Neutrino-nucleus DIS data and their consistency with nuclear PDFs

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General remarks

- **Neutrino DIS probes different partonic combinations than e.g. the charged lepton DIS**

→ **Complemtentary information on the PDFs (especially the strange quark)**

$$d^2\sigma^{\nu A} \propto \left(d^A + s^A + b^A\right) + (1-y)^2 \left(\overline{u}^A + \overline{c}^A\right)$$
$$d^2\sigma^{\overline{\nu} A} \propto \left(\overline{d}^A + \overline{s}^A + \overline{b}^A\right) + (1-y)^2 \left(u^A + c^A\right)$$

vs.

$$d^2\sigma^{\ell^\pm A} \propto \frac{4}{9}\left(u^A + c^A + \overline{u}^A + \overline{c}^A\right) + \frac{1}{9}\left(d^A + s^A + b^A + \overline{d}^A + \overline{s}^A + \overline{b}^A\right)$$

- **Data taken with heavy targets (Fe, Pb)**

  Need to account for the nuclear effects in PDFs

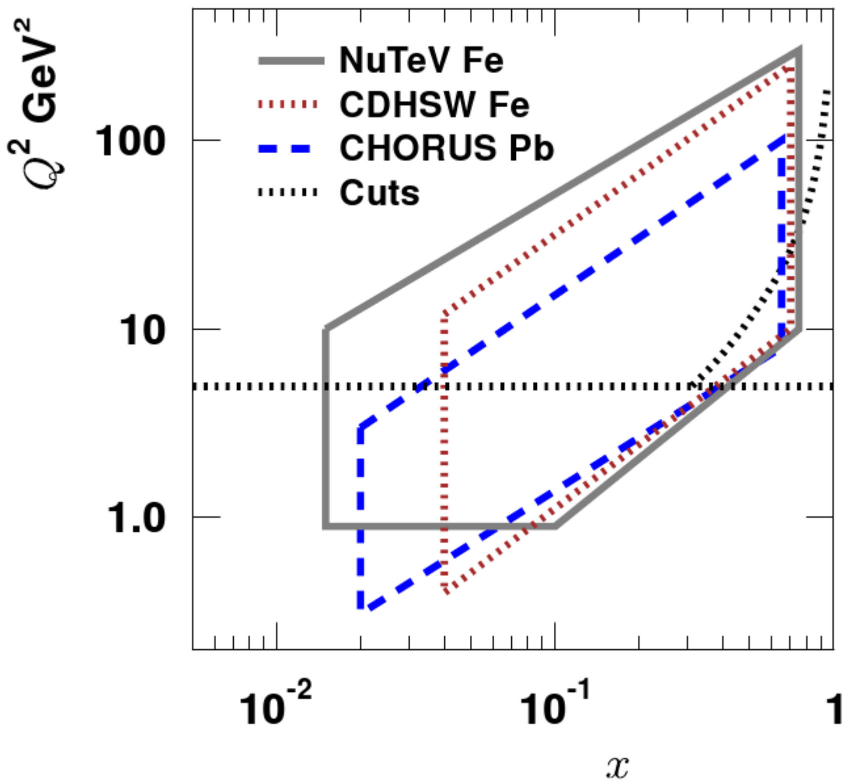
  Are these effects the same as extracted from charged lepton nuclear processes – are the nPDFs universal?

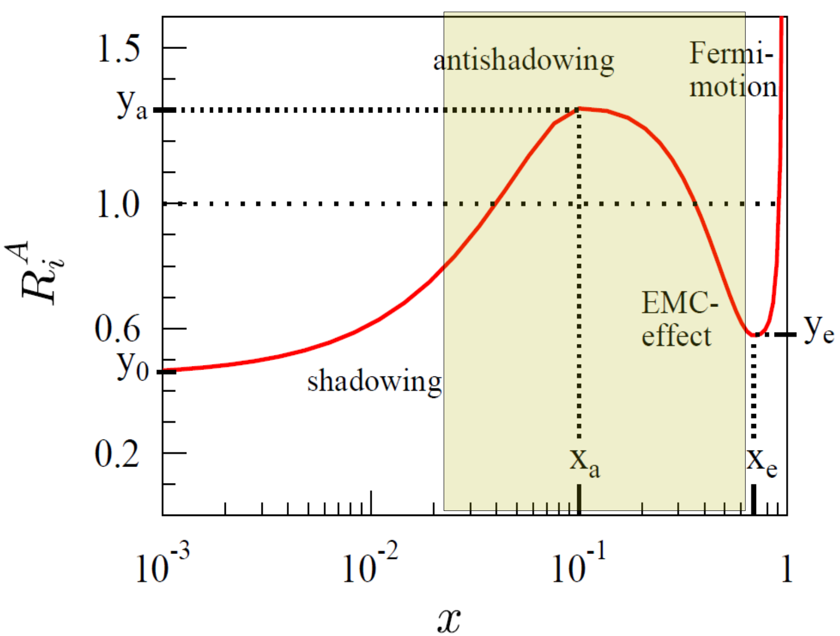
- **The adequacy of the factorization in nuclear neutrino DIS has been studied by independent groups. The conclusions contradictory:**

nCTEQ: **No** ; *Paukkunen & Salgado*: **Yes** ; *De Florian et.al (DSSZ)*: **Yes**

The experimental input

- **Three independent data sets:** **NuTeV (Fe), CDHSW (Fe) and CHORUS (Pb)**





- **Kinematical cuts:** $Q^2_{\rm cut} > 4\,{\rm GeV}^2$, and $W^2_{\rm cut} > 12.25\,{\rm GeV}^2$

