Impact of W and Z Boson Production Data and Compatibility of Neutrino DIS Data in Nuclear Parton Density Extraction

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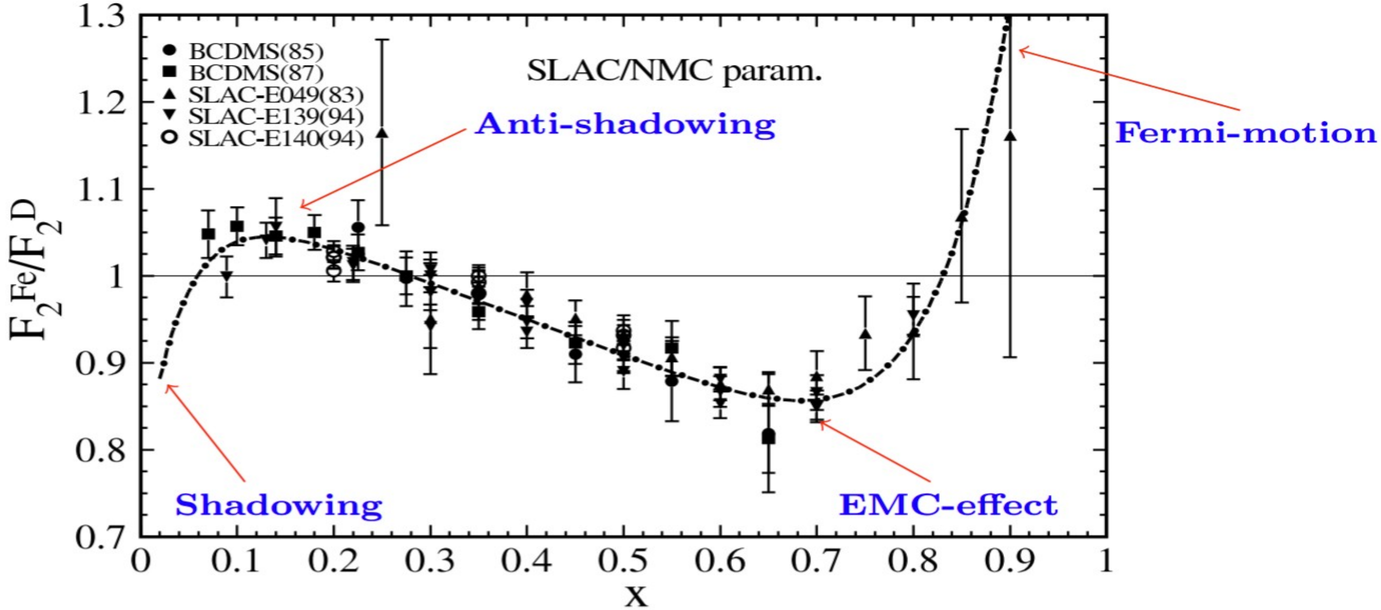
nCTEQ
nuclear parton distribution functions

