On the consistency of νA DIS data with the present PDFs

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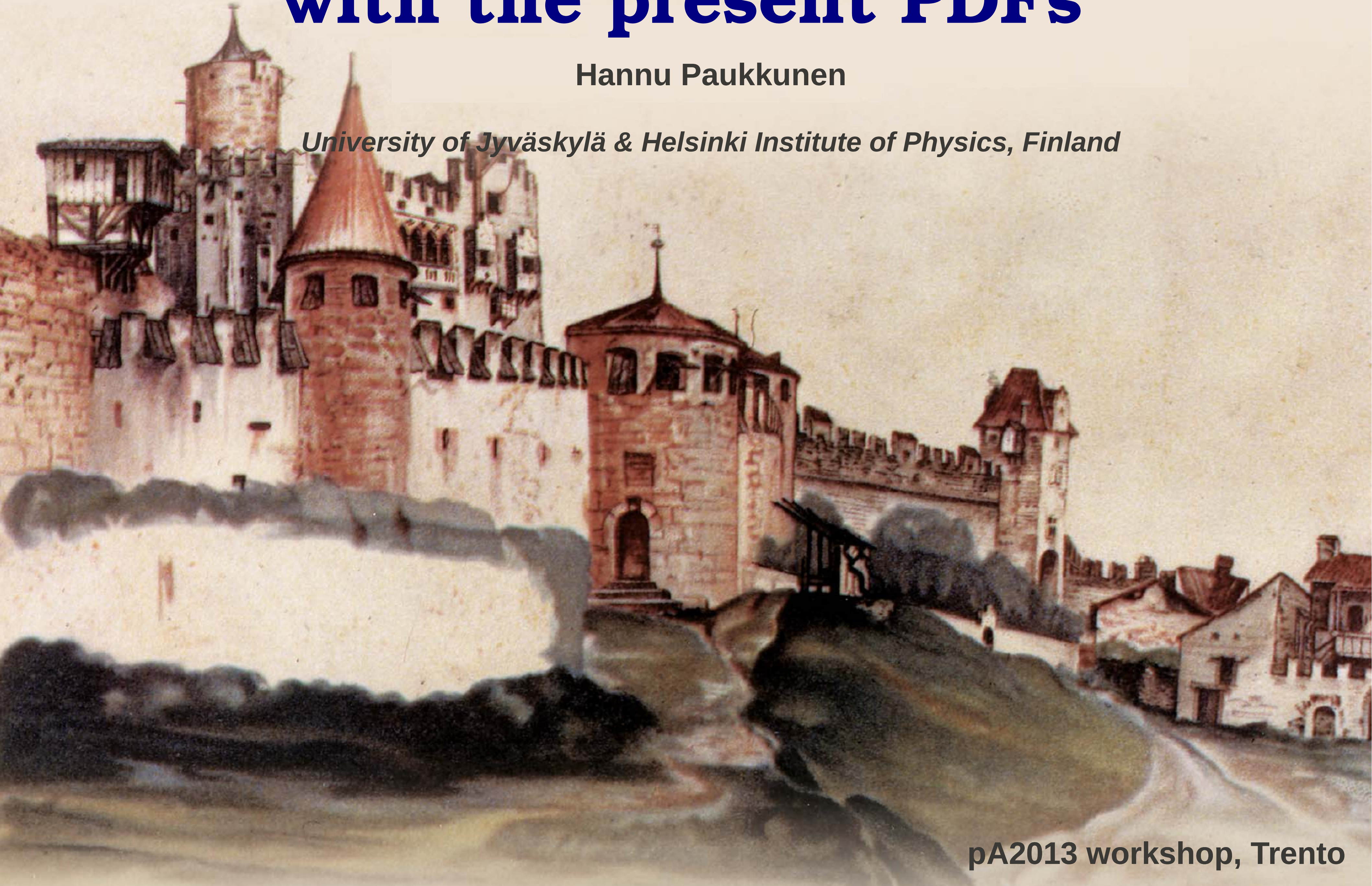


pA2013 workshop, Trento

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

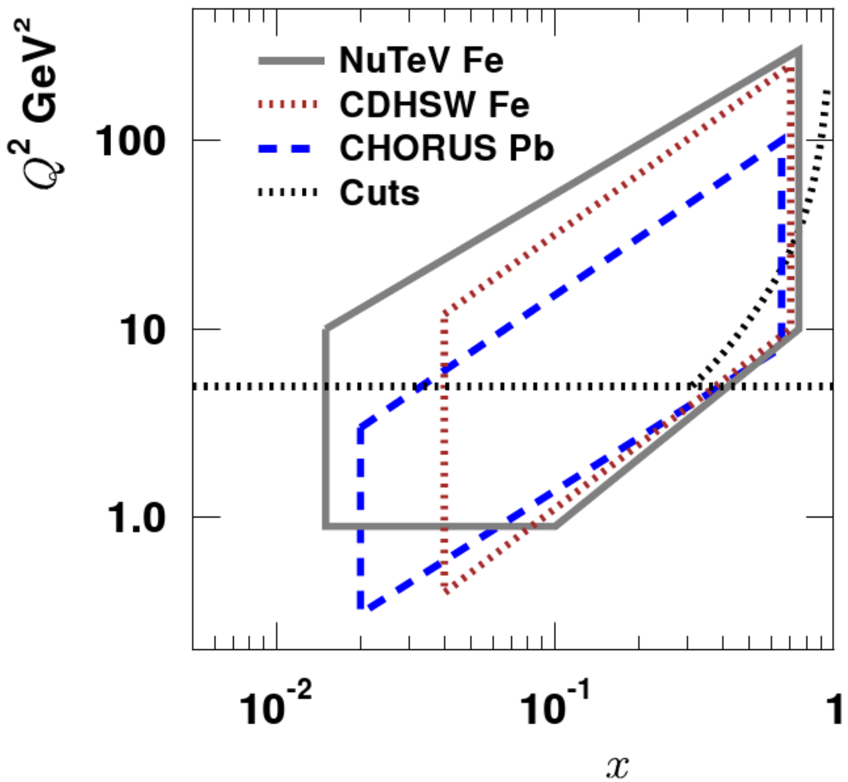
  Are these effects the same as extracted from charged lepton nuclear processes – are the nPDFs universal?