→ **2136 NuTeV, 824 CHORUS, 937 CDHSW datapoints**

- **The large kinematical overlap enables us to study the mutual compatibilty**

The framework of the present analysis

- **The main elements of our calculations**
  - NLO pQCD & SACOT prescription for the heavy quarks
  - Target mass correction (Qiu et.al. *JHEP 0807 (2008) 090*)

$$\int_x^1 \frac{dz}{z}\omega_{ik}(z)\, f_k^A\left(\frac{x}{z}\right) \rightarrow \int_x^1 \frac{dz}{z}\omega_{ik}(z)\, f_k^A\left(\frac{\xi}{z}\right) \qquad \xi \equiv 2x/(1+\sqrt{1+4x^2M^2/Q^2})$$

  - Electroweak radiation (Bardin et.al *JHEP 0506 (2005) 078*)

$$F_i^A = \sum_k \left[\omega_{ik}^{\mathrm{LO}}\left(1+\Delta_k^{\mathrm{radiative}}\right) + \omega_{ik}^{\mathrm{NLO}}\right] \otimes f_k^A$$

  - Use CTEQ6.6 free proton PDFs & EPS09 nuclear modifications

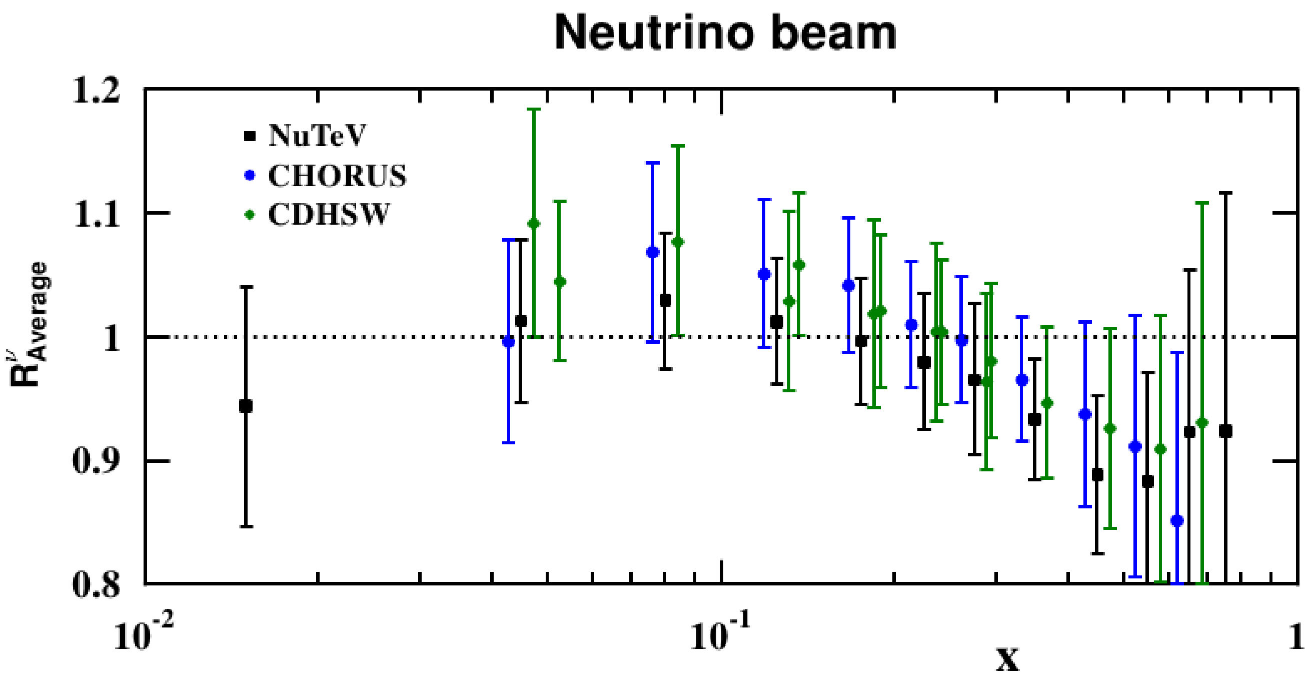
- **Plot the data as a weighted average**

$$R_{\mathrm{Average}}^{\mathrm{CTEQ6.6}} \equiv \left(\sum_{i\in\mathrm{fixed}\,x}^{N} \frac{R_i^{\mathrm{CTEQ6.6}}}{\sigma_i}\right)\left(\sum_{i\in\mathrm{fixed}\,x}^{N} \frac{1}{\sigma_i}\right)^{-1} \pm N \times \left(\sum_{i\in\mathrm{fixed}\,x}^{N} \frac{1}{\sigma_i}\right)^{-1}$$

