Nuclear Uncertainties in the Determination of Proton PDFs

Rosalyn Pearson

r.l.pearson@ed.ac.uk

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The NNPDF Collaboration
University of Edinburgh

Based on work with R. D. Ball & E. R. Nocera

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The Current Status

The Current Status

- Global PDFs include data from nuclear targets
- Nuclear environment affects experimental observables
- Current techniques use nuclear models and fits to data
- Effects ”small”, but increasingly relevant
- These nuclear effects unaccounted for in NNPDF3.1
- We show how to determine associated errors and include them in future fits

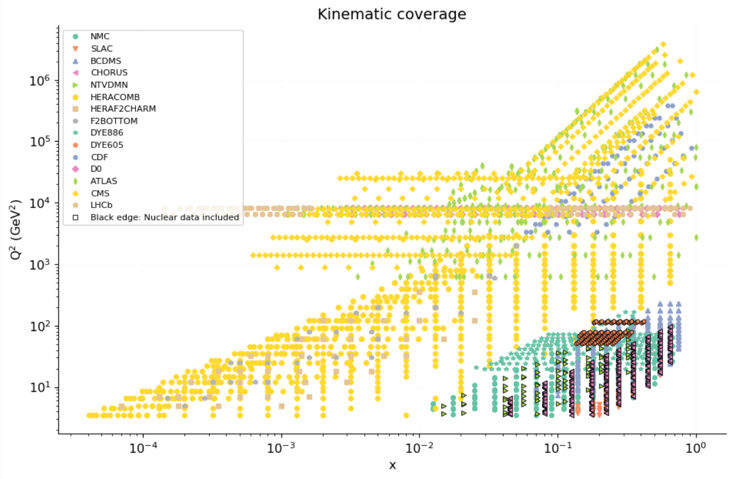
This Talk

- The nuclear dataset
- Techniques for theoretical uncertainties
- Theoretical covariance matrix
- Fits with nuclear uncertainties
- Outlook

The Nuclear Dataset

The Nuclear Dataset

- DIS and DY
- CHORUS (Pb), NuTeV (Fe), DYE605 (Cu)



The Nuclear Dataset

CHORUS

- CC inclusive DIS cross-sections
- for neutrino and antineutrino beams
- sensitive to $u_V = u - \bar{u}$, $d_V = d - \bar{d}$

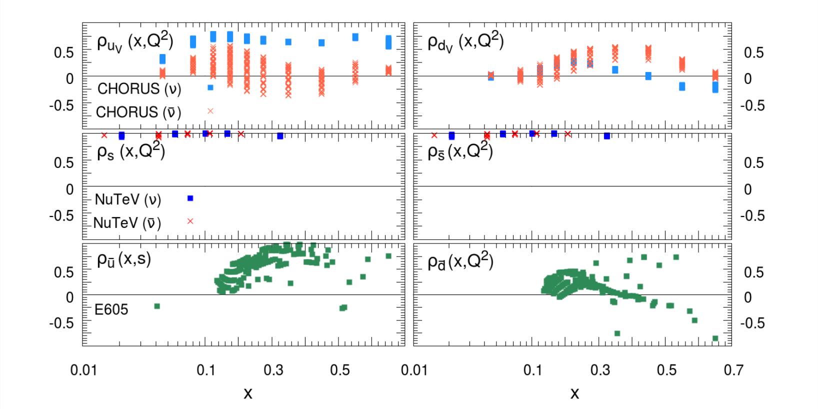
NuTeV

- DIS dimuon cross-sections
- for neutrino and antineutrino beams
- sensitive to $s, \bar{s}$

