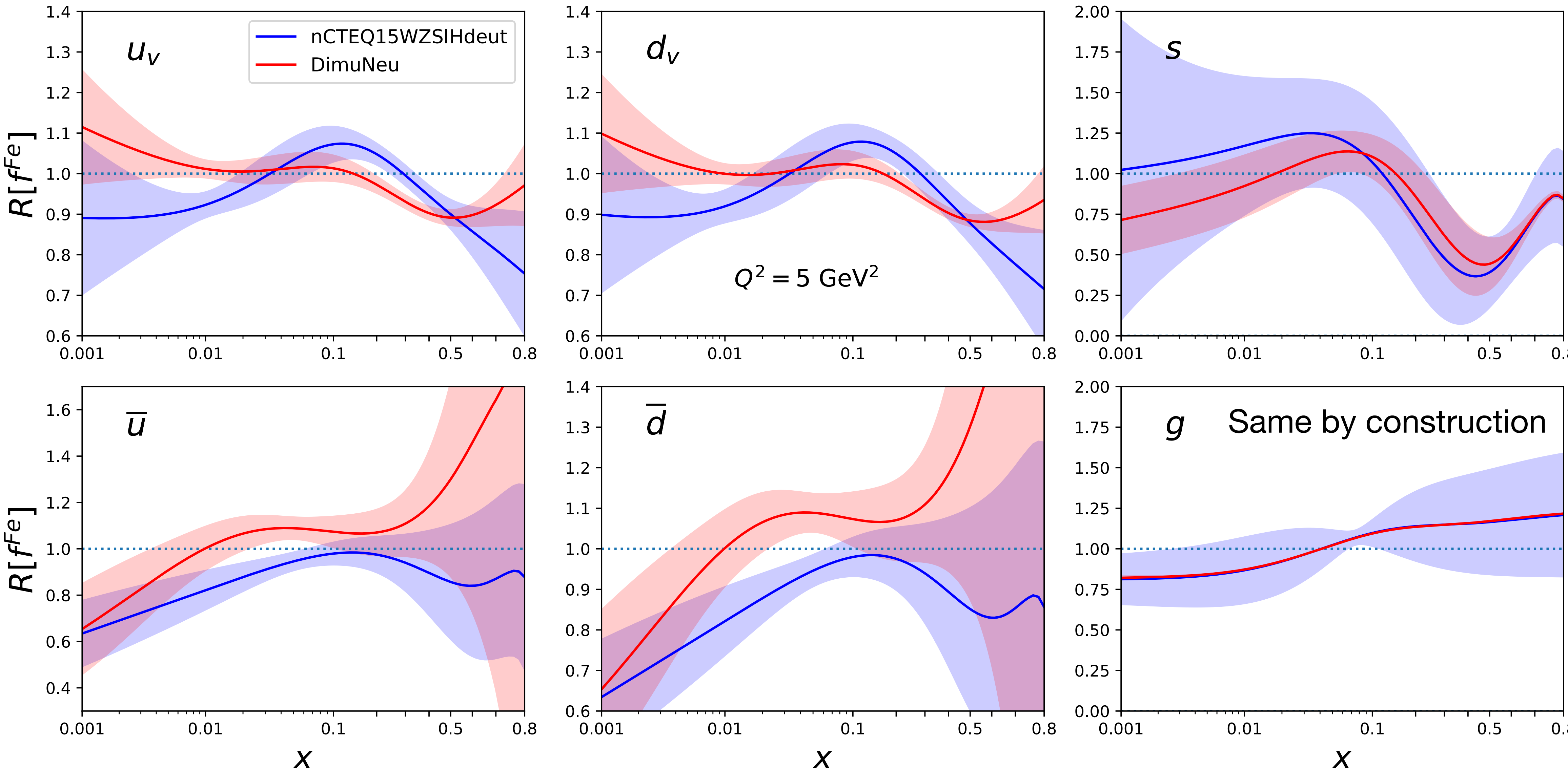
DimuNeu **fit:** χ^2/pt for each data set

Dimuon		NuTeV ν		NuTeV $\bar{\nu}$		CCFR ν		CCFR $\bar{\nu}$	
χ^2/pt	#pts	χ^2/pt	#pts	χ^2/pt	#pts	χ^2/pt	#pts	χ^2/pt	#pts
1.06	150	1.51	1170	1.25	966	1.00	824	1.00	826
Chorus ν		**Chorus $\bar{\nu}$**		**CDHSW ν**		**CDHSW $\bar{\nu}$**		**Total**	
χ^2/pt	#pts	χ^2/pt	#pts	χ^2/pt	#pts	χ^2/pt	#pts	χ^2/pt	#pts
1.21	412	1.09	412	0.68	465	0.72	464	1.12	5689

- DIS cuts: Q>2 GeV, W>3.5 GeV; CCFR: x<0.4
- Need assumptions since νA data cannot constrain all partons:
  - Fix gluon to gluon of ***Ref*** fit
  - Fix $\bar{d}/\bar{u}$ to free proton ratio
- 20 free parameters + 10 free normalisations; 5689 data points
- Generally good description but the most precise NuTeV neutrino cross section data have quite a bad χ^2/pt of **1.5**. Milder tensions for other NuTeV and Chorus data with $\chi^2/\mathrm{pt} \sim 1.2$.

DimuNeu fit vs Reference fit

Ratio of full nuclear PDF to free PDF: $R[f_i^A] = \dfrac{f_i^A(x,Q)}{(Zf_i^p + Nf_i^n)(x,Q)}$



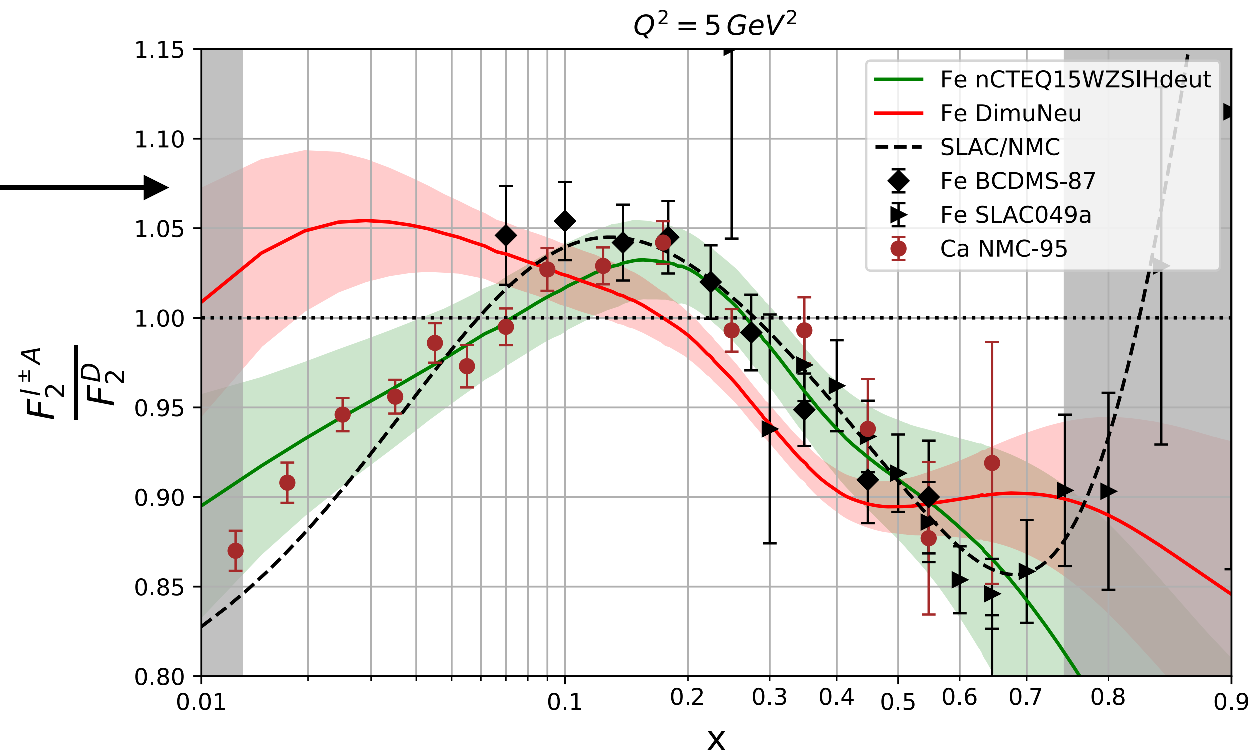
- Distinct differences between valence quarks and also the light sea quarks
- *DimuNeu* fit: shadowing only for x<0.01
- Similar picture for lead with significant differences also for the strange quark