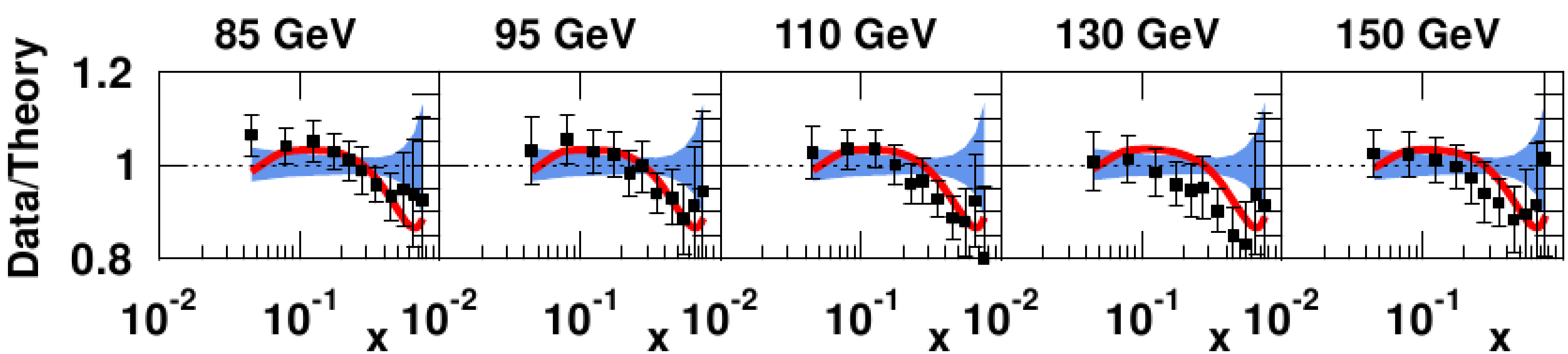
$$R^{\mathrm{CTEQ6.6}} \equiv \frac{\sigma^{\nu,\overline{\nu}}\,(\mathrm{Experimental})}{\sigma^{\nu,\overline{\nu}}\,(\mathrm{CTEQ6.6})}$$

← *practically independent of Q^2*

Inconsistecies in the absolute normalization



- **The NuTeV data few percents below the rest**
- **Not a big surprise as it has been shown (JHEP 1007 (2010) 032), that the NuTeV data shows different normalization from a neutrino energy to antoher. For example:**



Normalize the data "by itself"

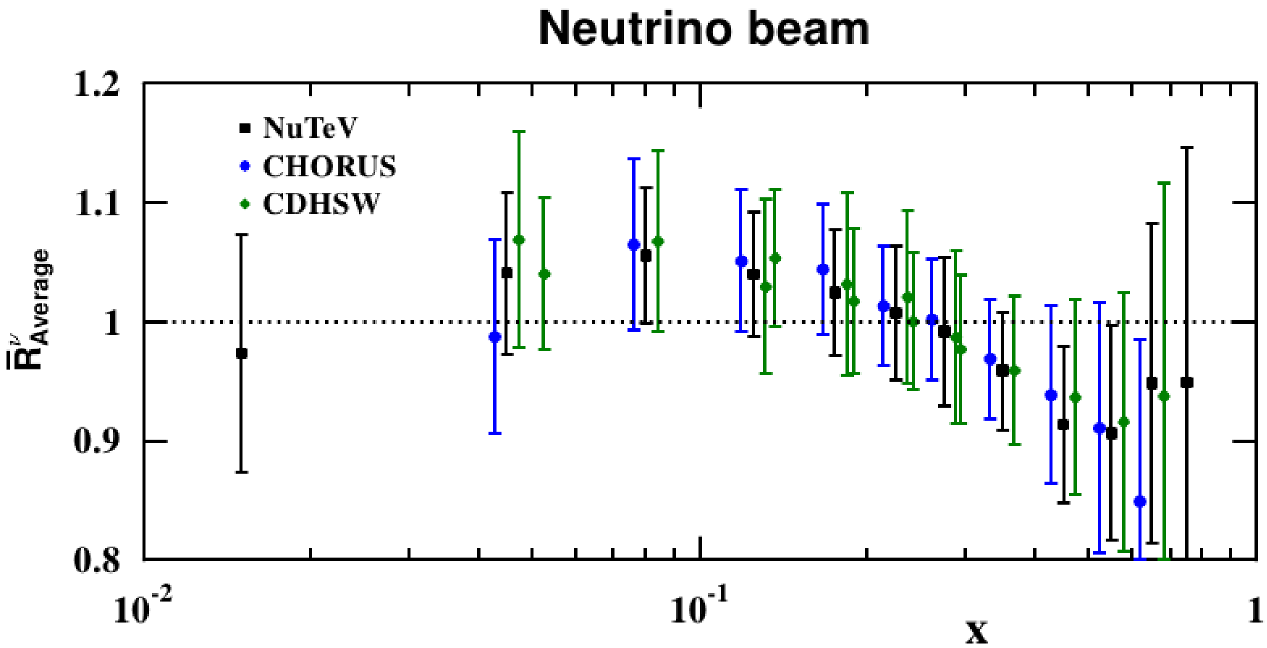
- **Try to account for the differences in the absolute normalization. Define**

$$I^{\nu}_{\rm exp}(E) \equiv \sum_{i \in \text{fixed } E} \sigma_{{\rm exp},i}(x,y,E) \times B_i(x,y)$$