WWU
MÜNSTER

INTRODUCTION : nPDFs

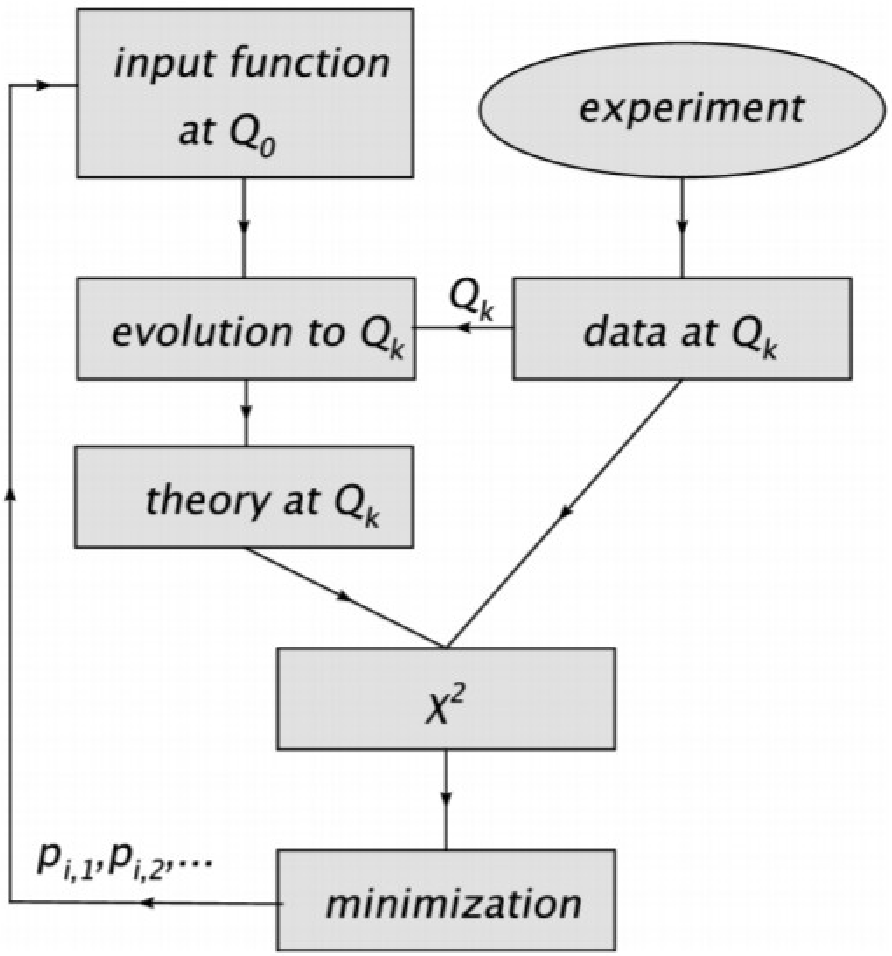
$$AF_2^A \neq ZF_2^p + (A-Z)F_2^n$$

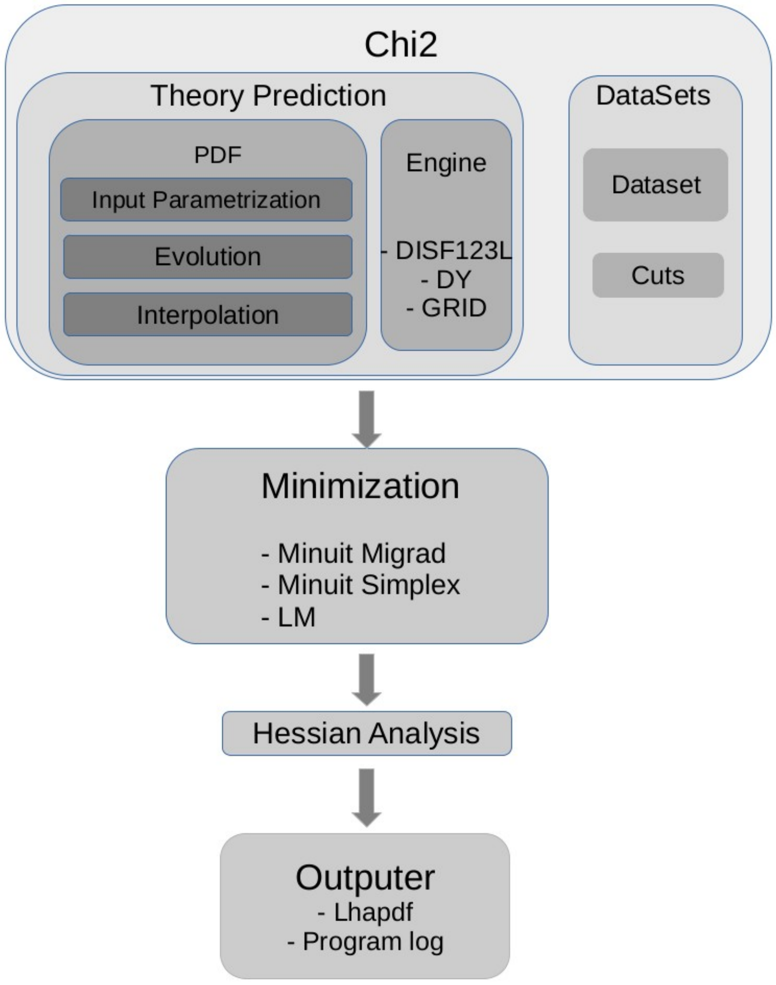


Working assumption : Factorization → **nPDFs**

$$d\sigma_{AB\to CX} = \sum_{a,b,c} f_{a/A} \otimes f_{b/B} \otimes d\hat{\sigma}_{ab\to cx} \otimes D_{c/C}$$

nPDF fitting with ncteq++





nCTEQ Framework

- **Full nPDFs :**

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

- **"Effective" Bound proton PDFs parametrization at** $Q_0 = 1.3$ GeV:

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

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

for $i = u_v, d_v, g, \bar{u}+\bar{d}, s+\bar{s}$.

- **A-dependence :** $c_k(A) = p_k + a_k(1 - A^{-b_k})$

Proton PDF parameters from CTEQ6M

- **Sum rules :**

$$\int_0^1 f_{u_v}^{p/A} dx = 2, \quad \int_0^1 f_{d_v}^{p/A} dx = 1, \quad \sum_i \int_0^1 x f_i^{p/A}(x, Q_0) dx = 1$$

Strange Quark PDF

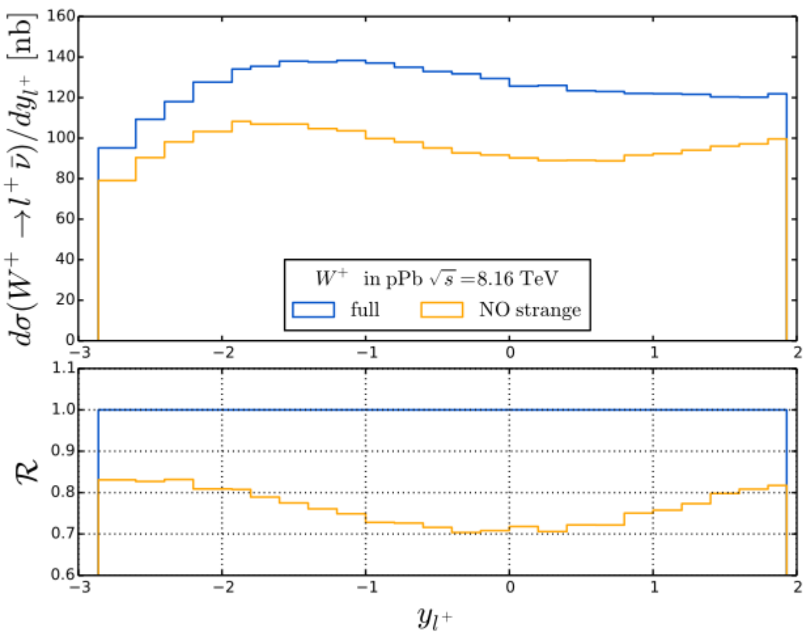
- Strange PDF has **much larger uncertainty** due to limited flavor separations