E605

- DY dimuon cross-sections
- sensitive to $\bar{u}$, $\bar{d}$

Correlations of observables with PDFs



Theoretical uncertainties in PDFs

Theory covariance matrix

- In a PDF fit we use data D_i and experimental covariance matrix C_{ij}
- Want to include theory covariance matrix S_{ij}
- $C_{ij} \to C_{ij} + S_{ij}$ [R. D. Ball & A. Desphande, arXiv:1801.04842]
- Nuisance parameters: $\Delta_i^{(n)} = T_i^{(n)} - T_i,\ n = 1, ..., N_{nuis}$
- $S_{ij} = \frac{1}{N_{nuis}} \sum_{n=1}^{N_{nuis}} \Delta_i^{(n)} \Delta_j^{(n)}$
- Treat theory errors like experimental systematics

Generating the matrix

Compare theoretical predictions computed using nuclear PDFs f_N to those using proton PDFs f_p.

1. Nuclear uncertainties

$$\Delta_i^{(n)} = T_i^N[f_N^{(n)}] - T_i^N[f_p]$$

2. Nuclear uncertainties + correction

$$\Delta_i^{(n)} = T_i^N[f_N^{(n)}] - T_i^N[f_N]$$

and apply shift

$$\delta T_i^N = T_i^N[f_N] - T_i^N[f_p]$$

Treat the three data sets separately: they are for different nuclei and the correlations are unknown. This is the conservative choice.

Generating the matrix

- n labels a replica in a MC nPDF ensemble
- combined recent nPDFs $\rightarrow \{\tilde{f}^{(n)}_{p/N}\}$:
  DSSZ12 [D. de Florian et al., arXiv:1112.6324] ,
  nCTEQ15 [K. Kovarik et al., arXiv:1509.00792] and
  EPPS16 [H. Paukunnen et al., arXiv:1704.04036]
- determined nuclear correction factors

$$R_f^{N,(n)} = \frac{\tilde{f}^{(n)}_{p/N}}{\tilde{f}_p}$$

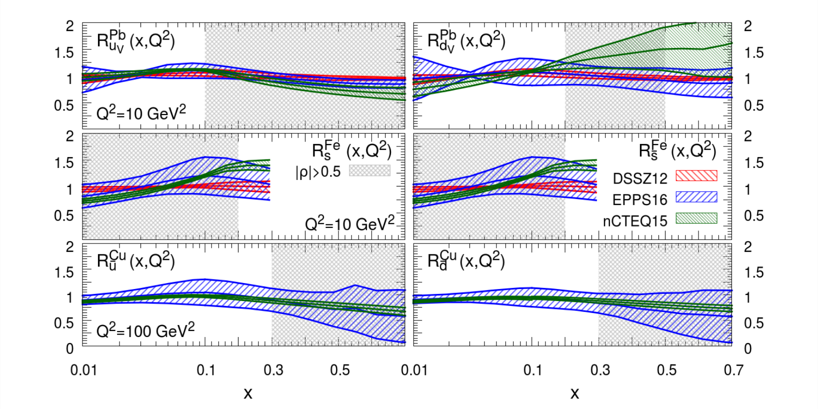
- use these to calculate bound proton PDF for NNPDF3.1