Nuclear correction factors

$$F_2^{CC} = (F_2^{\nu A} + F_2^{\bar{\nu} A})/2$$

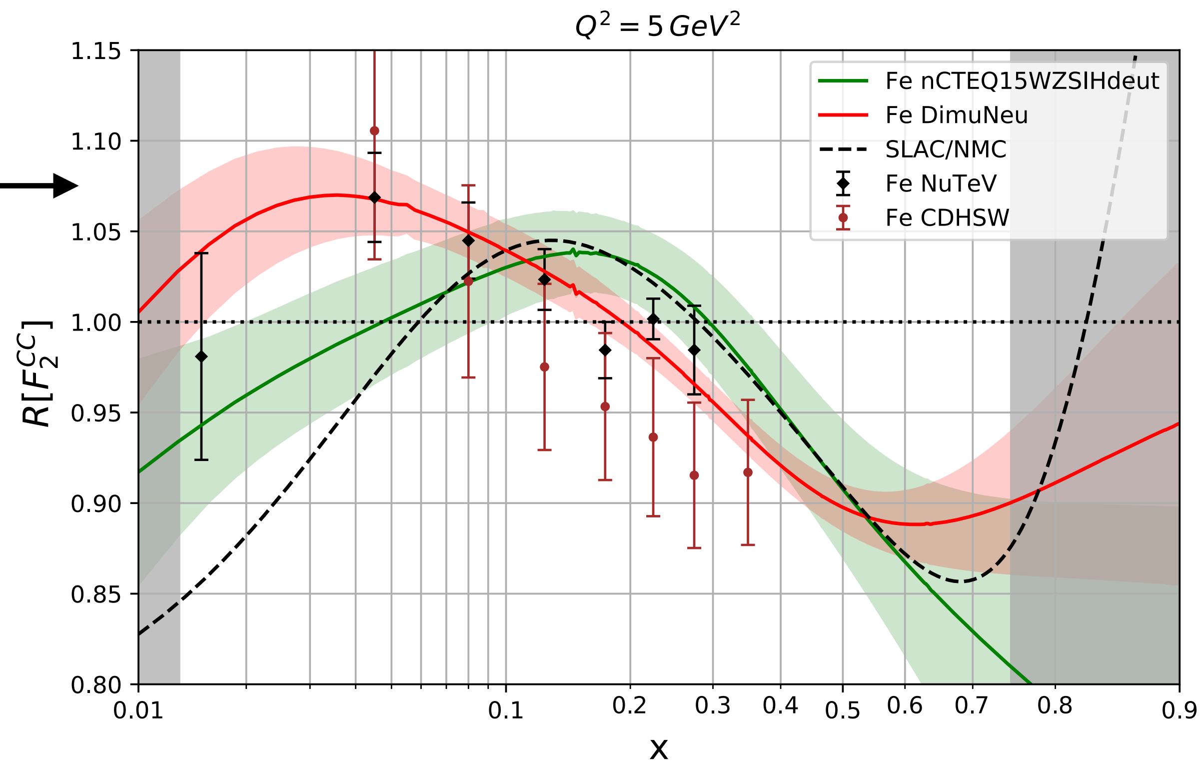
$$R[F_2^{CC}] = \frac{F_2^{CC}[f_i^A]}{F_2^{CC}[f_i^{A,\text{free}}]}$$

- The *Reference fit* to charged lepton DIS+DY+SIH+W,Z data describes the IA DIS data (by construction)



- The NPDFs from the neutrino only *DimuNeu fit* predict a different shape for the nuclear correction factor **not** describing the IA DIS data

- Conversely, the *DimuNeu fit* describes the neutrino data (by construction even if the structure function data have not been used)



- The prediction from the *Ref fit* does **not** describe the neutrino data well

Combined global analysis

- Usually one includes new data in a global analysis in order to improve the precision or the (x,Q) coverage of the previous analysis

- Is it possible to have a combined global analysis of all data?
  lA DIS + DY + SIH + LHC W,Z + νA DIS

- If there are tensions, there are two possibilities:

  a) **Theory wrong**?

  - Breakdown of twist-2 factorisation (no universal PDFs): Big problem!

  - Twist-2 factorisation valid but need to improve theory (higher orders, resummation, higher twists, TMC)

  b) **Data wrong** or unrealistically precise?

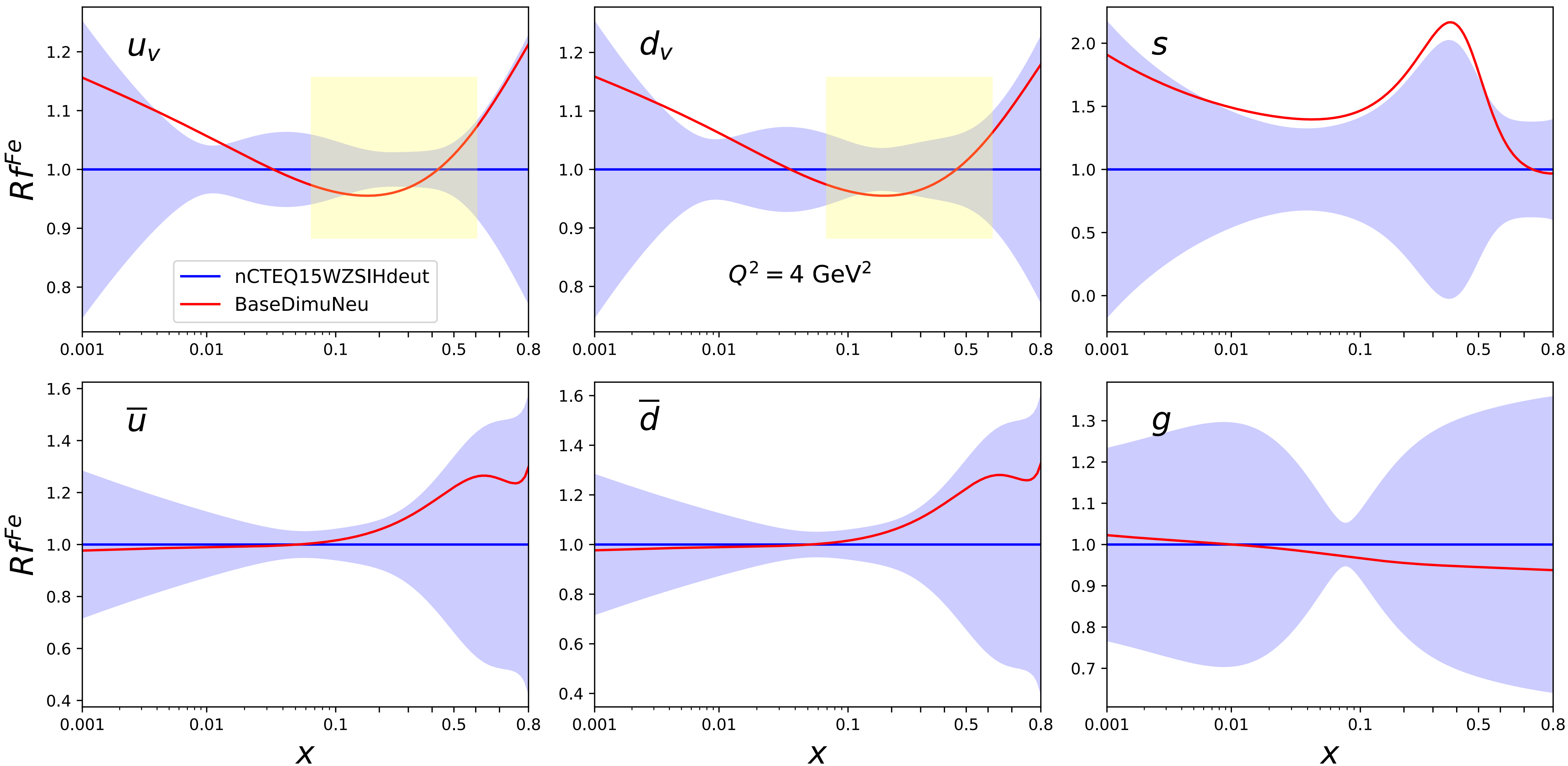
- How to quantify tensions or the compatibility of data? Not discussed here

Combined global analysis

Analysis name	χ^2_S/N	$\chi^2_{\bar{S}}/N$	$\Delta\chi^2_S$	$\Delta\chi^2_{\bar{S}}$	$p_S/p_{\bar{S}}$
nCTEQ15WZSIHdeut	735/940	-	0	-	0.500 / -
DimuNeu	-	6383/5689	-	0	- / 0.500
BaseDimuNeu	866/940	6666/5689	131	283	0.99987/0.990