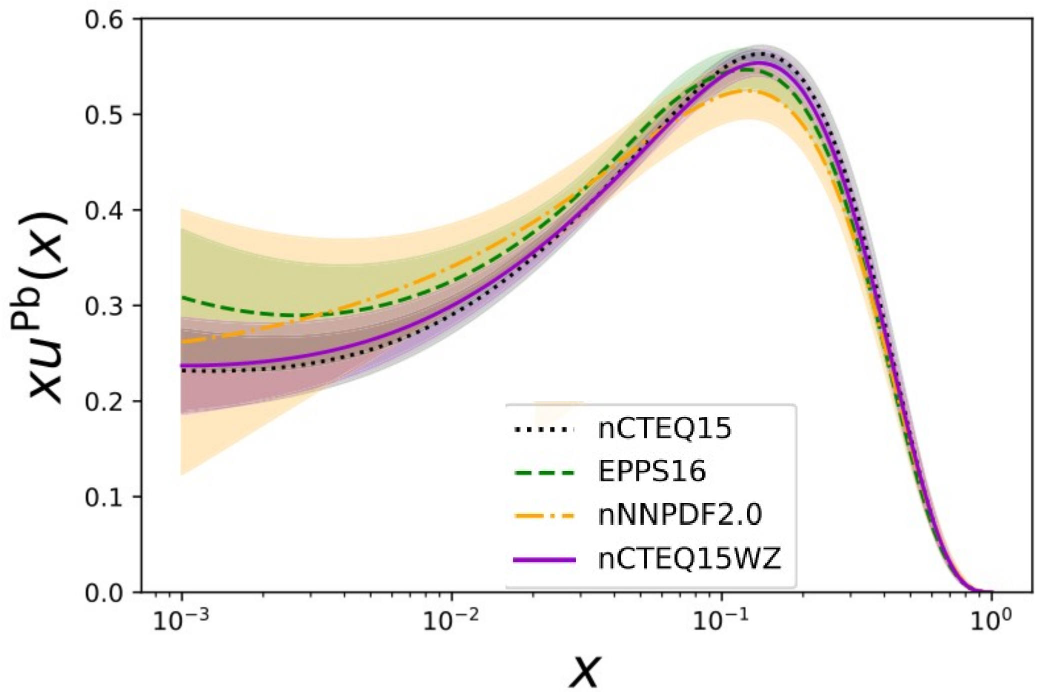
- Old assumption **:**

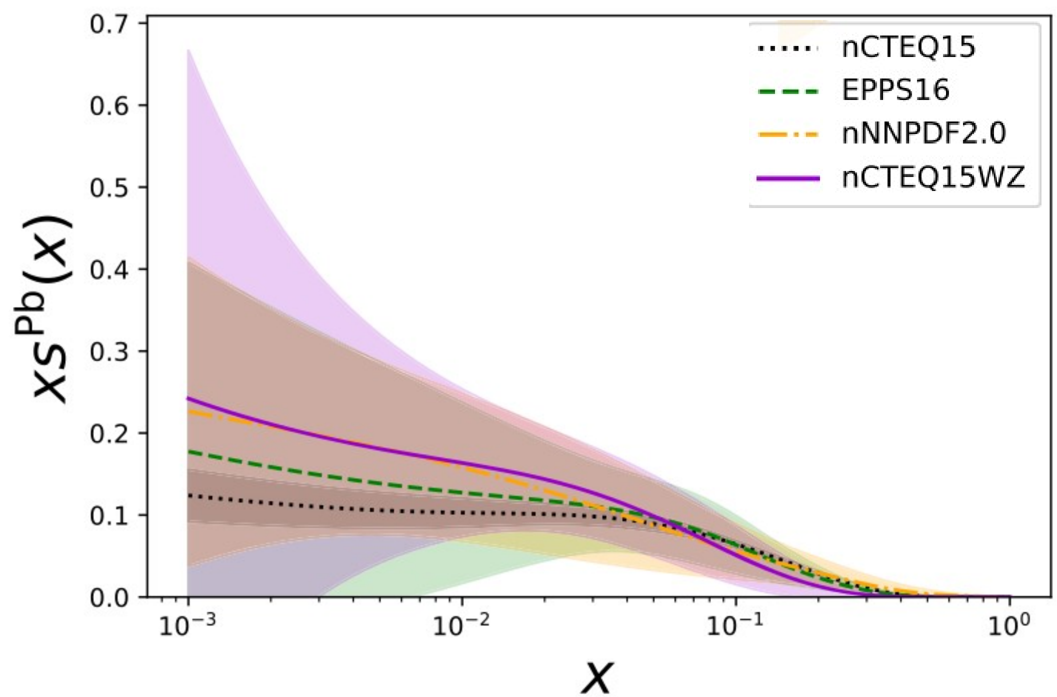
$$s(x) = \bar{s}(x) \sim \kappa \, \frac{\bar{u}(x) + \bar{d}(x)}{2}$$