$$f^{(n)}_{p/N} = R_f^{N,(n)} f_p$$

- compute observables

$$T_i^N[f_N] = \frac{1}{A}\{Z T_i[f_{p/N}] + (A-Z) T_i[f_{n/N}]\}$$

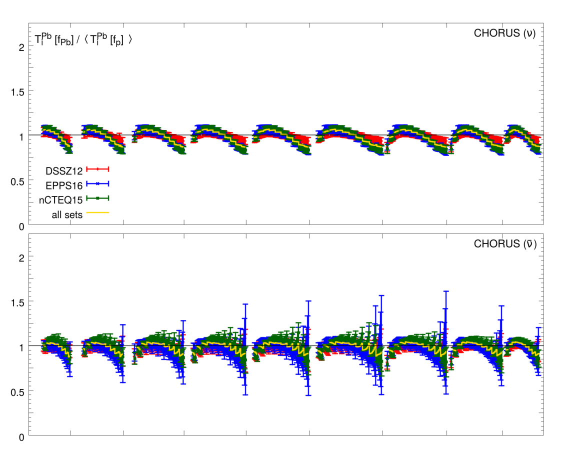
Nuclear correction factors



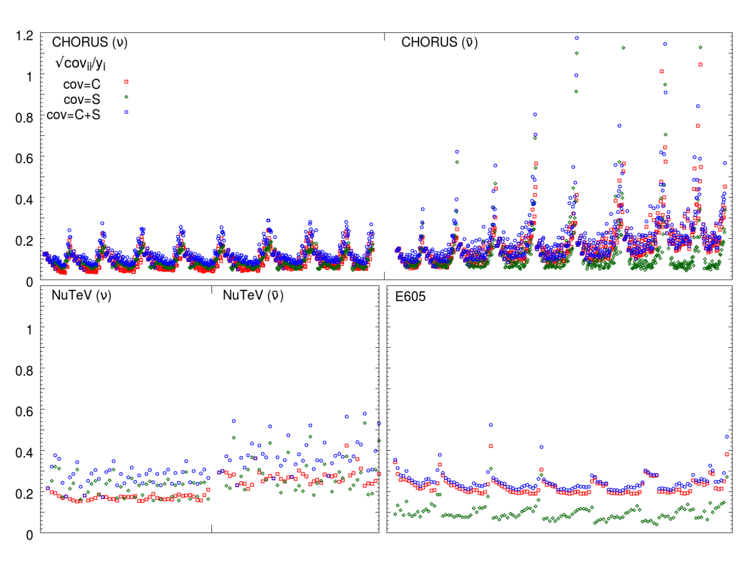
$$R_f^{N,(n)} = \frac{\tilde{f}^{(n)}_{p/N}}{\tilde{f}_p}$$

Observables

Figure 1: Points are binned in (anti-)neutrino beam energy E: 25, 35, 45, 55, 70, 90, 110, 120, 170 GeV. In each bin x increases from left to right, $0.045 < x < 0.65$.