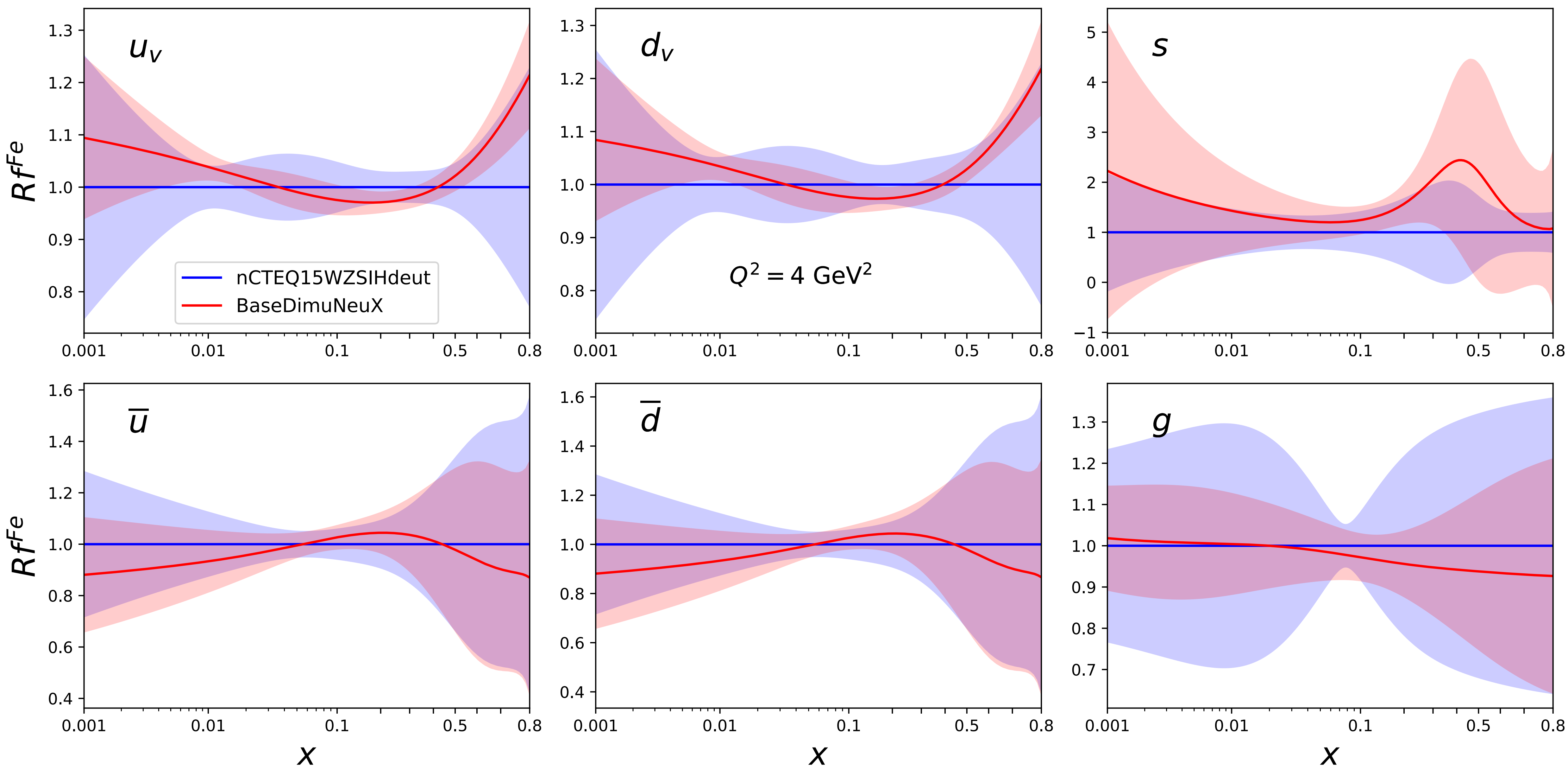
- *nCTEQ15WZSIHdeut=Ref=Base*: lA DIS + DY + SIH + LHC W,Z
- *DimuNeu*: Dimuon + CDHSW + CCFR + NuTeV + Chorus
- *BaseDimuNeu*: Ref data (S) + DimuNeu data ($\bar{S}$)
  (combined global analysis of Reference data and all neutrino data)
- Same 27 parameters in all fits
- Tolerance of *Ref* fit: $\Delta\chi^2_S = 45$
- $\Delta\chi^2_S = 131, \Delta\chi^2_{\bar{S}} = 283$: S and $\bar{S}$ data **not compatible**

Ratio of full iron PDFs to Reference PDFs



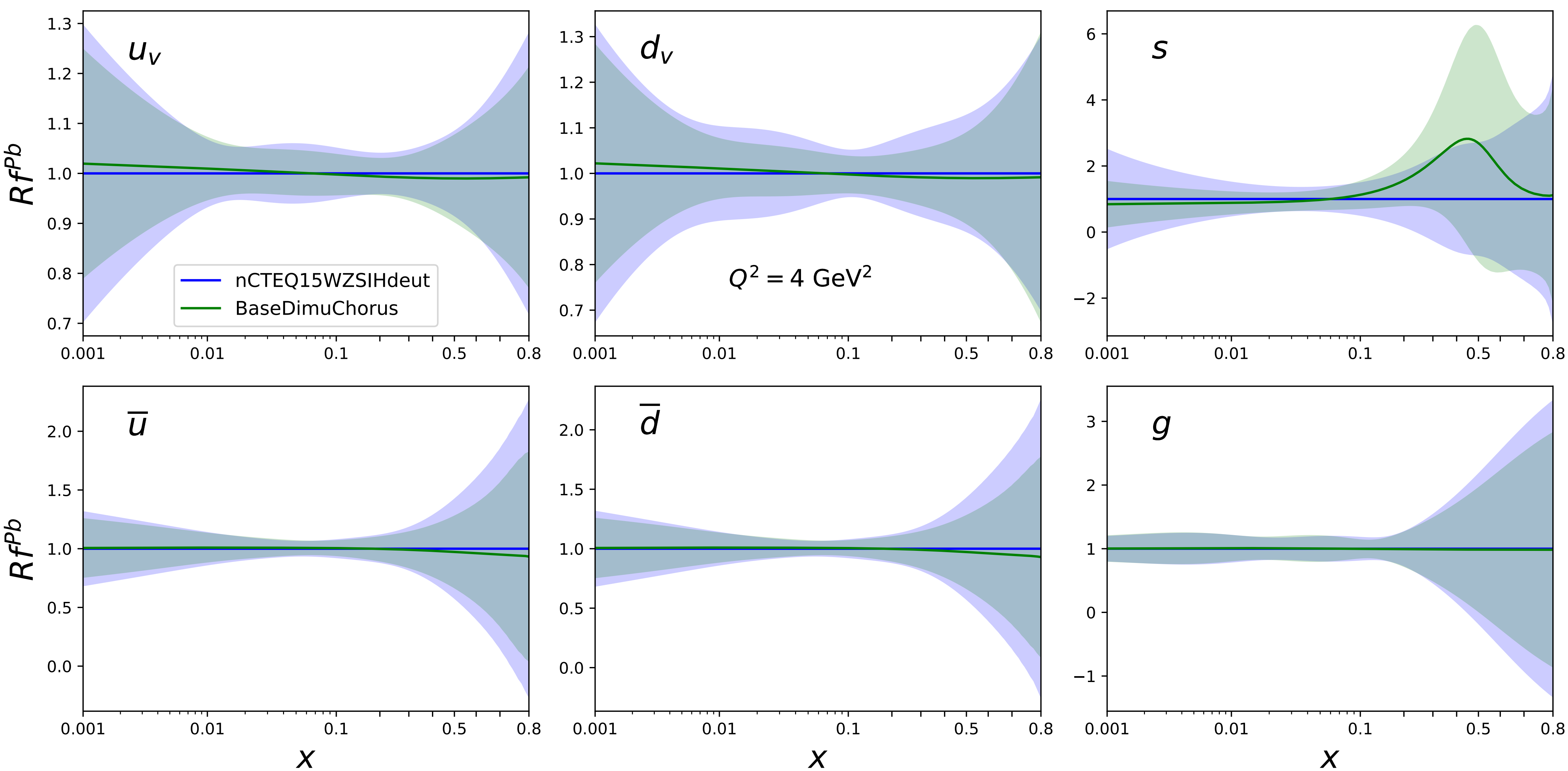
- Uncertainty bands: Hessian method with $\Delta\chi^2 = 45$
- Important differences between *Ref* fit and *BaseDimuNeu* fit for u_v, d_v PDFs
- No real tension for strange PDF since the neutrino data provide first strong constraint on s-PDF. However, neutrino differential cross section data prefer a different strange than dimuon data.