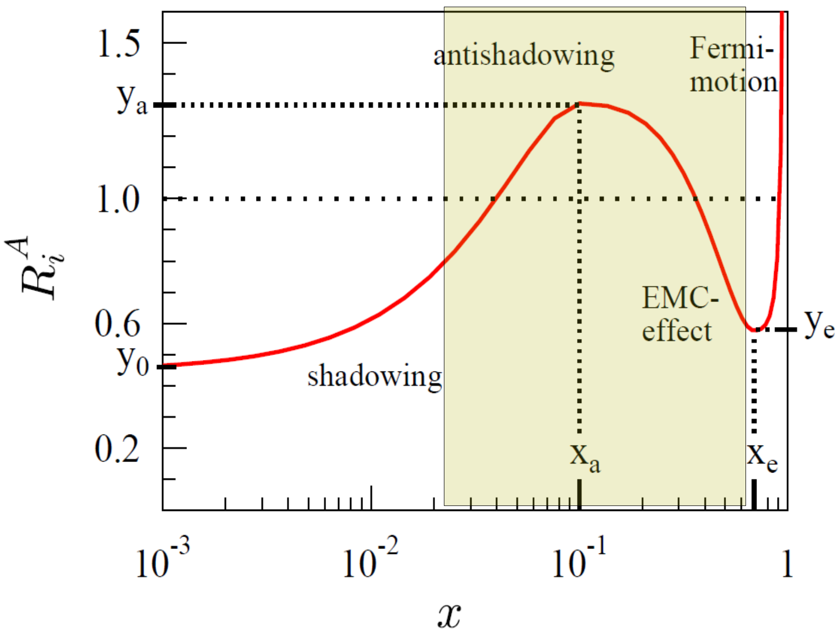
- **The adequacy of the factorization in nuclear neutrino DIS has been studied by independent groups. The conclusions contradictory:**

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

The high-energy neutrino data

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





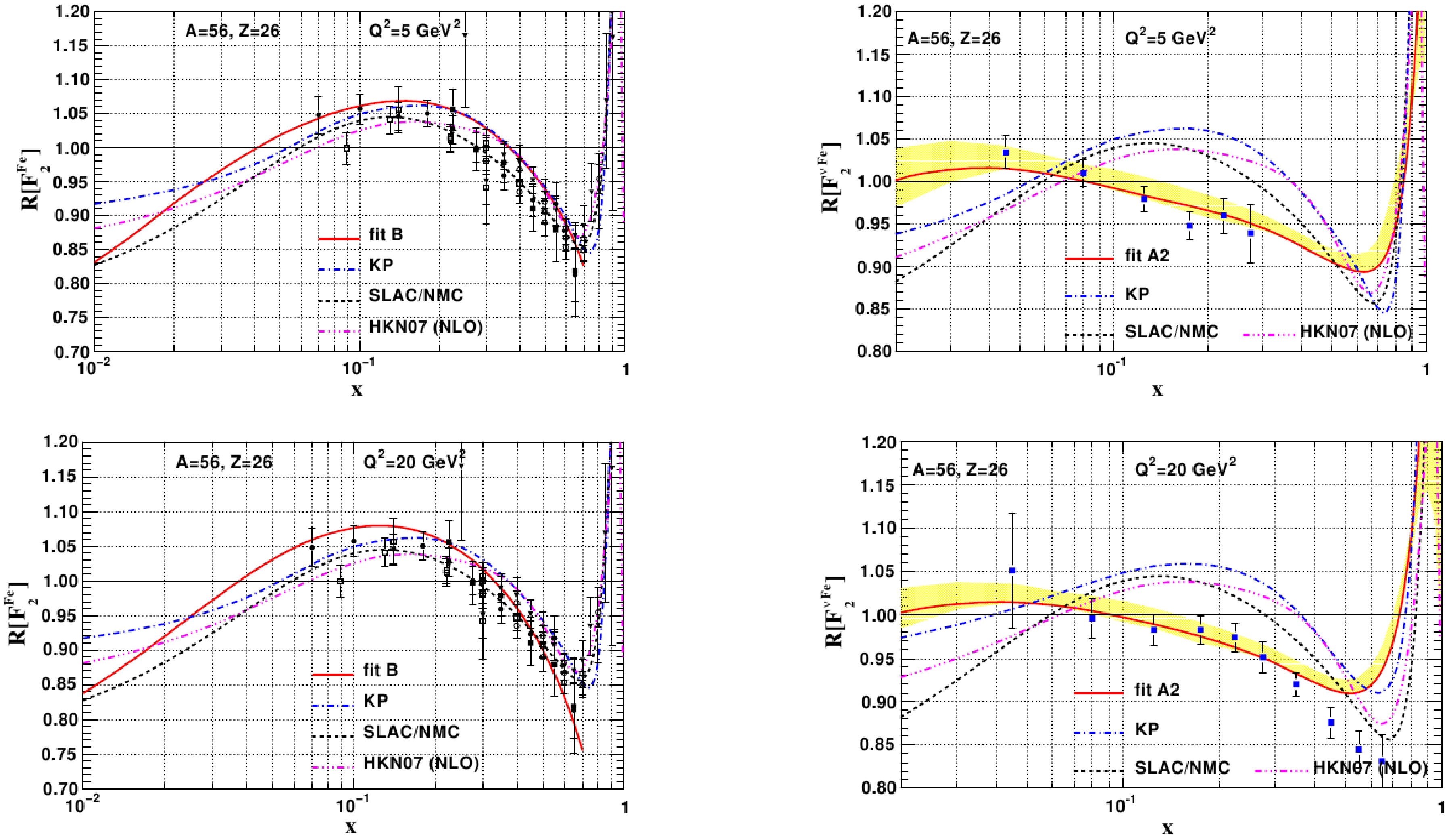
- **Typical kinematical cuts:** $Q^2_{\rm cut} > 4\,{\rm GeV}^2$, and $W^2_{\rm cut} > 12.25\,{\rm GeV}^2$

→ ~ 2000 NuTeV, 1000 CHORUS, 1000 CDHSW datapoints

- **The large kinematical overlap should enable to check the mutual compatibility**

The nCTEQ: Phys. Rev. D77 054013 (2008) & Phys. Rev. D80 094004 (2009)

- Separate NLO parton fits to the NuTeV neutrino data, and to other nuclear data
- Different nuclear modifications in neutrino and charged lepton DIS were found