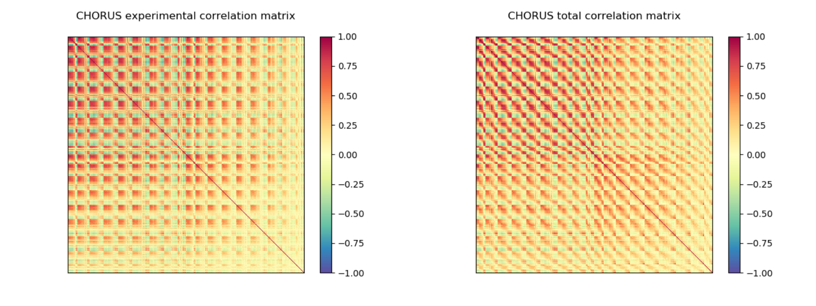


Diagonal elements of covariance matrix

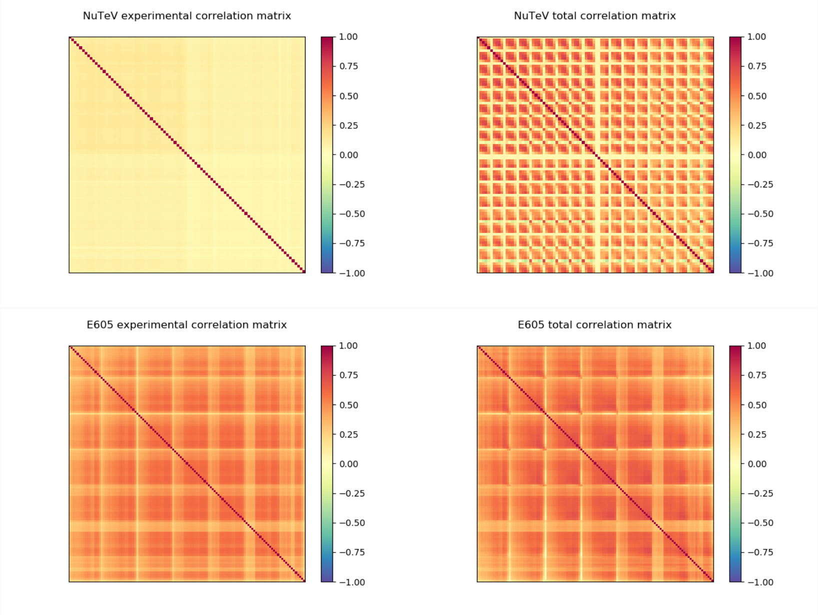


Correlation matrices

$$\rho^C_{ij} = \frac{C_{ij}}{\sqrt{C_{ii}C_{jj}}}$$



Correlation matrices



Impact on Global PDFs

Fit settings

We compared four different fits:

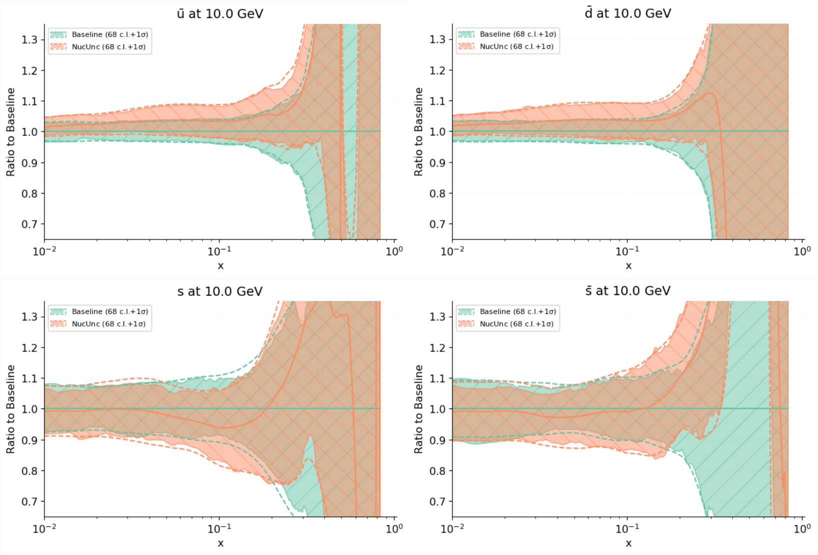
1. **Baseline** - NNPDF3.1 with small changes
2. **NoNuc** - Baseline with nuclear data removed
3. **NucUnc** - Baseline with nuclear uncertainties
4. **NucCor** - Baseline with nuclear uncertainties and correction

Fit quality

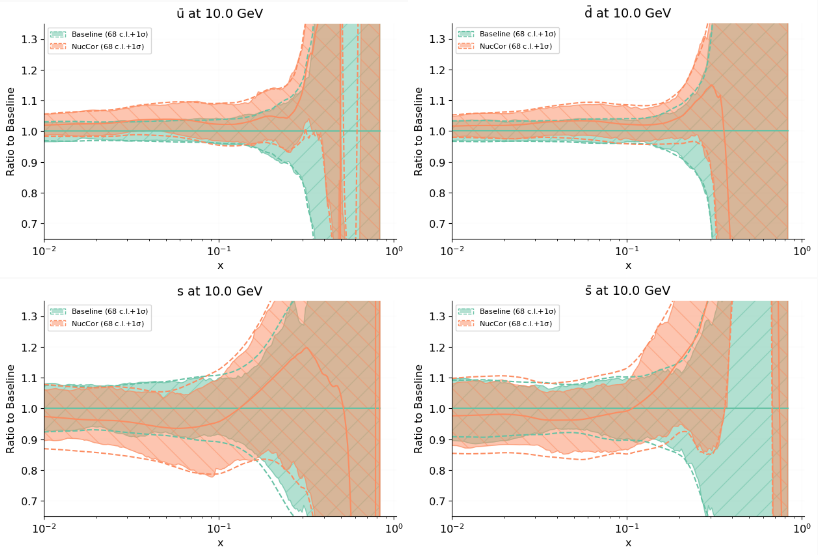
Experiment	N_{dat}	Baseline	NoNuc	NucUnc	NucCor
CHORUS ν	416	1.29	–	0.97	1.04
CHORUS $\bar{\nu}$	416	1.20	–	0.78	0.83
NuTeV ν	39	0.41	–	0.31	0.40
NuTeV $\bar{\nu}$	37	0.90	–	0.62	0.83
E605 σ^p	85	1.18	–	0.85	0.89
ATLAS	360	1.08	1.04	1.04	1.05
CMS	409	1.07	1.07	1.07	1.07
LHCb	85	1.46	1.27	1.32	1.37
Total	4285	1.18	1.14	1.07	1.09