Ratio of full iron PDFs to Reference PDFs



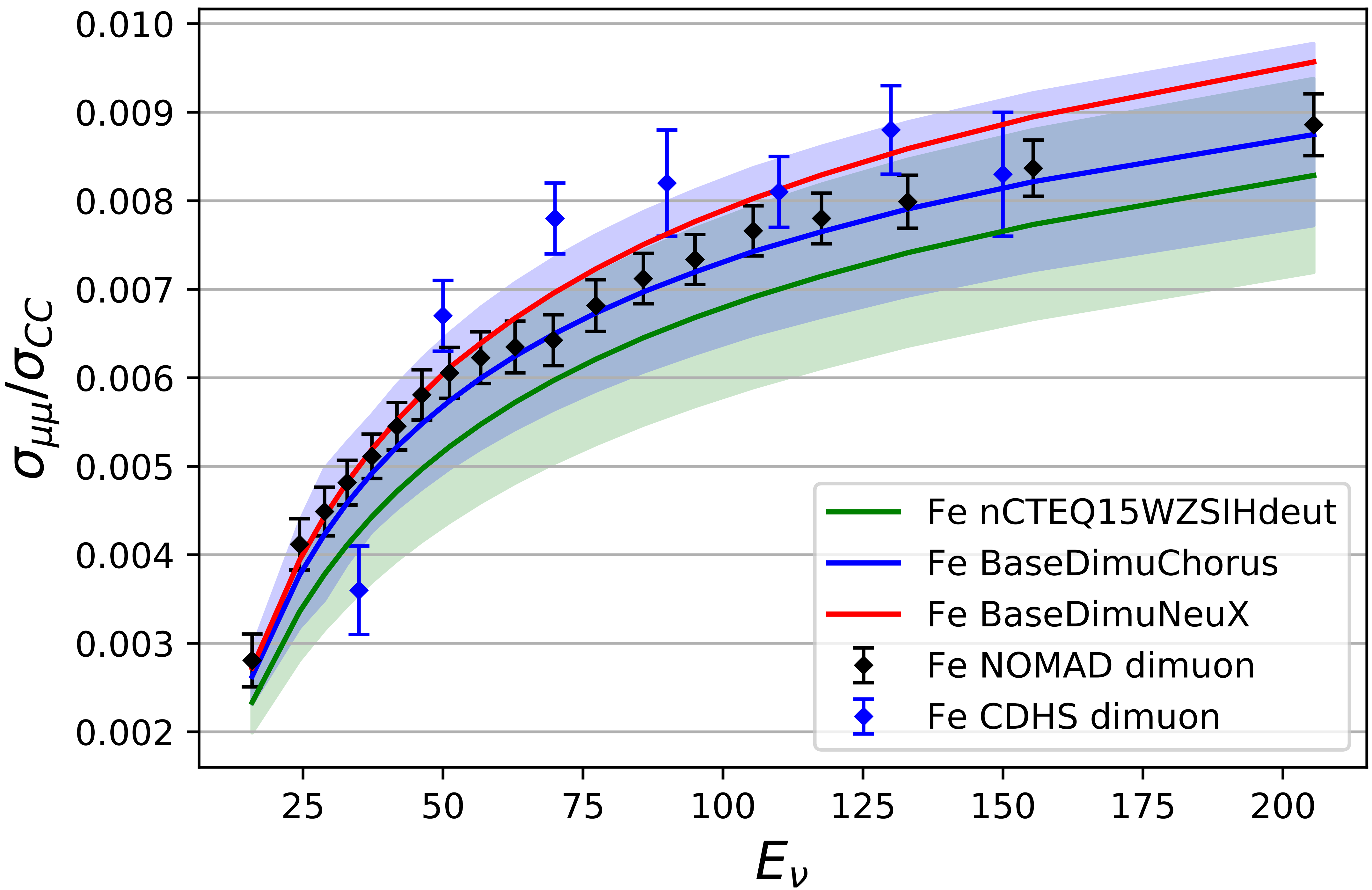
- Uncertainty bands: Hessian method with $\Delta\chi^2 = 45$
- νA DIS data with a cut $x > 0.1$
- Improved compatibility but cut x>0.1 difficult to justify

Ratio of full lead PDFs to Reference PDFs



- Uncertainty bands: Hessian method with $\Delta\chi^2 = 45$
- *BaseDimuChorus*: Ref data + Dimuon + Chorus data
- Dimuon + Chorus data compatible with Reference data; improved strange PDF

Comparison with NOMAD data



Conclusions

Neutrino DIS vs Charged lepton DIS

Ultimate analysis: " Compatibility of Neutrino DIS data and Its Impact on Nuclear Parton Distribution Functions", arXiv:2204.13157

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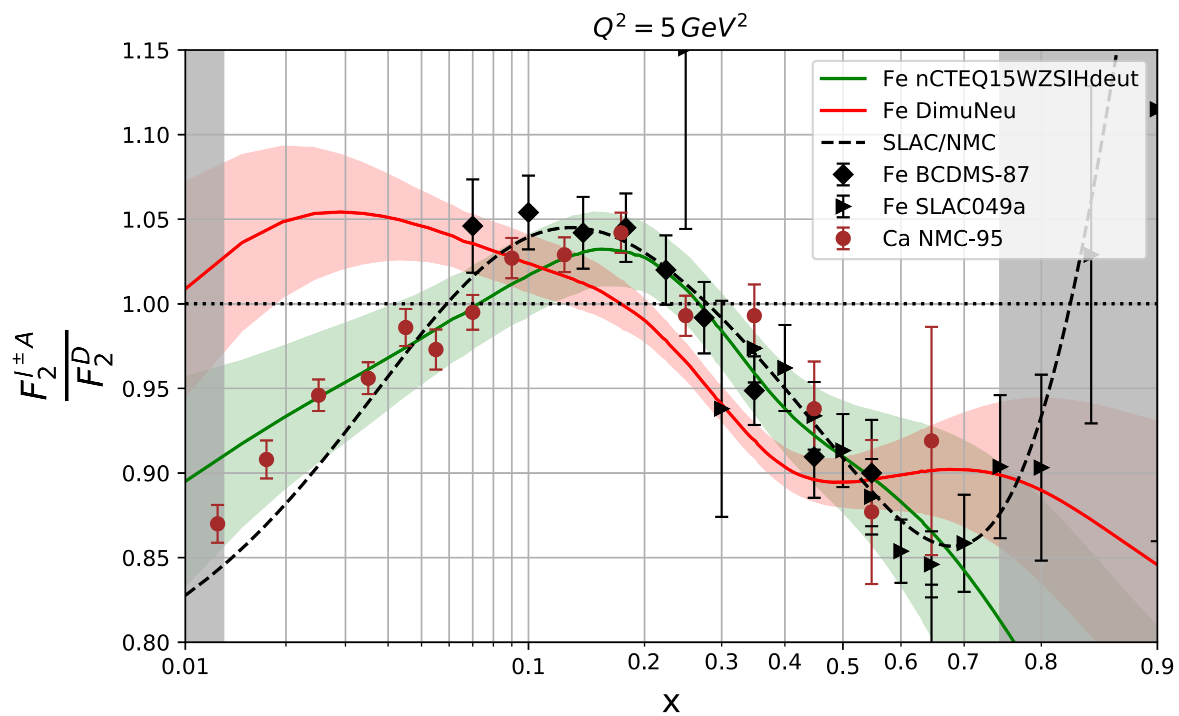
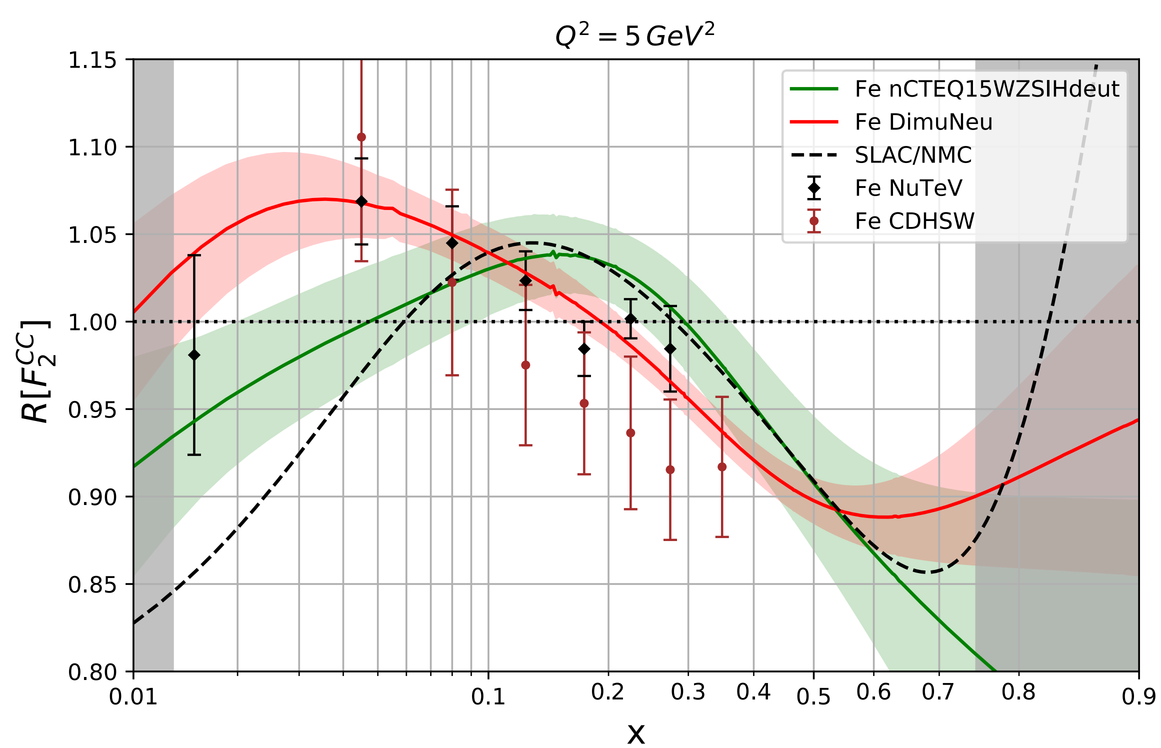


- Most thorough analysis so far (thesis K. F. Muzakka, U Münster): different tools to analyse compatibility of data
- Neutrino data creates significant tensions between key data sets: neutrino vs charged lepton+DY+LHC
- Tensions among different neutrino data sets: iron (CDHSW, NuTeV, CCFR) vs lead (CHORUS)?
- Next nCTEQ analysis will include CHORUS and Di-muon data but not NuTeV, CCFR, CDHSW data



Backup

Scale dependence predicted by QCD

- x-**dependence** of PDFs is NOT calculable in pQCD
- μ^2-**dependence** is calculable in pQCD – given by **DGLAP** (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) evolution equations

DGLAP evolution equations

$$\frac{df_q(x,\mu^2)}{d\log\mu^2} = \frac{\alpha_S(\mu^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{qq}\left(\frac{x}{y}\right)f_q(y,\mu^2) + P_{qg}\left(\frac{x}{y}\right)f_g(y,\mu^2)\right]$$

$$\frac{df_g(x,\mu^2)}{d\log\mu^2} = \frac{\alpha_S(\mu^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{gg}\left(\frac{x}{y}\right)f_g(y,\mu^2) + P_{gq}\left(\frac{x}{y}\right)f_q(y,\mu^2)\right]$$

- Different PDFs mix – set of $(2n_f+1)$ coupled integro-differential equations.