Paukkunen & Salgado: JHEP 1007 (2010) 032

- **Main differences in comparison to the nCTEQ analysis:**
  - More diverse set of neutrino DIS data: **NuTeV (Fe), CDHSW (Fe) and CHORUS (Pb)**
  - The target mass corrections according to Accardi & Qiu *[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]* as a part of the cross-sections

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

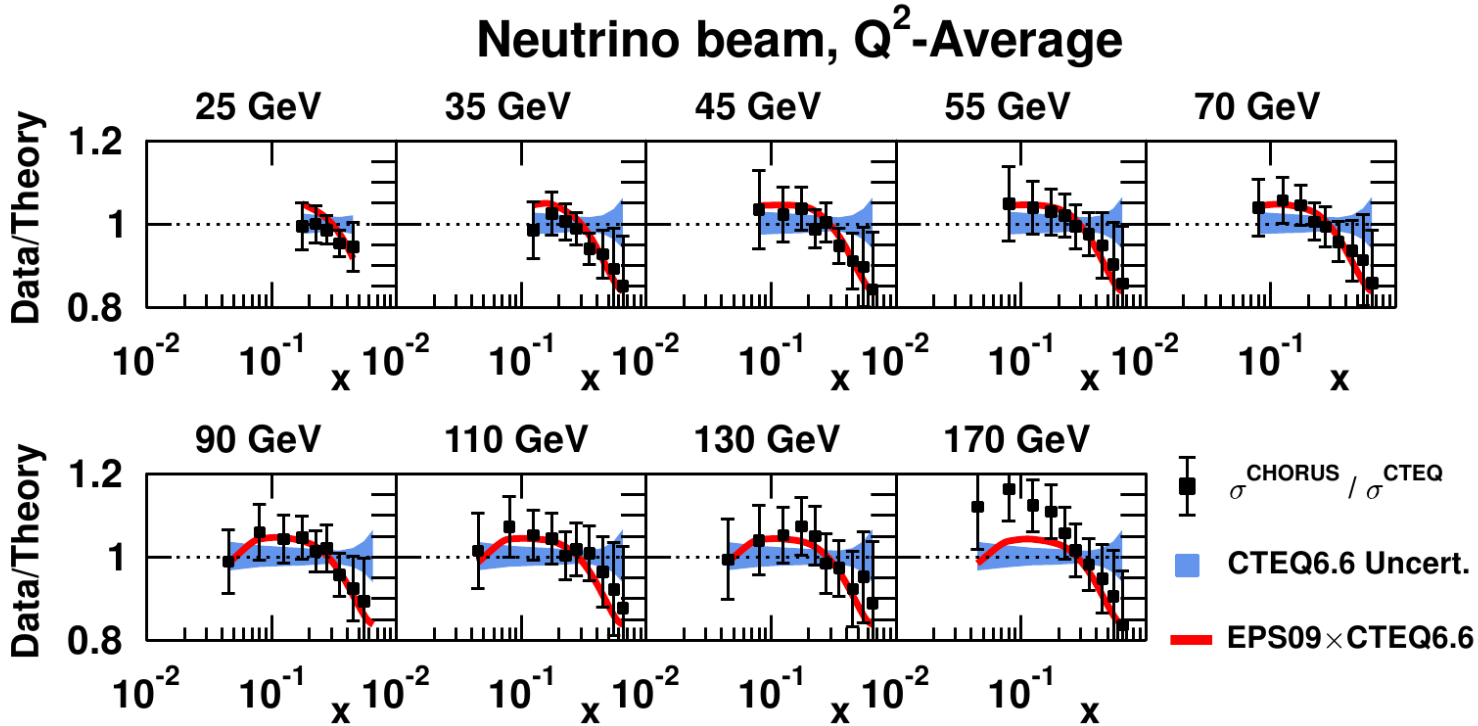
  - No PDF-fitting involved, just a systematic comparison employing CTEQ6.6 & EPS09