Table 1: χ^2 per data point

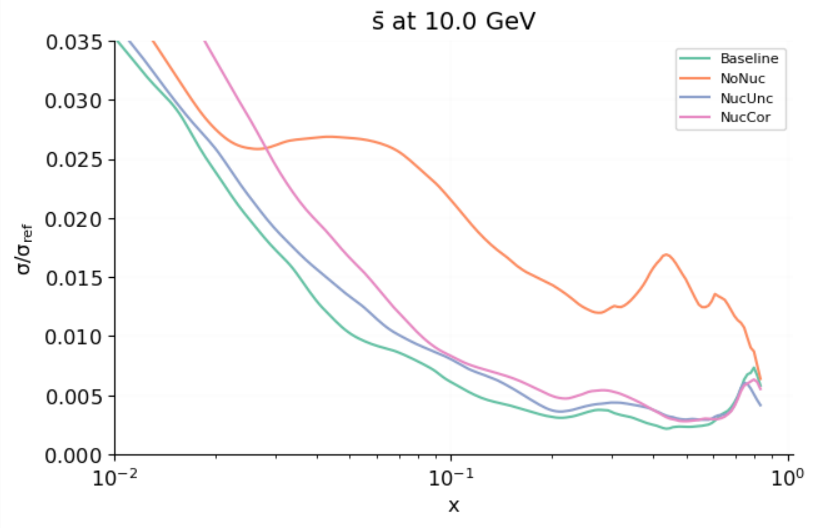
PDFs for NucUnc



PDFs for NucCor



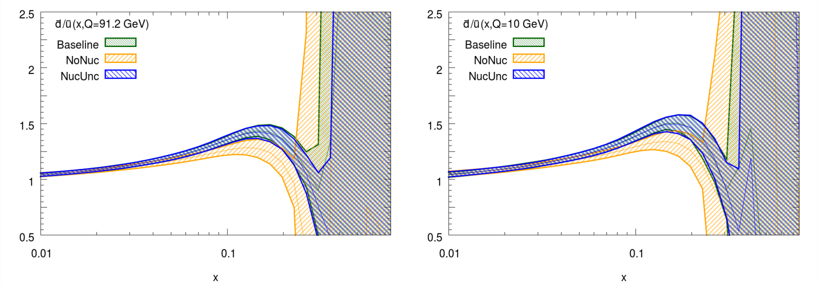
PDF errors



$\bar{s}$ at 10.0 GeV
Baseline
NoNuc
NucUnc
NucCor
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
σ/σ_{ref}
10^{-2}
10^{-1}
10^{0}
x

Phenomenology

Sea quark asymmetry



- Perturbatively, we expect $f_{\bar{u}} \sim f_{\bar{d}}$
- Observe an asymmetry (NA51 [A. Baldit et al., Phys. Lett. B332 (1994) 244-250] , NuSea/E866 [E. A. Hawker et al., hep-ex/9803011])
- Nuclear data has a significant effect
- Inclusion of nuclear uncertainty makes little difference