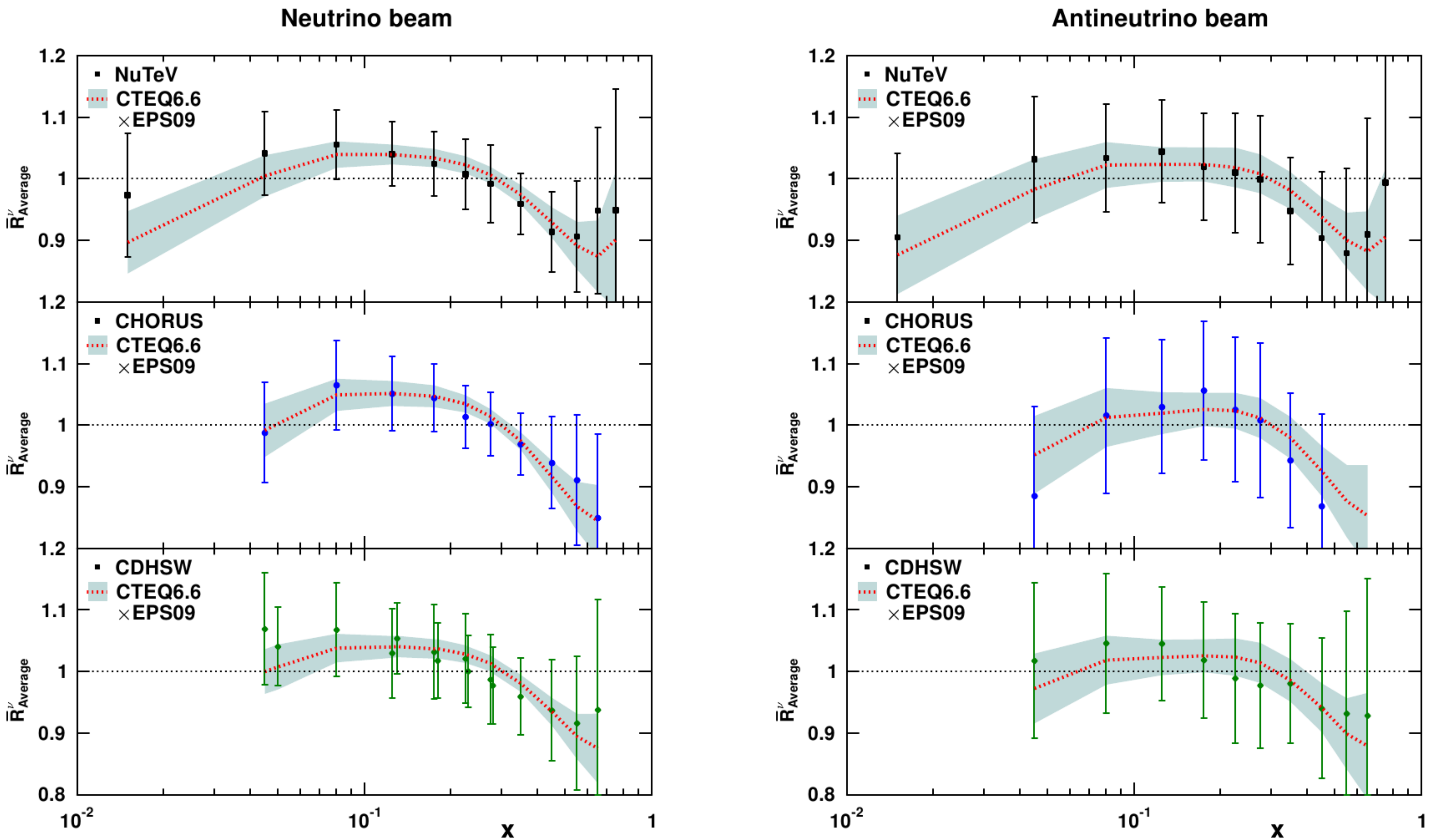
Size of the experimental bin

- **Instead of "bare" cross-section ratios, consider ratios of *normalized* cross-sections**

$$\overline{R}^{\nu}(x,y,E) \equiv \frac{\sigma^{\nu}_{\rm exp}(x,y,E)/I^{\nu}_{\rm exp}(E)}{\sigma^{\nu}_{\rm CTEQ6.6}(x,y,E)/I^{\nu}_{\rm CTEQ6.6}(E)}.$$



Compare to CTEQ6.6 x EPS09



Check the consistency by "Hessian reweighting"

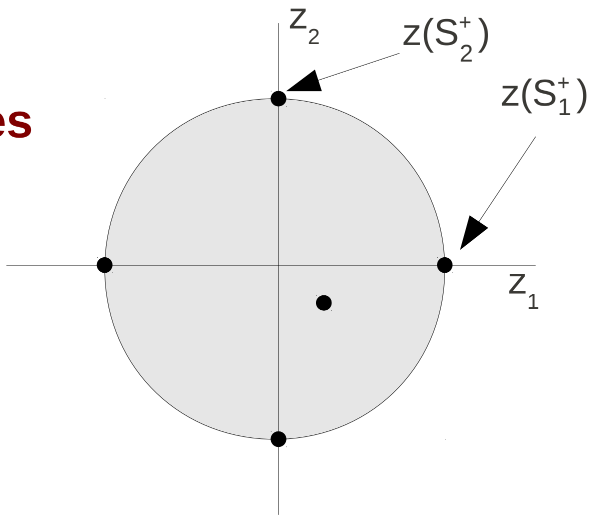
Based on work of NNPDF Nucl.Phys.B849:112-143,2011 and Thorne et. al. JHEP 1208:052,2012

- **Global fits with Hessian erroranalysis expand the χ^2 around the minimum as**

$$\chi^2 \approx \chi_0^2 + \sum_{ij} \delta a_i H_{ij} \delta a_j = \chi_0^2 + \sum_i z_i^2,$$

- **The central set & error sets are defined in z-space coordinates**

$$z(S_0) = (0, 0, ..., 0)$$
$$z(S_1^{\pm}) = \pm\sqrt{\Delta\chi^2}\,(1, 0, ..., 0)$$
$$z(S_2^{\pm}) = \pm\sqrt{\Delta\chi^2}\,(0, 1, ..., 0)$$



- **Any PDF-dependent quantity *X*, can be approximated close to the origin by**

$$X[S] \approx X[S_0] + \sum_k \left.\frac{\partial X[S]}{\partial z_k}\right|_{S=S_0} z_k \approx X_0 + \mathbf{D}\cdot\mathbf{w}$$

$$D_k \equiv \frac{X[S_k^+] - X[S_k^-]}{2}$$
$$w_k \equiv \frac{z_k}{\sqrt{\Delta\chi^2}}.$$

Check the consistency by "Hessian reweighting"