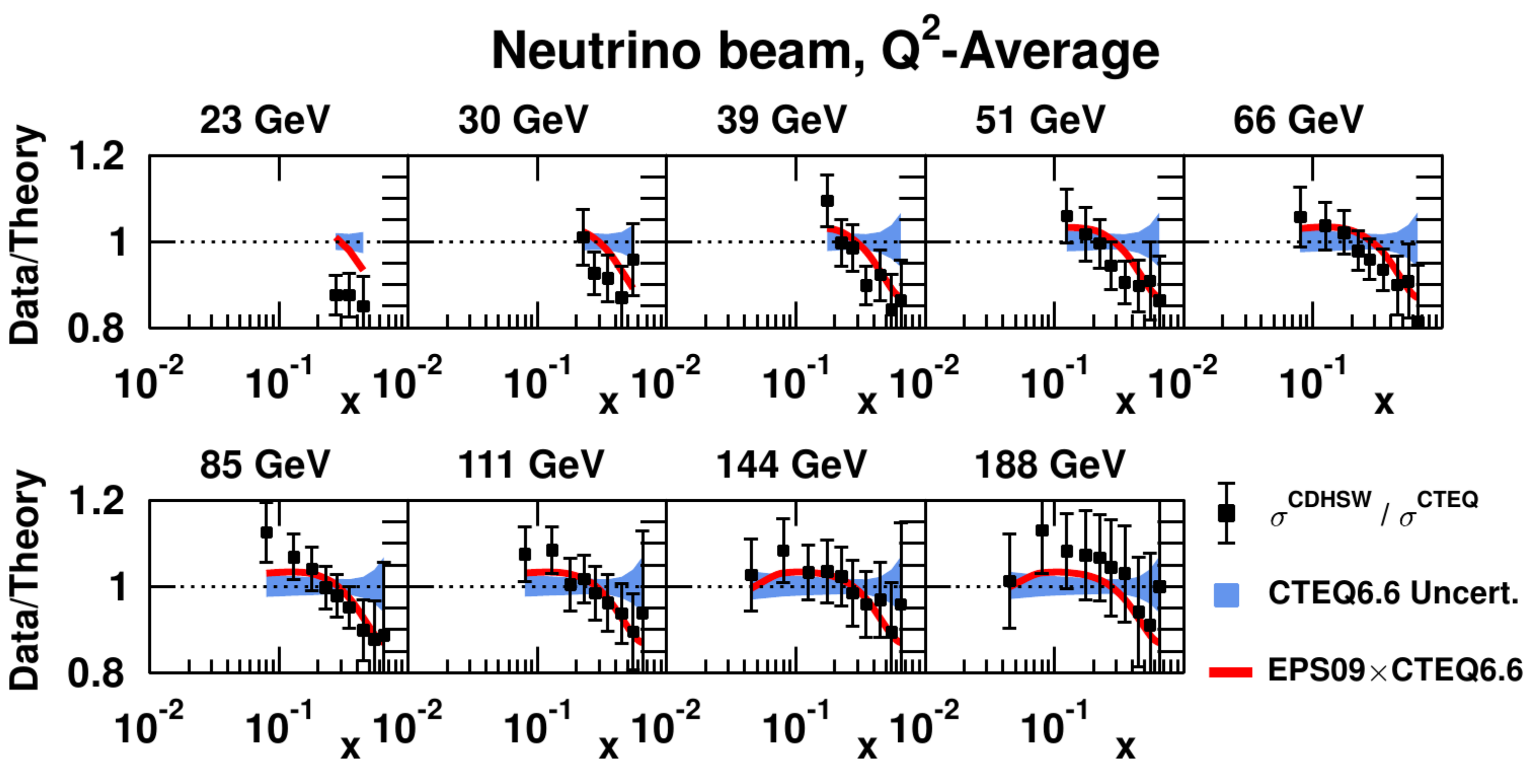
- **Plot the data as weighted average**

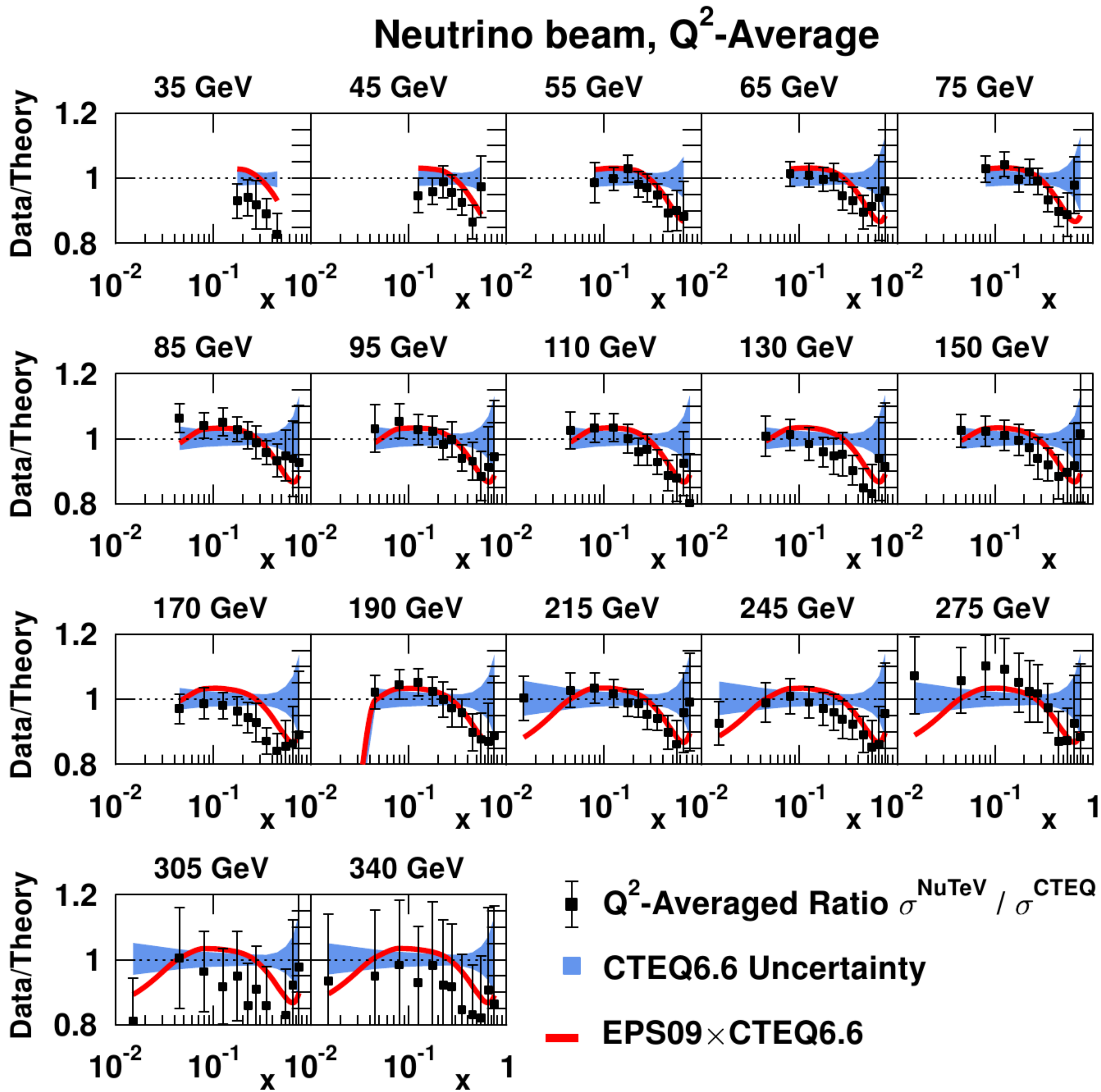
$$R_{\mathrm{Average}}^{\mathrm{CTEQ6.6}} \equiv \left(\sum_{i \in \mathrm{fixed}\, x}^{N} \frac{R_i^{\mathrm{CTEQ6.6}}}{\sigma_i}\right)\left(\sum_{i \in \mathrm{fixed}\, x}^{N} \frac{1}{\sigma_i}\right)^{-1} \pm N \times \left(\sum_{i \in \mathrm{fixed}\, x}^{N} \frac{1}{\sigma_i}\right)^{-1}$$

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

virtually independent of Q^2


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
σ^CHORUS / σ^CTEQ
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
σ^CDHSW / σ^CTEQ
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

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

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

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

$l^\pm$A gets worse as w is increased

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)