Strangeness fraction

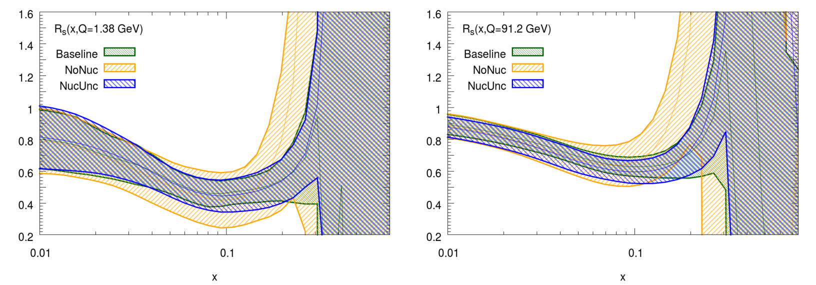
$$R_s(x, Q^2) = \frac{s(x, Q^2) + \bar{s}(x, Q^2)}{\bar{d}(x, Q^2) + \bar{u}(x, Q^2)} \quad (1)$$

$$K_s(x, Q^2) = \frac{\int_0^1 dx[s(x, Q^2) + \bar{s}(x, Q^2)]}{\int_0^1 dx[\bar{d}(x, Q^2) + \bar{u}(x, Q^2)]} \quad (2)$$

$R_s(x = 0.023,\ Q = 1.38\ \text{GeV})$; $K_s(Q = 1.38\ \text{GeV})$:

- Baseline: $R_s = +0.69 \pm 0.15$, $K_s = +0.63 \pm 0.09$
- NoNuc: $R_s = +0.68 \pm 0.14$, $K_s = +0.97 \pm 0.18$
- NucUnc: $R_s = +0.65 \pm 0.14$, $K_s = +0.63 \pm 0.09$
- NucCor: $R_s = +0.64 \pm 0.15$, $K_s = +0.61 \pm 0.10$
- ATLAS W/Z + HERA DIS: $R_s = +1.13 \pm 0.11$
  [ATLAS Collaboration, arXiv:1612.03016]

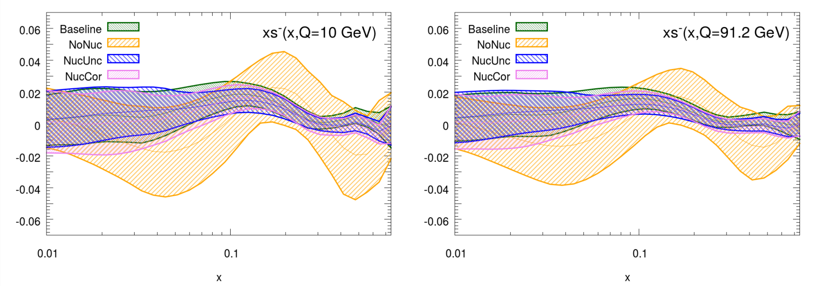
Strangeness fraction



- Tension with ATLAS W/Z + HERA DIS not reconciled
- NuTeV probes different kinematic region (cf χ^2s)

Strange valence distribution

$$xs^{-}(x,Q) = x[s(x,Q) - \bar{s}(x,Q)] \tag{3}$$



- Again, nuclear data important
- Little difference between Baseline, NucUnc and NucCor
- Choose NucUnc as this is more conservative

Summary

Summary

- Studied nuclear data in proton PDF fits
- Determined nuclear uncertainties based on comparison to nPDF sets DSSZ12, nCTEQ15 & EPPS16
- Used theoretical covariance matrix to include uncertainties in fits
- Fit quality improved, and largest impact on sea quark PDFs
- Future inclusion of new nPDF sets
- We will carry out a similar analysis of deuterium data
- Scope for application to other theoretical uncertainties

Thanks

Thanks for listening!