- Need boundary conditions **$f_i(x,Q_0)$** at some perturbative initial scale **$Q_0 \gtrsim 1$ GeV**
- The **x-dependence** is not calculable in pQCD, perform **global analysis** of **experimental data** **[EPPS, nCTEQ, nNNPDF, ...]**
- Progress on the **lattice**: see **arXiv:1711.07916, 2006.08636**

Sum rules provide constraints

- **Number sum rules** – connect partons to quarks from SU(3) flavour symmetry of hadrons; proton (uud), neutron (udd). For protons:

For all scales:

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

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

- **Momentum sum rule** – momentum conservation connecting all flavours

For all scales:

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

Momentum carried by up and down quarks is only around half of the total proton momentum the rest of the momentum is carried by gluons and small amount by sea quarks. In case of CT14NLO PDFs ($\mu = 1.3$ GeV):

At 1.3 GeV:

$$\int_0^1 dx \, x[f_u(x) + f_d(x)] \simeq 0.51$$

$$\int_0^1 dx \, x f_g(x) \simeq 0.40$$

Nuclear modifications

- Neutrino experiments use heavy nuclear targets:
  Pb, Fe, Ar, H_2O, C

- As discovered more than 30 years ago by the European Muon Collaboration, nucleon structure functions are modified by the nuclear medium (EMC effect)

- Studies of nucleon structure: need to correct for nuclear effects

- Nuclear effects interesting in its own right!

  - Many models exist.

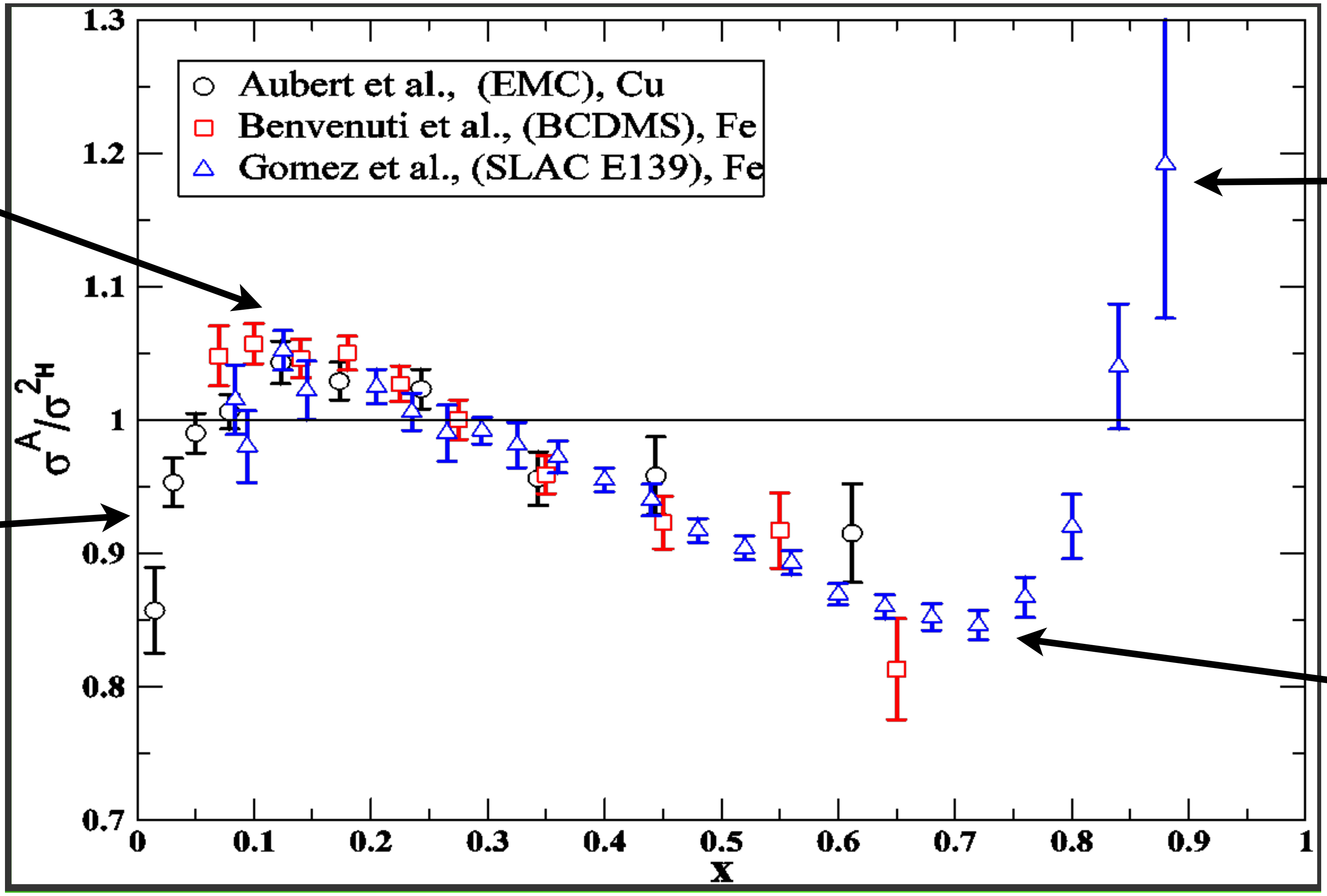
  - However, charged lepton nuclear effects still not fully explained, in particular the EMC effect ($0.3 < x < 0.7$)

The EMC effect

$$F_2^A(x) \neq ZF_2^p(x) + NF_2^n(x)$$

Anti-shadowing enhancement

Shadowing suppression at small x



Rise due to Fermi motion

EMC effect

Global analysis of nuclear PDFs

Same approach as for proton PDF determinations

1. Boundary conditions:
   Parameterize x-dependence of PDFs at initial scale Q_0

$$f(x,Q_0)=A_0 x^{A_1}(1-x)^{A_2} P(x;A_3,\ldots);\; f=u_v,d_v,g,\bar{u},\bar{d},s,\bar{s}$$

2. Evolve from Q_0 to Q solving the DGLAP evolution equations: $f(x,Q)$

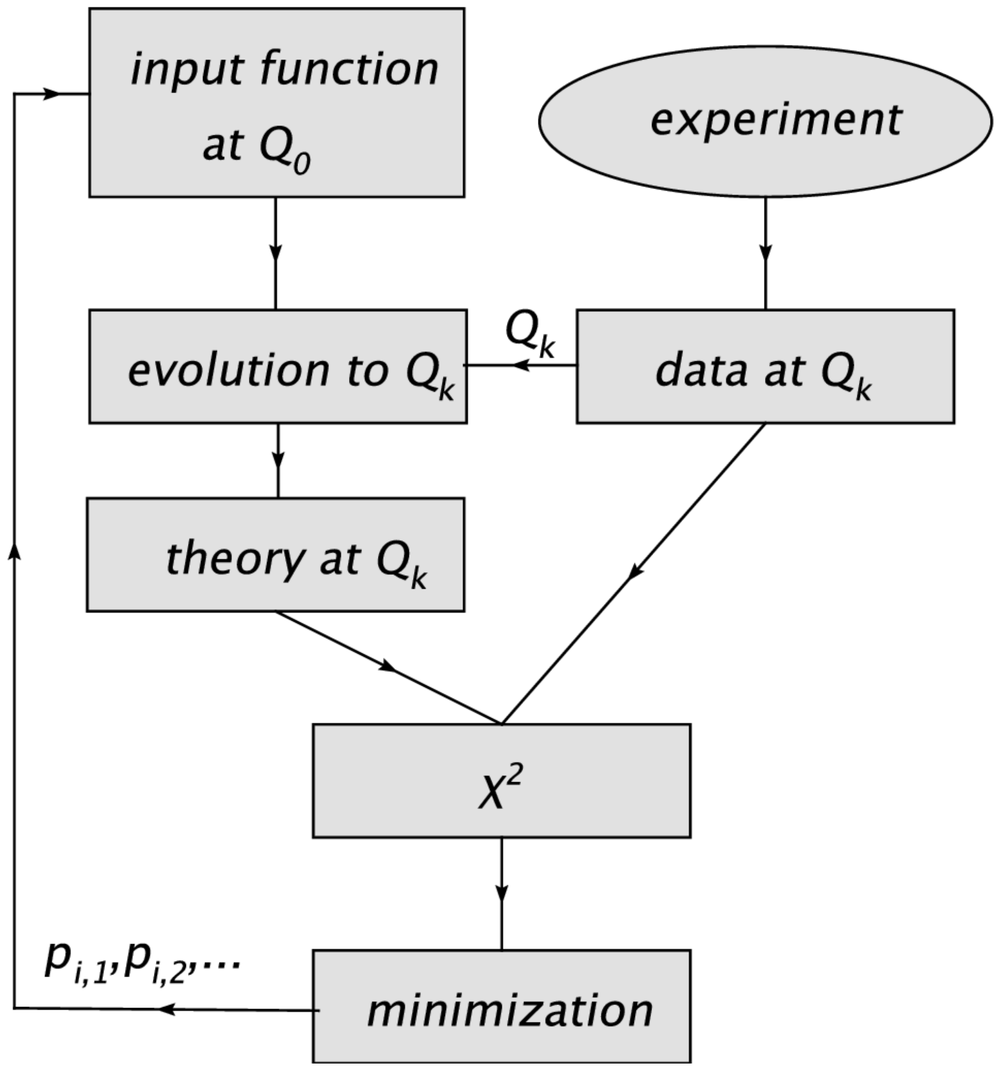
3. Define suitable χ^2 function and minimize w.r.t. fit parameters

$$\chi^2_{global}[A_i]=\sum_n w_n \chi^2_n;\; \chi^2_n=\sum_I \left(\frac{D_{nI}-T_{nI}}{\sigma_{nI}}\right)^2$$