νA gets worse as w is decreased

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

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

- **The use of NuTeV correlated errors was underscored**

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

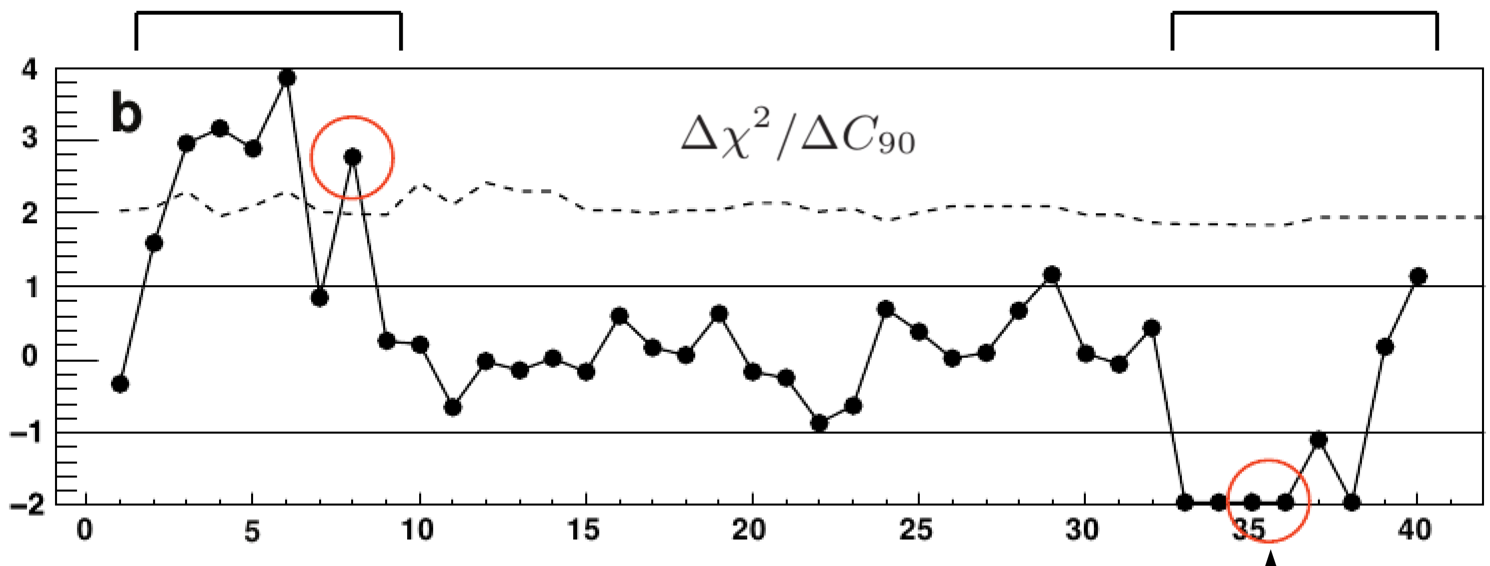
- **However, the same conclusion reached when adding errors in quadrature (w=1)**

Some data sets out of 90% criterion

Neutrino data

“90% confidence level”

The best fit with no neutrino data



Goes negative as compared to the χ^2 with correlations

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

- A global nPDF fit including neutrino <u>structure function</u> F_2 & F_3 data from NuTeV, CHORUS & CDHSW

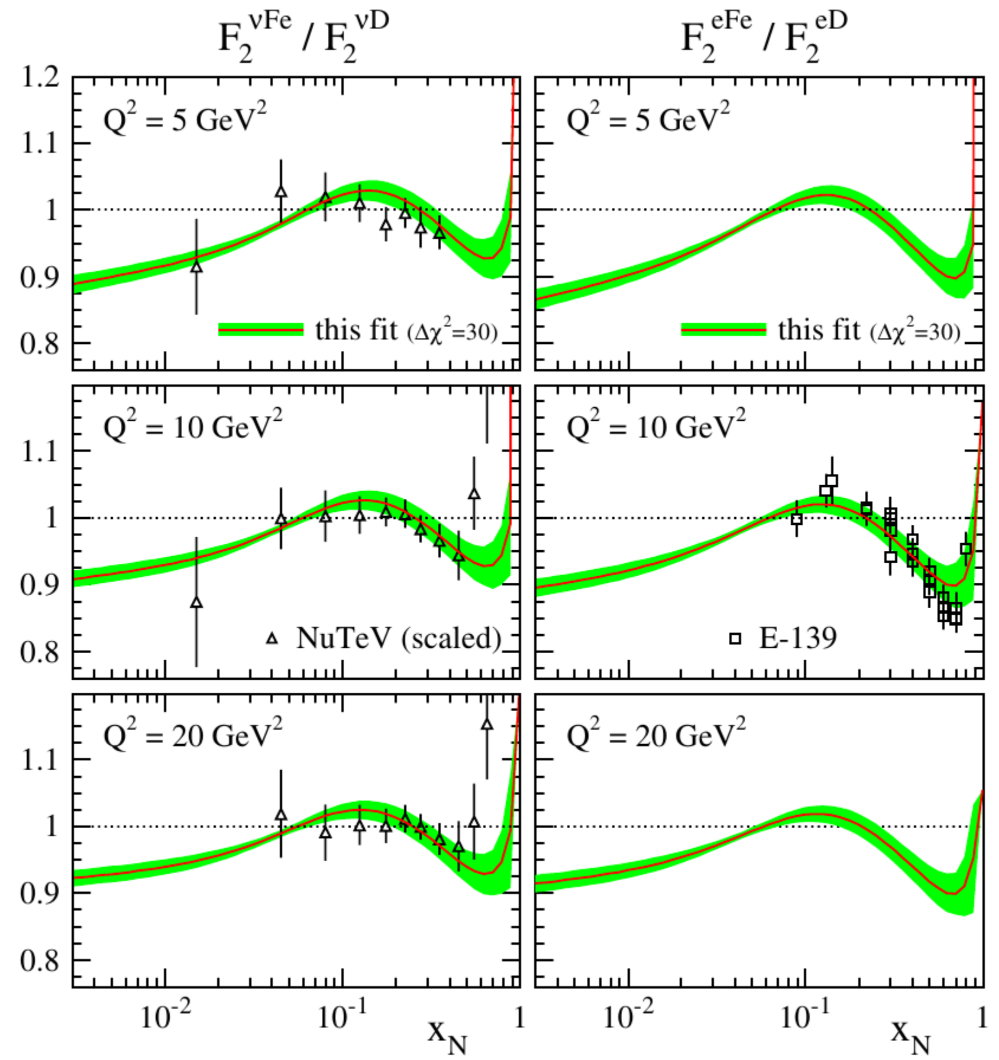
  much more scarce than the absolute cross-section data