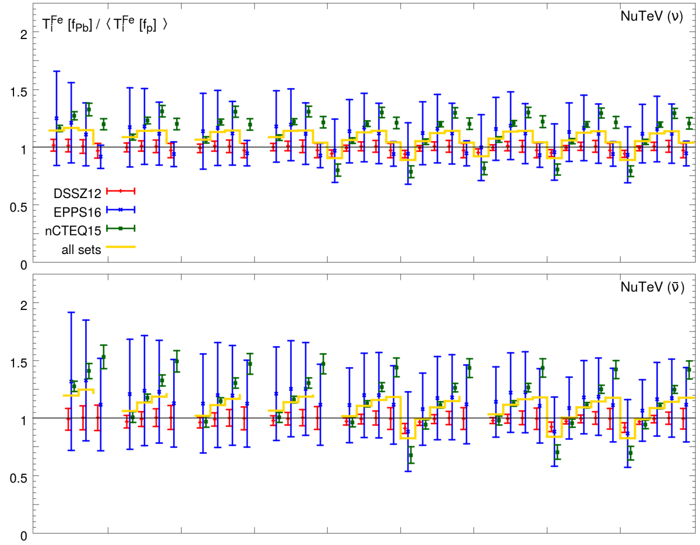
Additional slides

Correlation

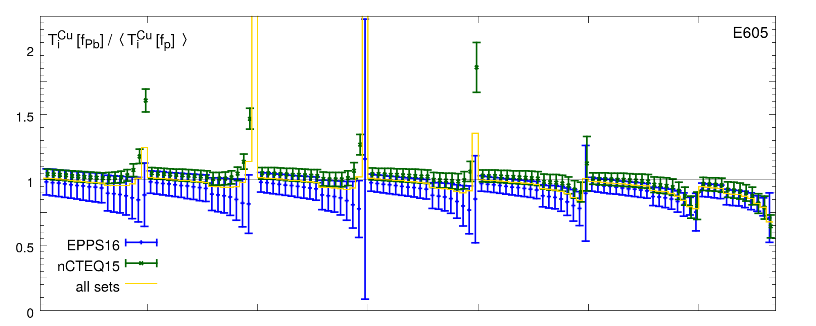
$$\rho[A, B] = \frac{< AB >_{rep} - < A >_{rep} < B >_{rep}}{\sigma_A \sigma_B}$$

[A. Guffanti & J. Rojo, arXiv:1008.4671]