→ **Underestimation of uncertainty!**

- The recent WZ production data can helps constrain strange PDF







nCTEQ15WZ [EPJC 77, 163]

	ATLAS Run I			CMS Run I			CMS Run II		ALICE		LHCb	DIS	DY	Pion	LHC	LHC Norm χ^2	**Total**
	W^-	W^+	Z	W^-	W^+	Z	W^-	W^+	W^-	W^+	Z						
nCTEQ15	1.38	0.71	2.88	6.13	6.38	0.05	9.65	13.20	2.30	1.46	0.70	0.91	0.73	0.25	6.20	—	**1.66**
nCTEQ15WZ	0.54	0.15	1.59	1.08	0.85	0.01	0.66	0.72	0.81	0.11	0.62	0.90	0.78	0.25	0.71	23	**0.87**

- NLO fit
- Starting scale : 1.3 GeV
- Treatment of heavy quark : ACOT
- Kinematic cuts :

$$Q > 2\text{GeV},\ W > 3.5\text{GeV}$$
$$p_T > 1.7\ \text{GeV}$$

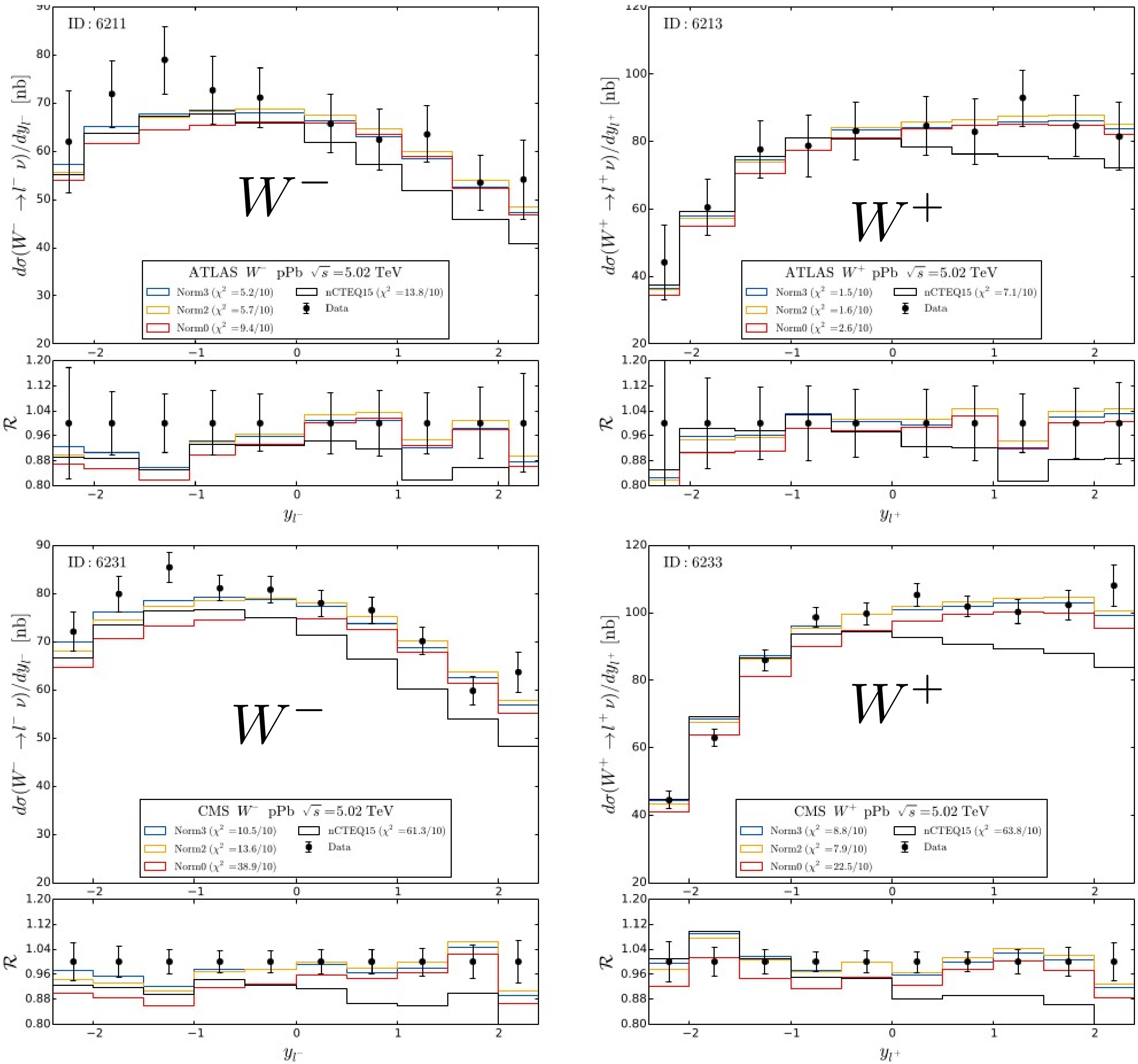
- Data Sets :
  DIS : 616
  DY : 92
  Pion : 31
  WZ LHC : 120