- 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

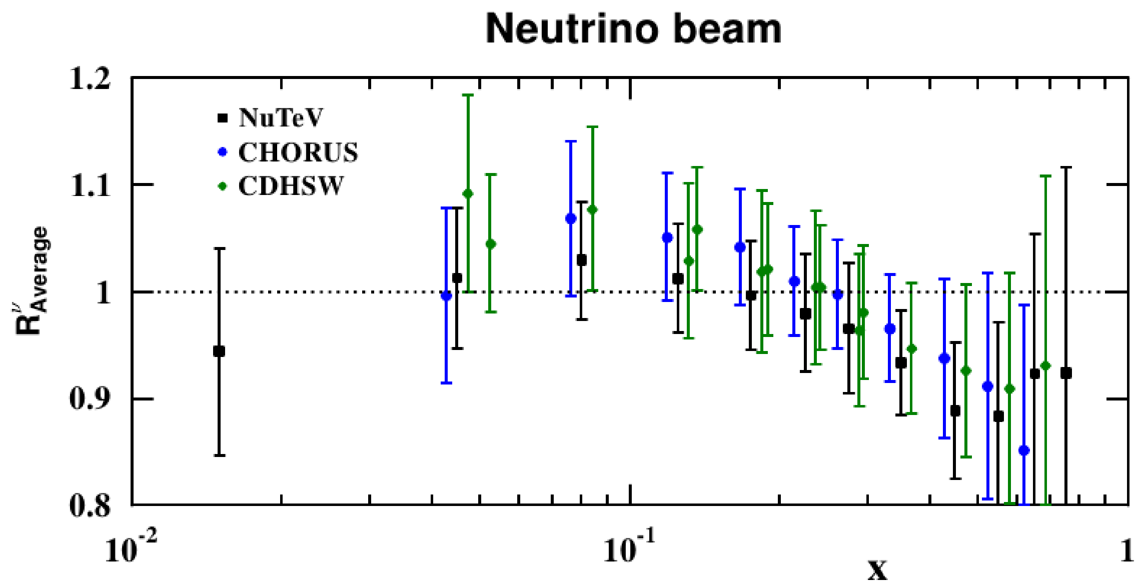
  as they were point-to-point uncorrelated errors.



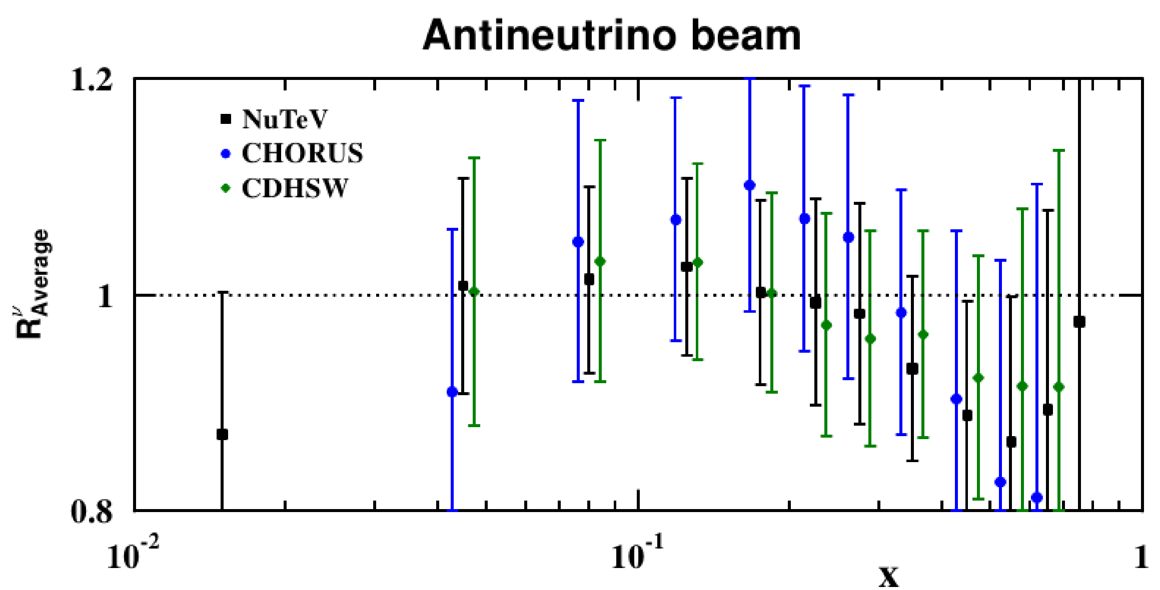
to accommodate all the features of the data. We do not observe any noticeable tension among the different sets of data in the fit. The parameters describing our optimum set

Paukkunen & Salgado: *arXiv:1302.2001*

- Average over all incident neutrino energy bins



- The NuTeV data few percents below the rest
- The antineutrino data much more scattered (significantly large errors, too)



Possible solution: normalize the data "by itself"

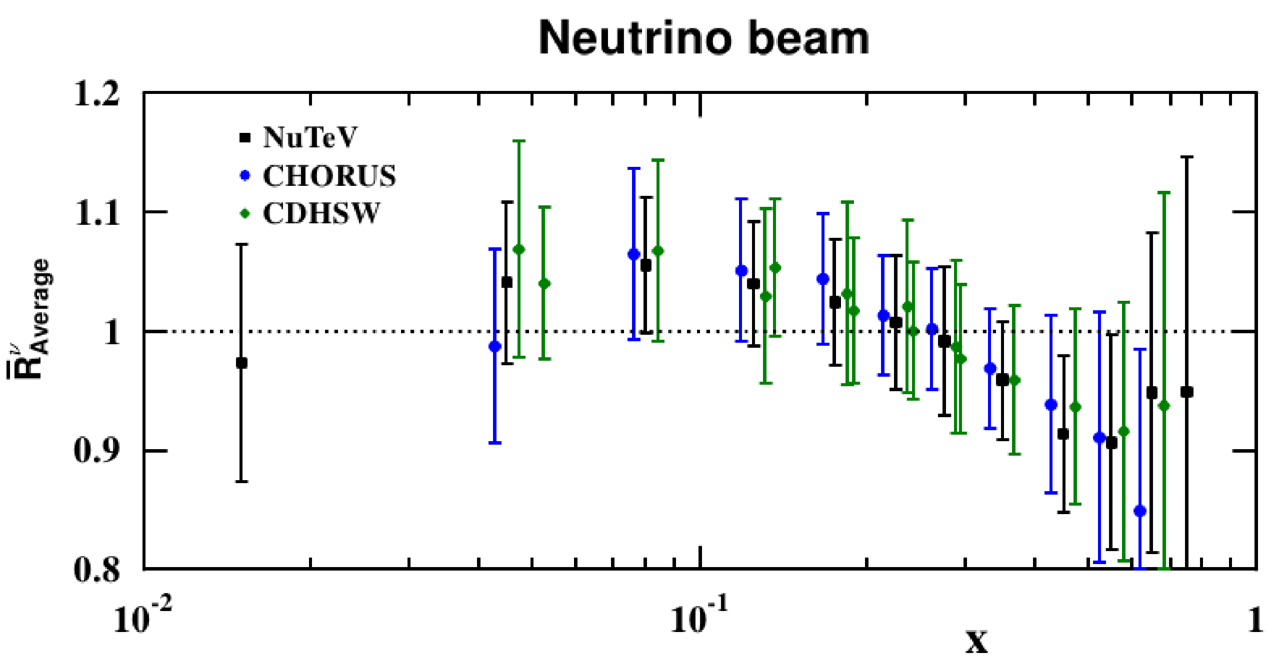
- Try to account for the differences in the absolute normalization. Define