Sum over experiments

Sum over data points

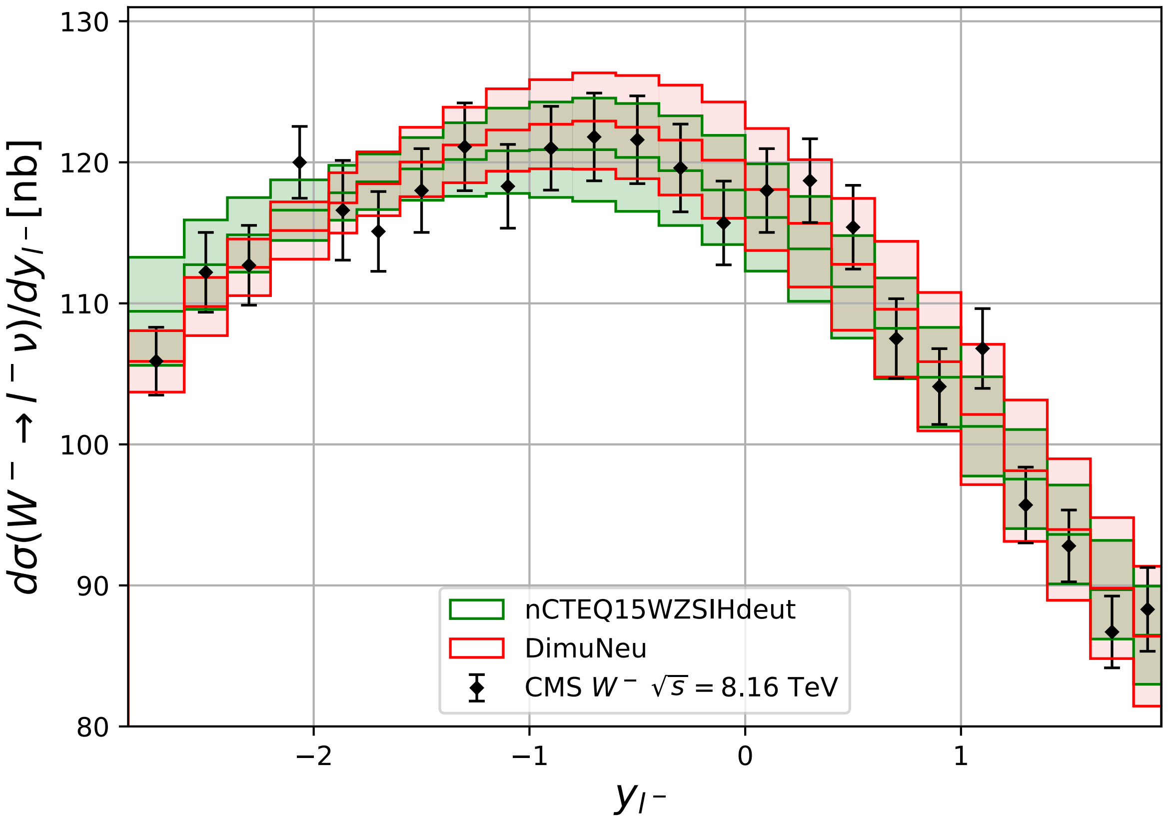
weights: default=1, allows to emphasize certain data sets

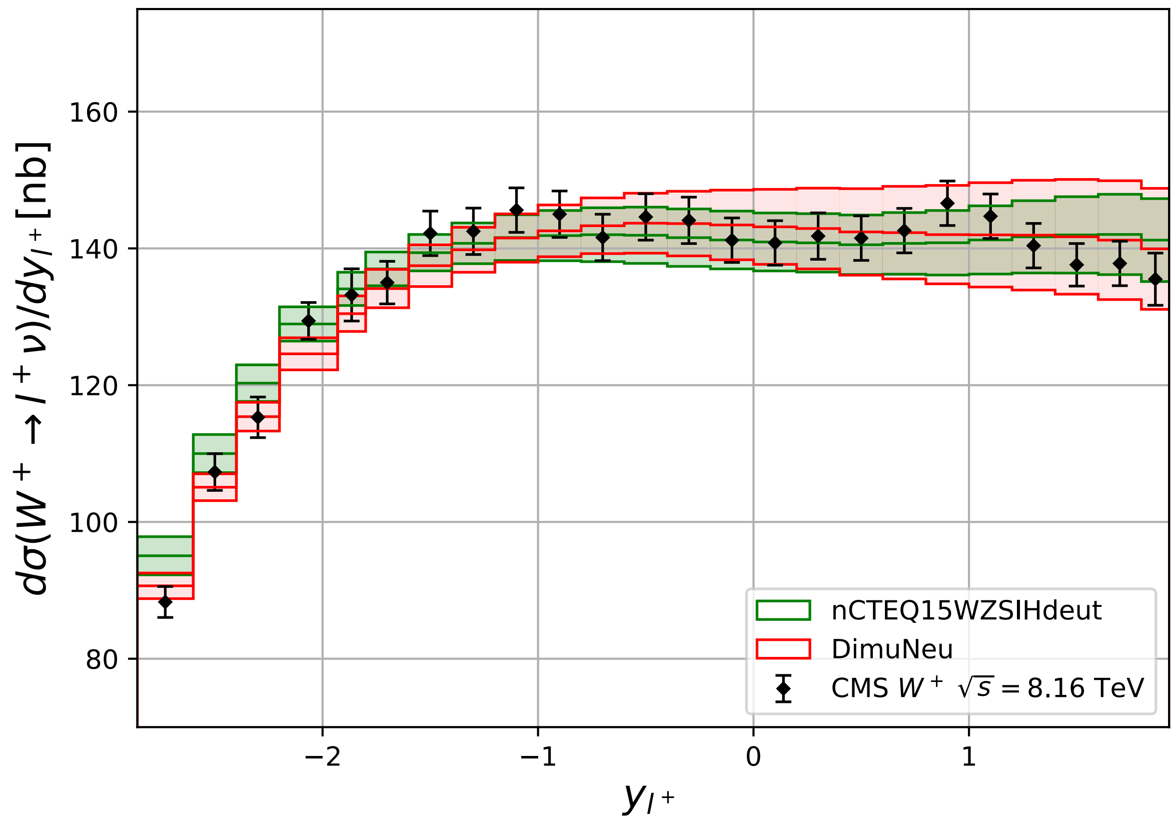


Analysis of neutrino DIS data within nCTEQ

- Are there tensions between different neutrino data sets?
- Are there tensions between neutrino DIS data and other data used in nCTEQ global analyses?
    - Global analyses with and without neutrino data
    - Careful treatment of data correlation and normalisation uncertainties
    - Taking into account nuclear effects in the calculation of the deuteron structure function F_2^D
- Confirm evidence of tensions employing different criteria
- Identify data points and kinematic regions that create the tensions
    - Can tensions be relieved using a kinematic cut x>0.1?
    - Can tensions be relieved using uncorrelated systematic errors?
- Identify a subset of neutrino data allowing for a consistent global analysis