- Number Free Parameters : 19
- Error analysis : Hessian method, with

$$\Delta\chi^2 = 35$$

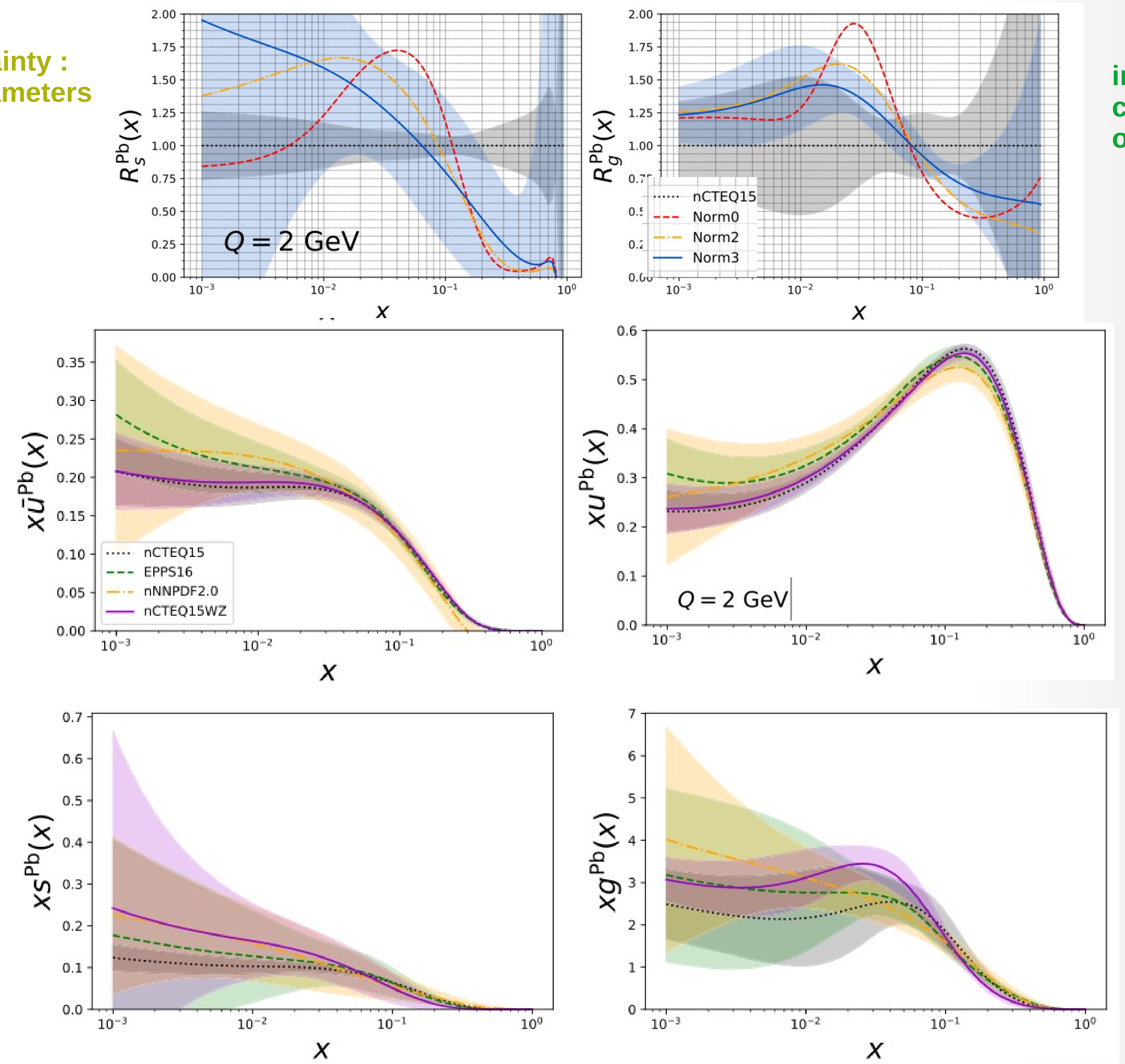
			$\sqrt{s_{NN}}$ [TeV]	σ_{norm} (%)	No points
Data overview					
ATLAS	Run I	$W^\pm$	5.02	2.7	10+10
ATLAS	Run I	Z	5.02	2.7	14
CMS	Run I	$W^\pm$	5.02	3.5	10+10
CMS	Run I	Z	5.02	3.5	12
CMS	Run II	$W^\pm$	8.16	3.5	24+24
ALICE	Run I	$W^\pm$	5.02	2.0	2+2
LHCb	Run I	Z	5.02	2.0	2