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

Size of the experimental bin

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

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



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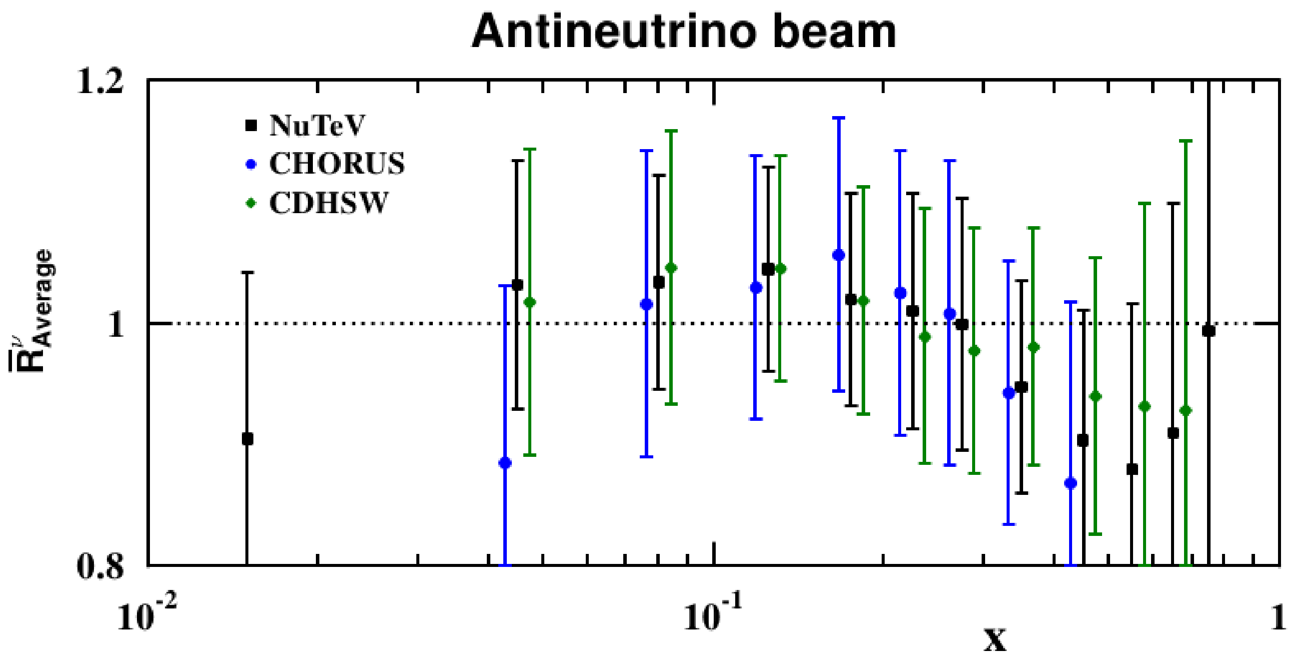
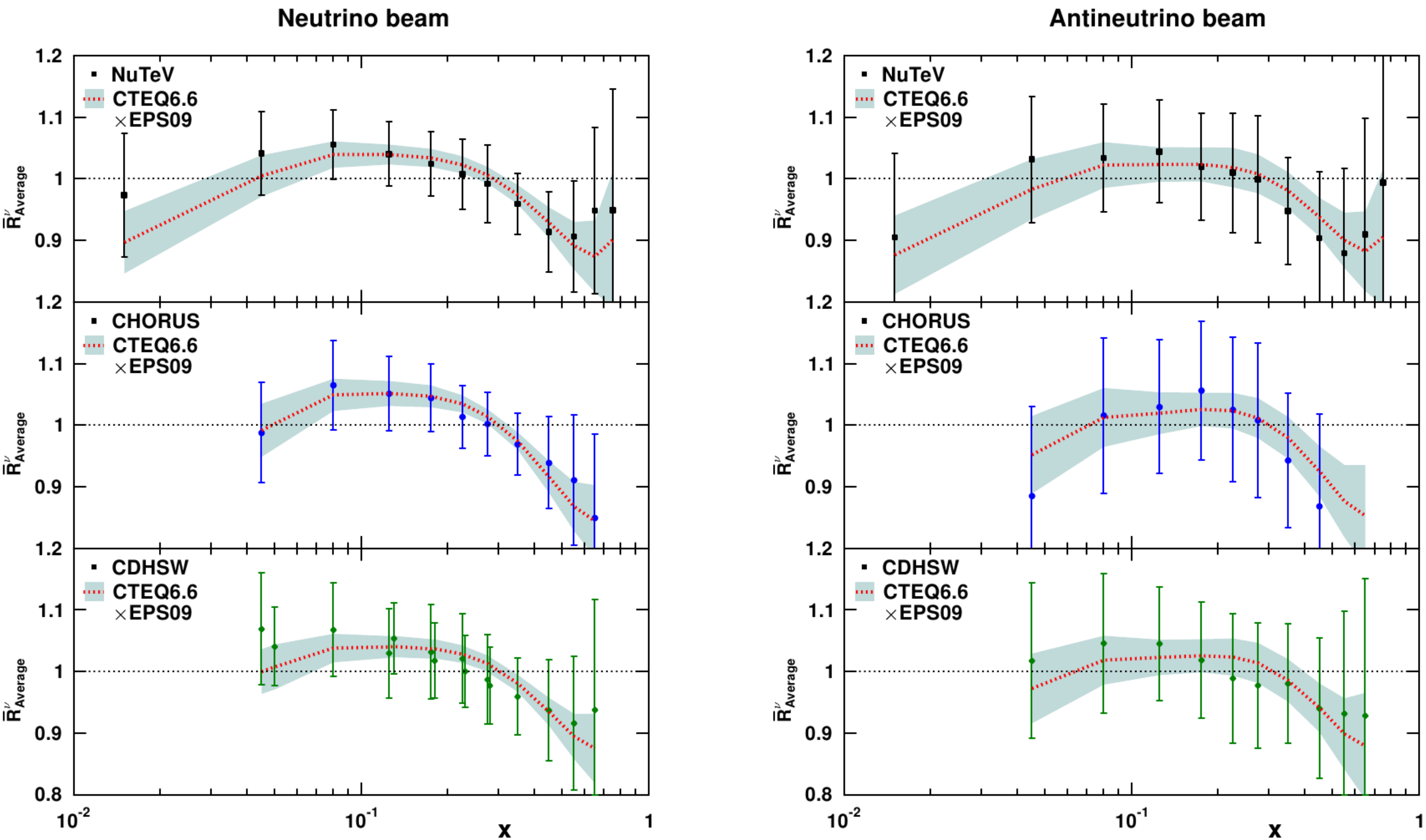