- **Consider adding a new data set into the analysis**

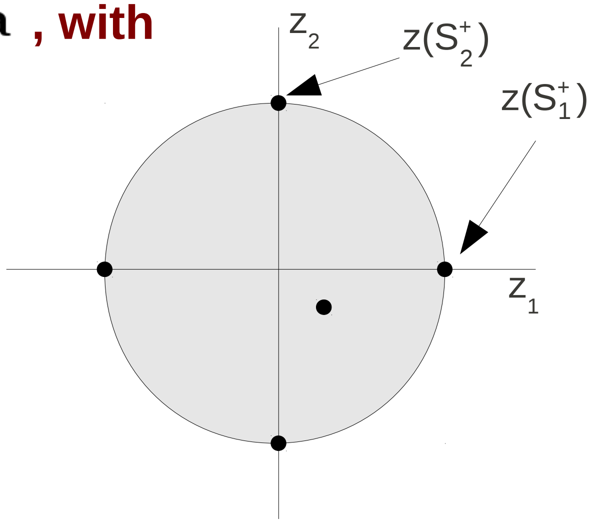
$$\chi^2 = \chi_0^2 + \sum_{\{X^{\rm data}\}} \left[\frac{X_k\left[S\right] - X_k^{\rm data}}{\delta_k^{\rm data}} \right]^2 + \Delta\chi^2 \sum_k w_k^2,$$

- **The minimum of this expression is given by** $\mathbf{w}_{\rm min} = -\mathbf{B}^{-1}\mathbf{a}$ **, with**

$$B_{ij} = \sum_k \frac{D_l^k D_j^k}{\left(\delta_k^{\rm data}\right)^2} + \Delta\chi^2 \delta_{ij}$$

$$a_i = \sum_k \frac{D_i^k \left(X_k\left[S_0\right] - X_k^{\rm data}\right)}{\left(\delta_k^{\rm data}\right)^2}$$

$$D_l^k = \frac{X_k\left[S_l^+\right] - X_k\left[S_l^-\right]}{2}.$$



- **If the new data set is in agreement within the original fit, the "penalty"** $\Delta\chi^2 \sum_k w_k^2$ **should be less than** $\Delta\chi^2$.

Check the consistency by "Hessian reweighting"

- **Apply the method to the neutrino data with:**

$$\Delta\chi^2 \sum_k w_k^2 \rightarrow \Delta\chi^2_{\rm EPS09} \sum_{k=1}^{15} w_k^2 + \Delta\chi^2_{\rm CTEQ6.6} \sum_{k=16}^{37} w_k^2 \quad \textbf{with} \quad \Delta\chi^2_{\rm EPS09} = 50 \quad \Delta\chi^2_{\rm CTEQ} = 100$$

	All CTEQ6.6 and EPS09 error sets				Only EPS09 error sets	
NuTeV	$\chi^2_{w=0}/N$	$\chi^2_{w_{\rm min}}/N$	EPS09-penalty	CTEQ-penalty	$\chi^2_{w_{\rm min}}/N$	EPS09-penalty
Normalization	0.84	0.77	13.9	35.4	0.81	33.8
No normalization	1.04	0.90	40.3	42.5	0.94	77.4
CHORUS	$\chi^2_{w=0}/N$	$\chi^2_{w_{\rm min}}/N$	EPS09-penalty	CTEQ-penalty	$\chi^2_{w_{\rm min}}/N$	EPS09-penalty
Normalization	0.70	0.69	2.13	2.63	0.70	2.48
No normalization	0.86	0.81	3.35	14.4	0.84	5.13
CDHSW	$\chi^2_{w=0}/N$	$\chi^2_{w_{\rm min}}/N$	EPS09-penalty	CTEQ-penalty	$\chi^2_{w_{\rm min}}/N$	EPS09-penalty
Normalization	0.70	0.64	7.20	17.3	0.68	9.26
No normalization	0.81	0.74	10.4	17.8	0.78	14.1

- **The normalized neutrino data could be added to the global fits**

Summary

- **Without the normalization, NuTeV data disagrees with CHORUS & CDHSW**

  As shown by the nCTEQ, accounting for the internal correlations of the NuTeV data only makes this disagreement more pronounced.

- **Disagreements between different data sets are nothing new, recall e.g.**

  BCDMS & NMC vs. EMC controversy (see e.g. Sloan, Wimpenny, Bazizi 1990),
  Controversy between D0 Run-I vs Run-II data on W charge asymmetry

- **We propose to use the normalized, instead of the absolute neutrino DIS cross-sections, in global PDF fits.**

  All data seems to get in mutual agreement

- **We used the “Hessian reweighting” for studying the compatibility of a new data set in a existing global PDF fit.**

Backup slides

The DSSZ analysis : Phys. Rev. D85, 074028 (2012)

- A global nPDF fit including neutrino structure function data from NuTeV, CHORUS & CDHSW.