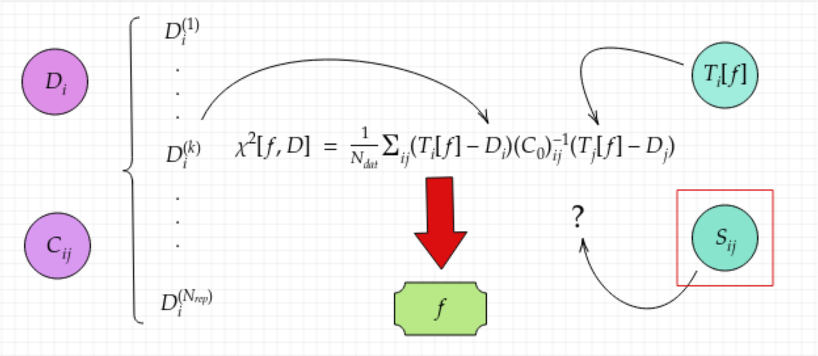
Observables: NuTeV



Observables: E605



NNPDF fitting methodology



$$< D_i^{(k)} >= D_i,$$
$$< (D_i^{(k)} - D_i)(D_j^{(k)} - D_j) >= C_{ij}$$

Theory covariance matrix

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- Nuisance parameters: $\Delta_i^{(n)} = T_i^{(n)} - T_i$, $n = 1, ..., N_{nuis}$
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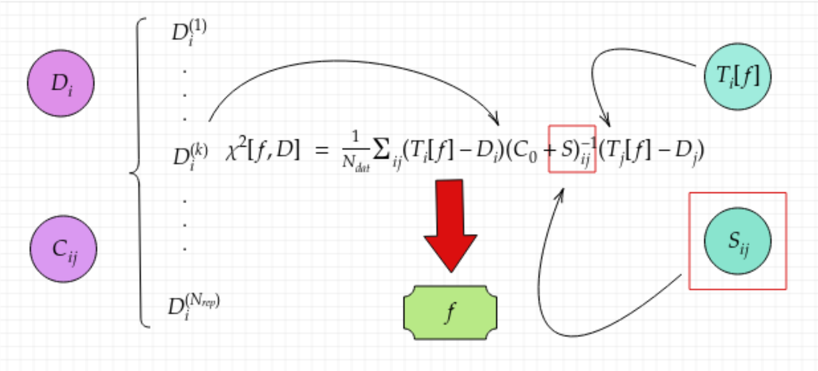
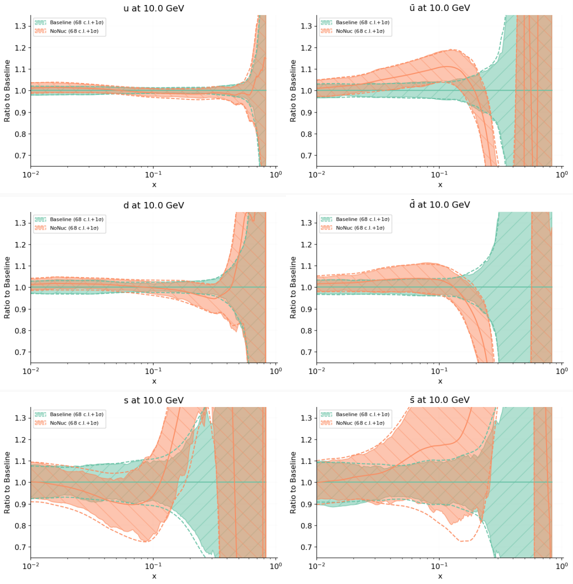
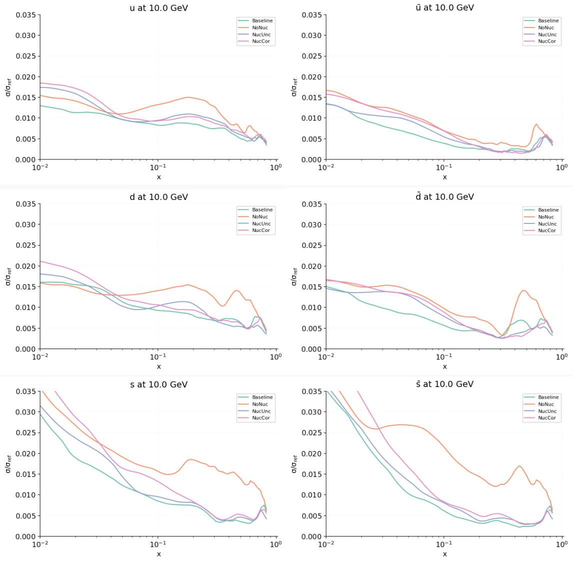


PDFs without nuclear data



PDF errors



u at 10.0 GeV
ū at 10.0 GeV
d at 10.0 GeV
d̄ at 10.0 GeV
s at 10.0 GeV
s̄ at 10.0 GeV
Baseline
NoNuc
NucUnc
NucCor
σ/σ_ref
x

Optimal fluctuations

Optimal fluctuations $\sum_n a_n \delta_i^{(n)}$, obtained by minimising

$$\chi^2 = \sum_i \left[\frac{D_i - T_i - \sum_n a_n \delta_i^{(n)}}{error_i} \right]^2 + \sum_n a_n^2 \tag{4}$$

[J. Pumplin et al., arXiv:hep-ph/0201195]

Optimal fluctuations

Figure 2: Comparison between the optimal fluctuations obtained with our NucUnc and NucCor fits, and the shifts δT_i^N.