Compare to CTEQ6.6 x EPS09



Check the consistency by “Hessian reweighting”

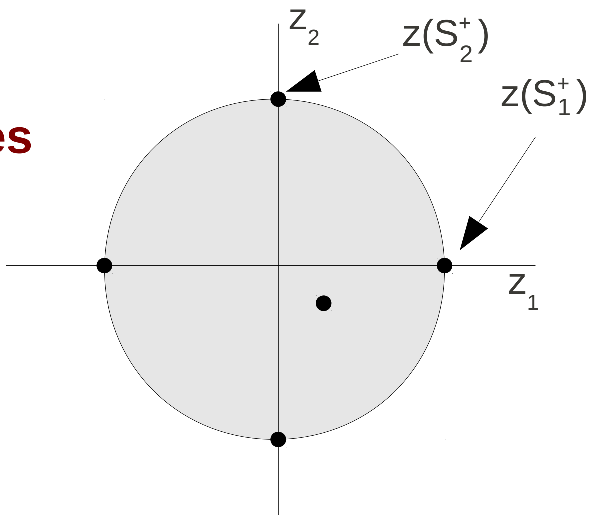
Similar ideas as in NNPDF reweigting [Nucl.Phys.B849:112-143,2011] & in MSTW work [JHEP 1208 (2012) 052]

- **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**

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



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

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

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

Check the consistency by “Hessian reweighting”

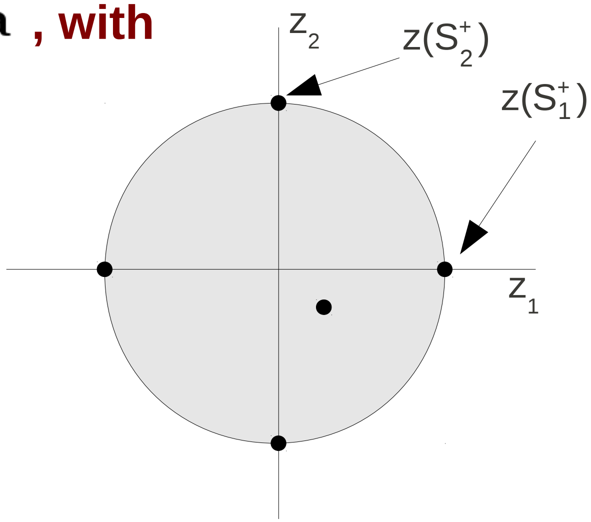
- **Formally add the contribution of a new data set into the χ^2**

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

Not known

The “new” data

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



$$\begin{aligned} B_{ij} &= \sum_k \frac{D_l^k D_j^k}{\left(\delta_k^{\rm data}\right)^2} + \Delta\chi^2 \delta_{ij} \\ a_i &= \sum_k \frac{D_i^k \left(X_k\left[S_0\right] - X_k^{\rm data}\right)}{\left(\delta_k^{\rm data}\right)^2} \\ D_l^k &= \frac{X_k\left[S_l^+\right] - X_k\left[S_l^-\right]}{2}. \end{aligned}$$

- **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:**

$$\Delta\chi^2 \sum_k w_k^2 \rightarrow \Delta\chi^2_{\mathrm{EPS09}} \sum_{k=1}^{15} w_k^2 + \Delta\chi^2_{\mathrm{CTEQ6.6}} \sum_{k=16}^{37} w_k^2$$

with $\Delta\chi^2_{\mathrm{EPS09}} = 50$ $\Delta\chi^2_{\mathrm{CTEQ}} = 100$

	All CTEQ6.6 and EPS09 error sets				Only EPS09 error sets	
NuTeV	$\chi^2_{w=0}/N$	$\chi^2_{w_{\min}}/N$	EPS09-penalty	CTEQ-penalty	$\chi^2_{w_{\min}}/N$	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	$\chi^2_{w=0}/N$	$\chi^2_{w_{\min}}/N$	EPS09-penalty	CTEQ-penalty	$\chi^2_{w_{\min}}/N$	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	$\chi^2_{w=0}/N$	$\chi^2_{w_{\min}}/N$	EPS09-penalty	CTEQ-penalty	$\chi^2_{w_{\min}}/N$	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

This corresponds to the nCTEQ result

- **The normalized neutrino data in accord with 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 charge asymmetry**
- **We propose to use the normalized, instead of the absolute neutrino DIS cross-sections in global PDF fits**
  - **All data seems to be in mutual agreement**
  - **Nothing extraordinary: e.g. Z-boson data is often presented as (1/σ) dσ/dy**
- **Introduced the “Hessian reweighting” for studying the compatibility of a new data set in a existing global PDF fit.**