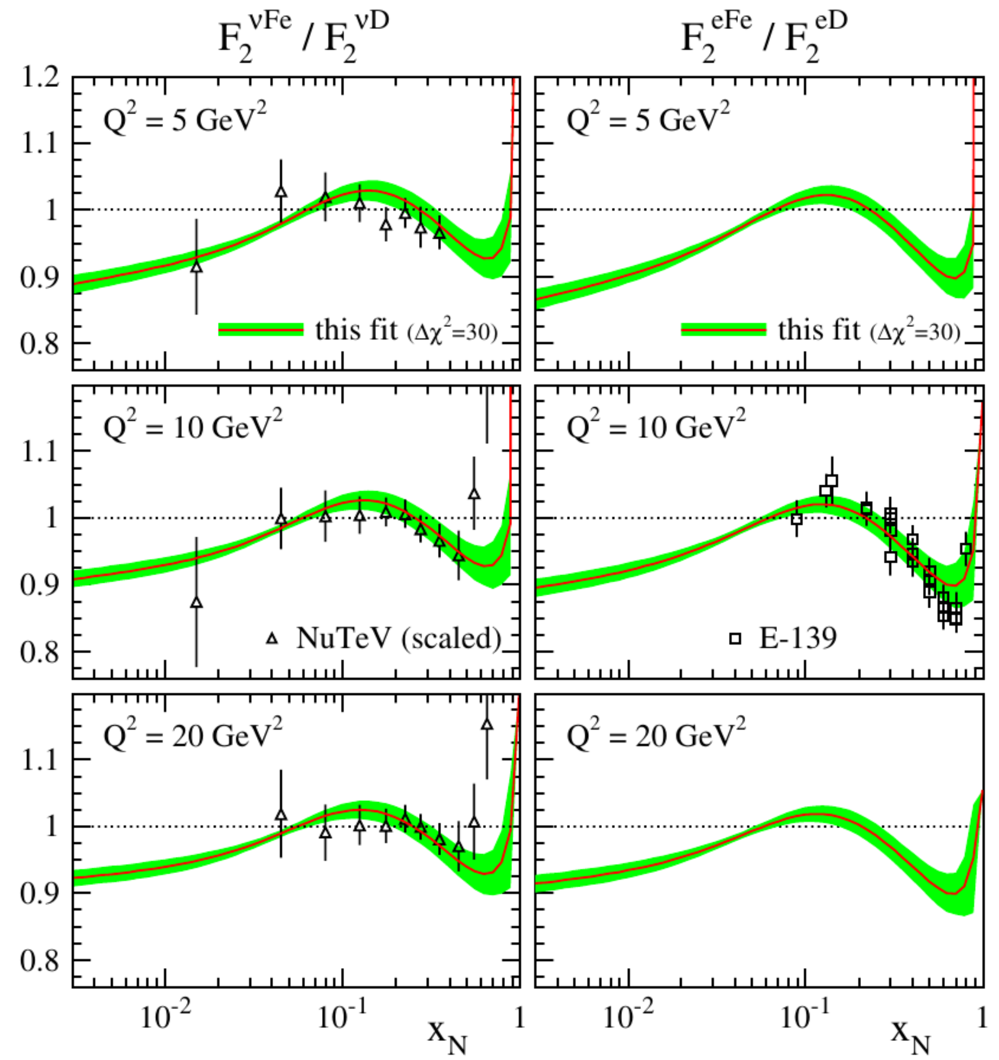
  much more scarce than the absolute cross-section data

- Used MSTW2008 free proton PDFs as a baseline.

  this set was already constrained by the NuTeV data

- Added the MSTW2008 uncertainties in quadrature to the experimental errors.

  as they were point-to-point uncorrelated errors.



to accommodate all the features of the data. We do not observe any noticeable tension among the different sets of data in the fit. The parameters describing our optimum set

The nCTEQ analysis: Phys. Rev. Lett. 106, 122301 (2011)

- A global nPDF analysis with **NuTeV & CHORUS** neutrino data included

$$\chi^2 = \sum_{l^\pm A \text{ data}} \chi_i^2 + \sum_{\nu A \text{ data}} w\chi_i^2$$

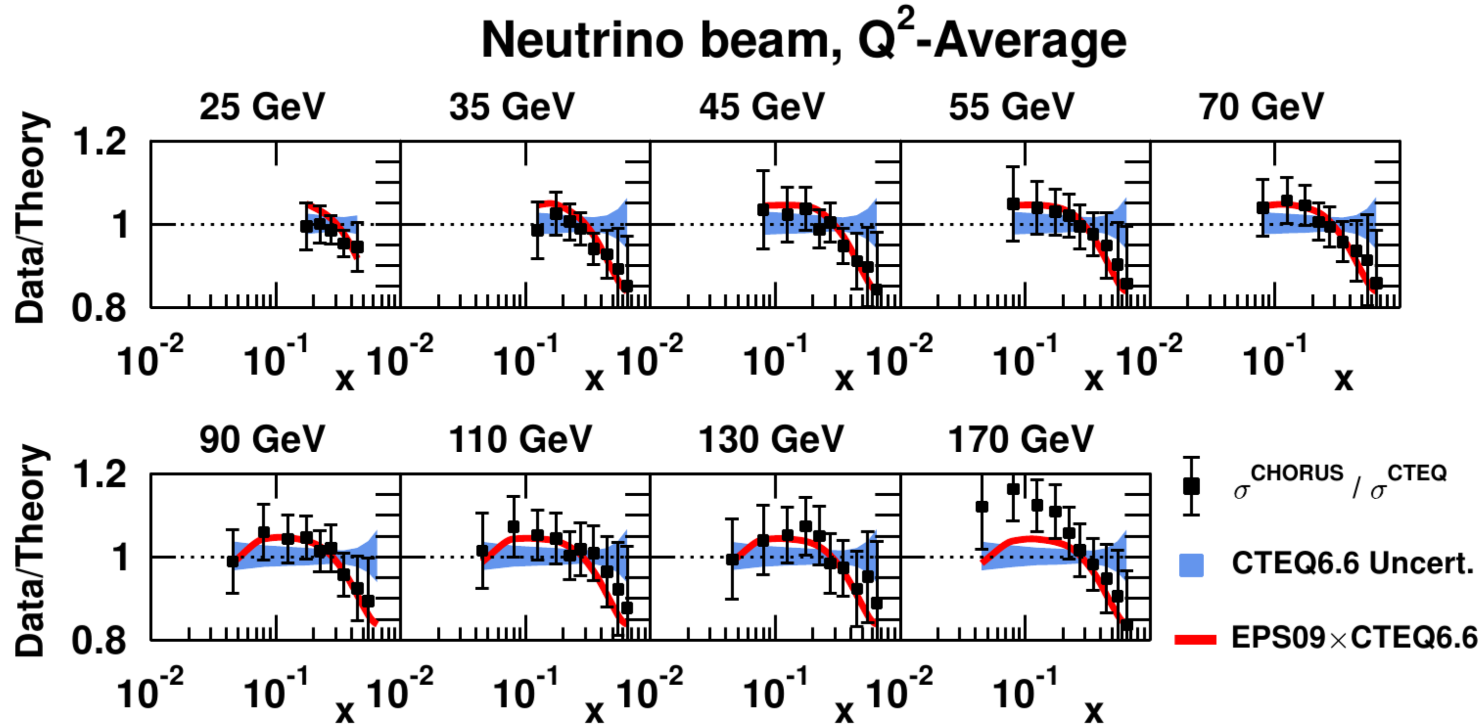
- Used the NuTeV correlation matrix to compute the χ^2