Comparison with CMS W,Z data





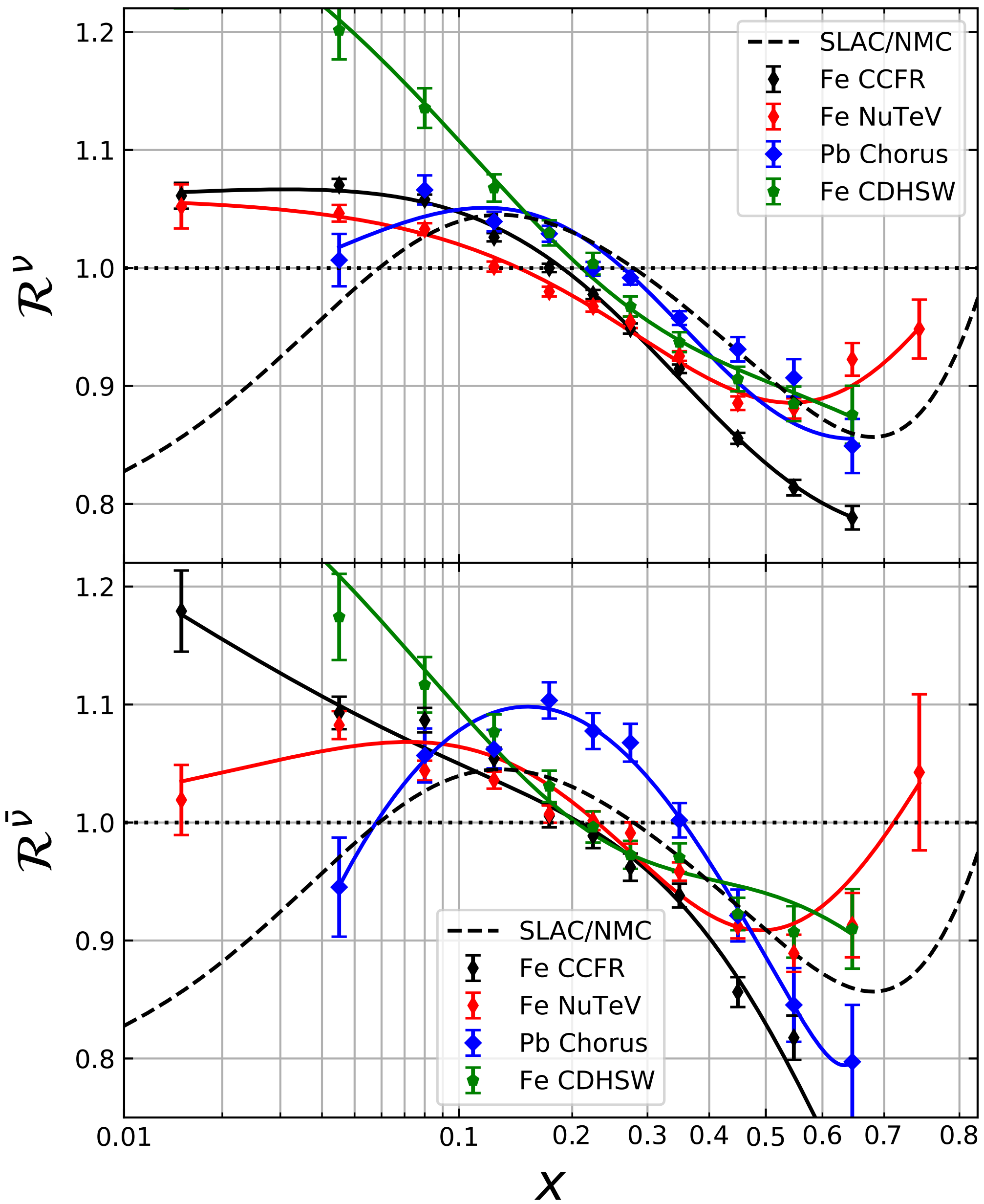
- Similar predictions from the DimuNeu and the Ref fits for LHC W,Z production data
- Not a surprise since this observable is quite sensitive to the gluon PDF which has been fixed to be the same at the initial scale.

Nuclear corrections from neutrino data

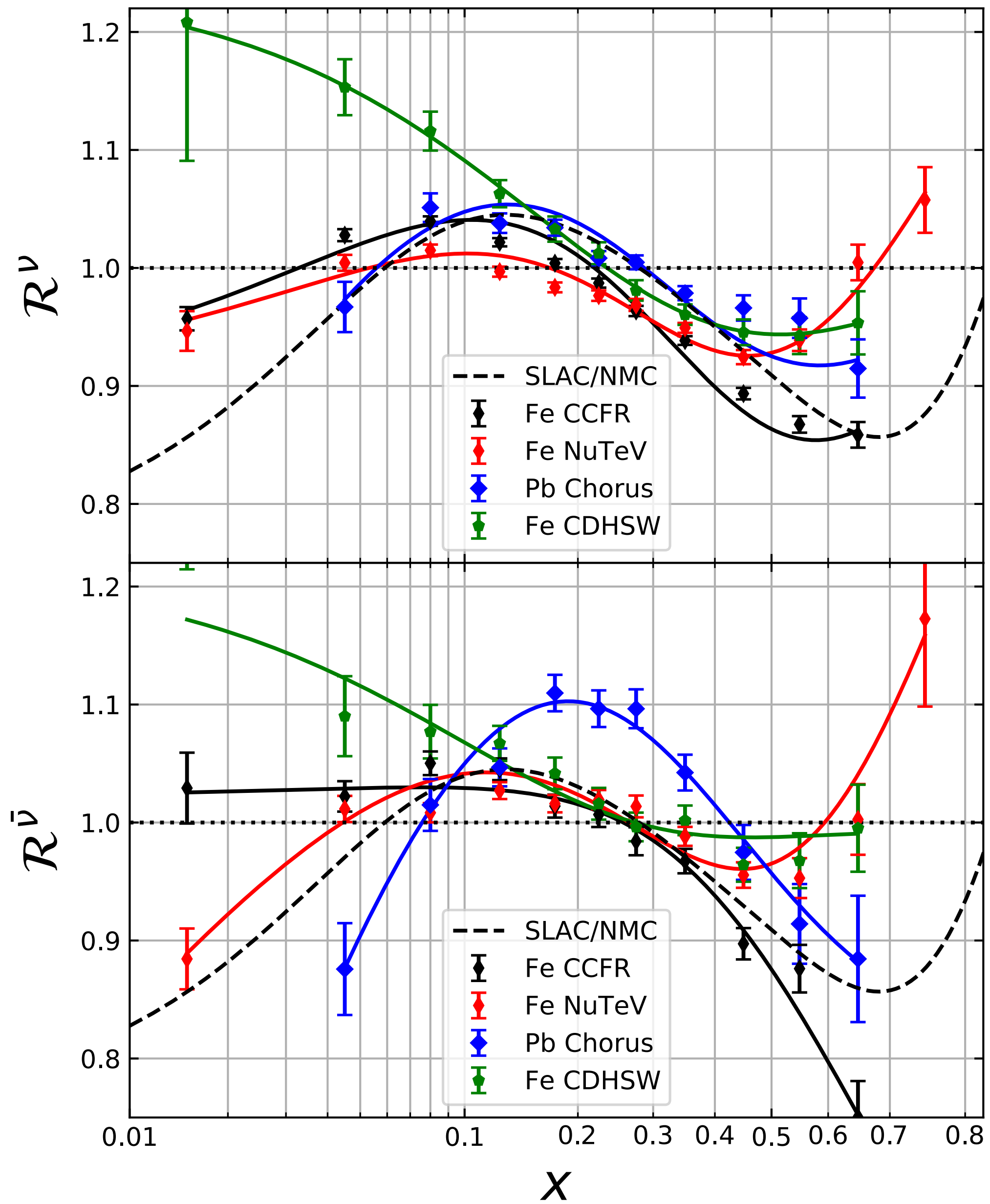
Weighted average of neutrino cross section ratios

$$R_i^{\sigma}(x) = \frac{\sigma(x, y_i, E_i)}{\sigma_{\text{free}}(x, y_i, E_i)}$$

Denominator: nCTEQ15 proton



Denominator: CT18 proton

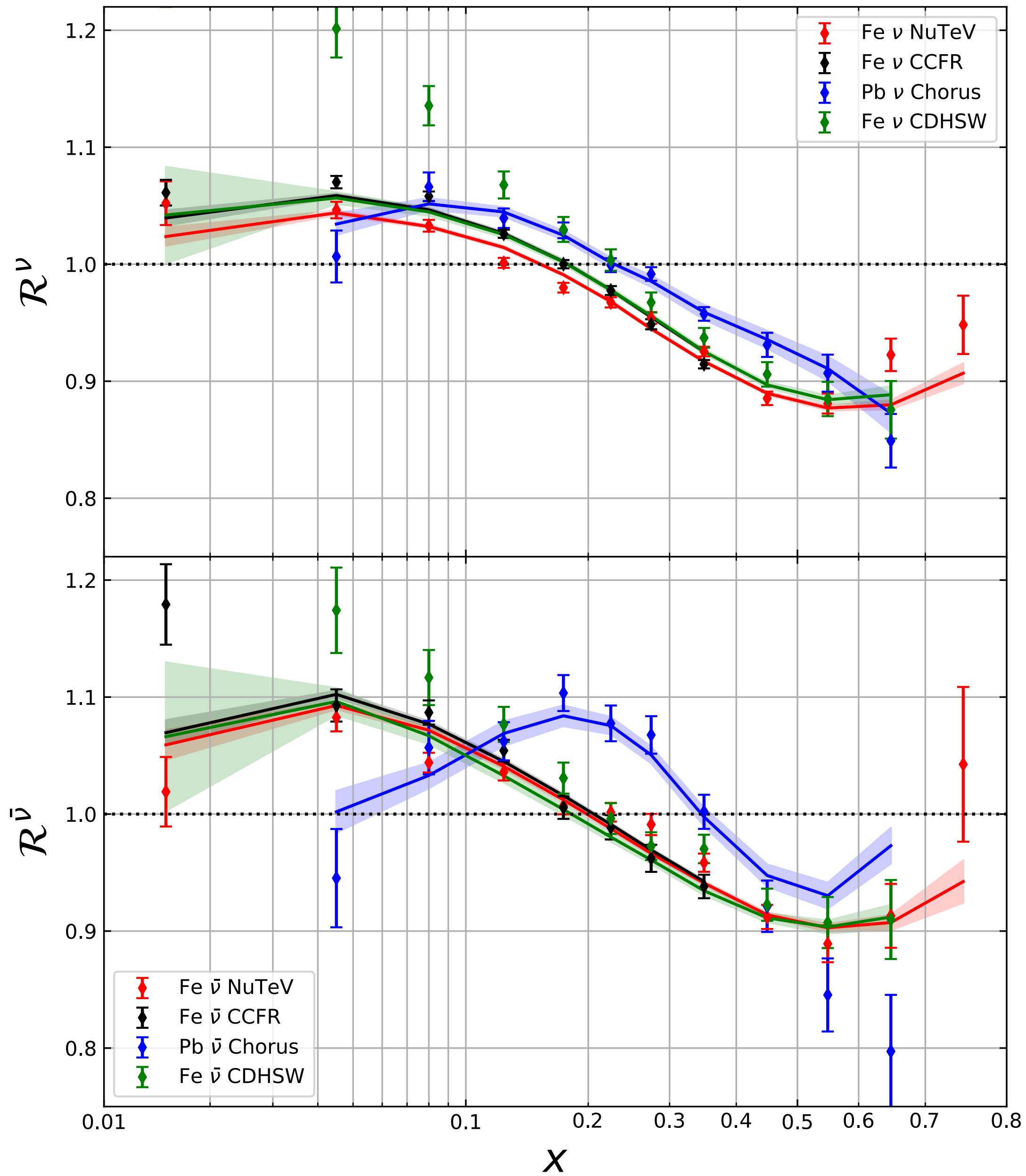


Nuclear corrections from neutrino data

Weighted average of neutrino cross section ratios

$$R_i^\sigma(x) = \frac{\sigma(x, y_i, E_i)}{\sigma_{\text{free}}(x, y_i, E_i)}$$