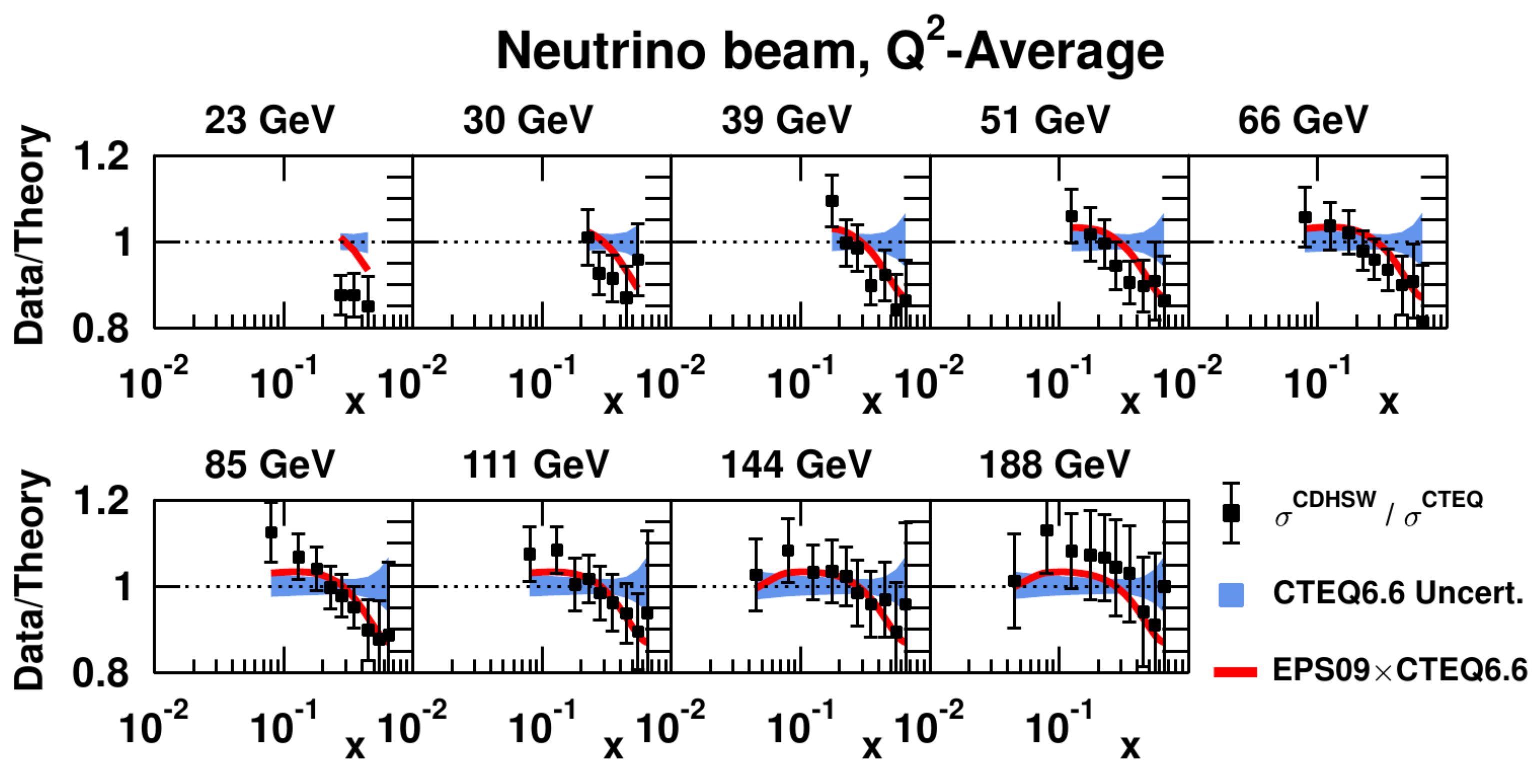
$$\chi^2 = \sum_{\alpha,\beta=1}^{N^{\nu}_{DATA}} \left[\frac{d^2\sigma}{dxdy}^{th}_{\alpha} - \frac{d^2\sigma}{dxdy}^{D}_{\alpha} \right] (\mathbf{M}_{\nu}^{-1})_{\alpha\beta} \left[\frac{d^2\sigma}{dxdy}^{th}_{\beta} - \frac{d^2\sigma}{dxdy}^{D}_{\beta} \right]$$

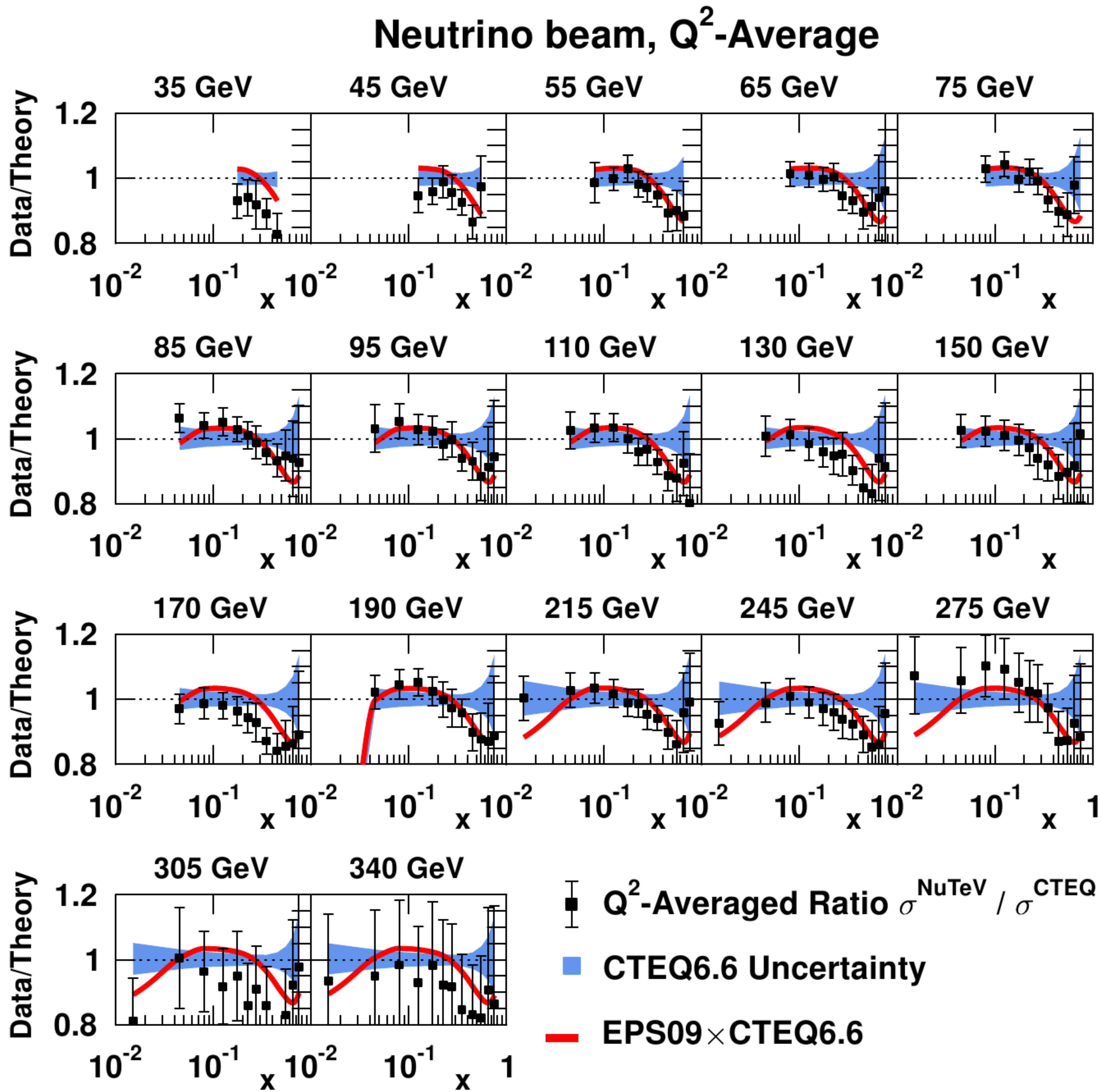
TABLE II. Summary table of a family of compromise fits.

w	$l^\pm A$	χ^2 (/pt)	νA	χ^2 (/pt)	total χ^2(/pt)
0	708	638 (0.90)	···	···	638 (0.90)
1/7	708	645 (0.91)	3134	4710 (1.50)	5355 (1.39)
1/2	708	680 (0.96)	3134	4405 (1.40)	5085 (1.32)
1	708	736 (1.04)	3134	4277 (1.36)	5014 (1.30)
∞	···	···	3134	4192 (1.33)	4192 (1.33)

- **Strategy:** Find *w* that keeps χ^2(neutrino) & χ^2(other data) from growing beyond "90% condifence criteria" from the best fit.
- **Result:** No acceptable fit.


Neutrino beam, Q²-Average
25 GeV
35 GeV
45 GeV
55 GeV
70 GeV
90 GeV
110 GeV
130 GeV
170 GeV
Data/Theory
x
σCHORUS / σCTEQ
CTEQ6.6 Uncert.
EPS09×CTEQ6.6


Neutrino beam, Q²-Average
23 GeV
30 GeV
39 GeV
51 GeV
66 GeV
85 GeV
111 GeV
144 GeV
188 GeV
Data/Theory
x
σCDHSW / σCTEQ
CTEQ6.6 Uncert.
EPS09×CTEQ6.6


Neutrino beam, Q²-Average
35 GeV
45 GeV
55 GeV
65 GeV
75 GeV
85 GeV
95 GeV
110 GeV
130 GeV
150 GeV
170 GeV
190 GeV
215 GeV
245 GeV
275 GeV
305 GeV
340 GeV
Data/Theory
x
Q²-Averaged Ratio σ^NuTeV / σ^CTEQ
CTEQ6.6 Uncertainty
EPS09×CTEQ6.6