Denominator: nCTEQ15 proton



- Data vs predictions from the *DimuNeu fit*
- Iron: A=56, Z=26
- Lead: A=208, Z=82

Iron only and lead only fits

- *DimunuIron* fit:
  Only neutrino-iron data from CDHSW, CCFR and NuTeV

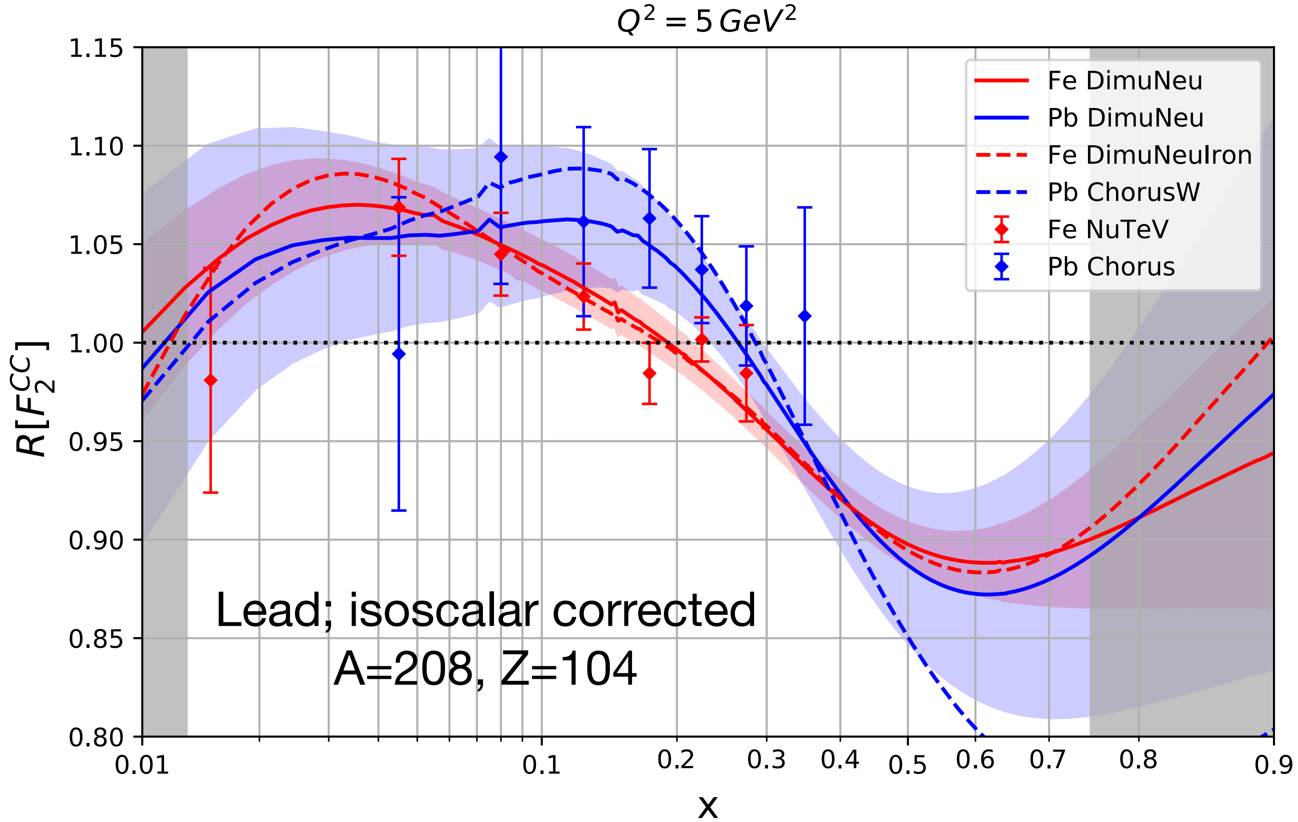
- *ChorusW* fit:
  Only data only lead from Chorus and LHC W,Z
  The prediction from the *Ref fit* does **not** describe the neutrino data well

- 14 free parameters
  (since no A-dependence needed)

- Nuclear corrections generally similar to global *DimuNeu* analysis

- *ChorusW* prediction for lead higher at $x \sim 0.1, 0.2$ and much lower at high x (no pull from NuTeV data)

$$R[F_2^{CC}] = \frac{F_2^{CC}[f_i^A]}{F_2^{CC}[f_i^{A,\text{free}}]}$$



- Difference between iron and lead nuclear correction factors:
  - Large excess of neutrons in lead nucleus whereas iron almost isoscalar
  - Nuclear A-dependence (subleading)

More global analyses with neutrino data

	Analysis name	χ^2_S/N	χ^2_S/pt	$\chi^2_{\bar{S}}/N$	$\chi^2_{\bar{S}}/pt$	$\Delta\chi^2_S$	$\Delta\chi^2_{\bar{S}}$	$p_S/p_{\bar{S}}$
Ref fit = Base	nCTEQ15WZSIHdeut	735/940	0.78	-	-	0	-	0.500 / -
Dimuons+Chorus	DimuChorus	-	-	1059/974	1.09	-	0	- / 0.500
Ref data + Chorus	BaseChorus	737/940	0.78	969/824	1.18	2	-	0.530 / -
Ref data + CDHSW	BaseCDHSW	778/940	0.83	584/929	0.63	43	-	0.895 / -
Ref data + CCFR	BaseCCFR	815/940	0.87	2119/2207	0.96	80	-	0.989 / -
Ref data + NuTeV	BaseNuTeV	807/940	0.86	3049/2136	1.43	72	-	0.981 / -
Ref data + NuTeV (uncor)	BaseNuTeVU	787/940	0.84	1984/2136	0.93	52	-	0.933 / -
Ref data + all neutrinos	BaseDimuNeuU	861/940	0.92	5569/5689	0.98	126	-	0.99978 / -
νA DIS with x>0.1	BaseDimuNeuX	781/940	0.83	5032/4644	1.08	46	-	0.908 / -
Ref data + DimuChorus	BaseDimuChorus	740/940	0.79	1117/974	1.15	5	58	0.559 / 0.885

χ^2/pt of Ref data

χ^2/pt of neutrino data

How much the description of the Ref data worsens by including neutrino Data

TABLE VII. Statistical information on the description of the selected neutral current DIS data sets used in the reference nCTEQ15WZSIHdeut and BaseDimuNeu analyses.

Experiment	Target	ID	#pts	χ^2/pt (S_E) Reference	χ^2/pt (S_E) BaseDimuNeu
NMC-95	C/D	5113	12	0.88 (-0.20)	1.70 (1.59)
NMC-95,re	C/D	5114	12	1.18 (0.53)	2.16 (2.40)
NMC-95	Ca/D	5121	12	1.15 (0.46)	2.98 (3.66)
BCDMS	Fe/D	5101	10	0.63 (-0.81)	2.00 (1.97)
BCDMS	Fe/D	5102	6	0.48 (-0.93)	1.62 (1.09)

TABLE VI. Statistical information on the description of the neutrino data sets used in different analyses.

Data set	#pts	χ^2/pt (S_E) DimuNeu	χ^2/pt (S_E) BaseDimuNeu
CDHSW ν	465	0.68 (-5.29)	0.59 (-7.01)
CDHSW $\bar{\nu}$	464	0.73 (-4.47)	0.69 (-5.22)
CCFR ν	824	0.99 (-0.09)	1.03 (0.56)
CCFR $\bar{\nu}$	826	1.00 (0.07)	1.02 (0.45)
NuTeV ν	1170	1.51 (11.12)	1.61 (13.05)
NuTeV $\bar{\nu}$	966	1.25 (5.16)	1.27 (5.50)
Chorus ν	412	1.21 (2.85)	1.25 (3.40)
Chorus $\bar{\nu}$	412	1.09 (1.26)	1.25 (3.35)
CCFR dimuon ν	40	1.70 (2.79)	2.52 (5.32)
CCFR dimuon $\bar{\nu}$	38	0.79 (-0.89)	0.64 (-1.68)
NuTeV dimuon ν	38	0.98 (-0.06)	2.11 (4.01)
NuTeV dimuon $\bar{\nu}$	34	0.73 (-1.16)	1.16 (0.70)