Data-Theory comparison : good agreement.



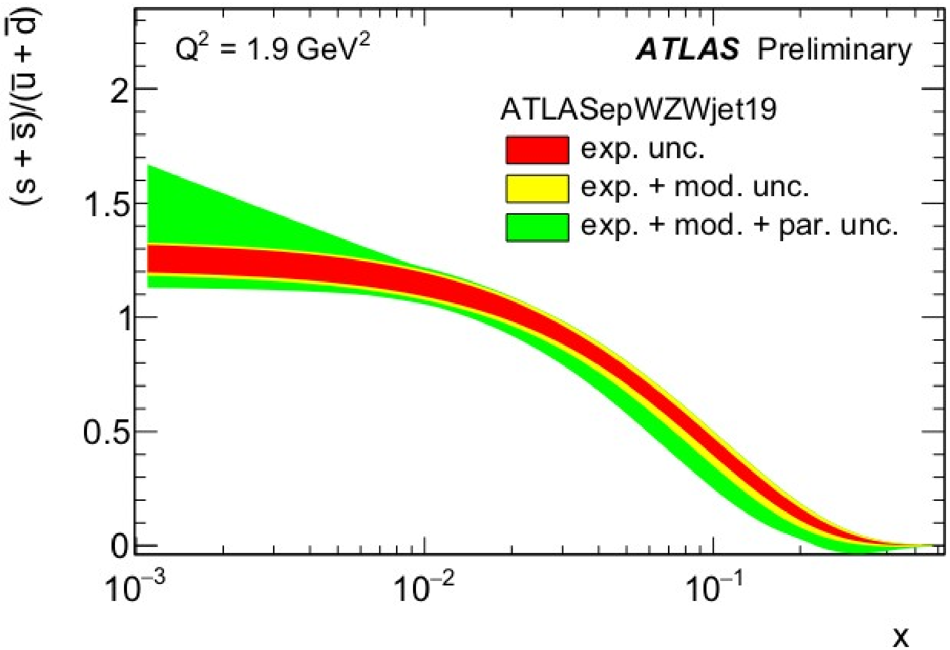
nCTEQ15WZ nPDFs

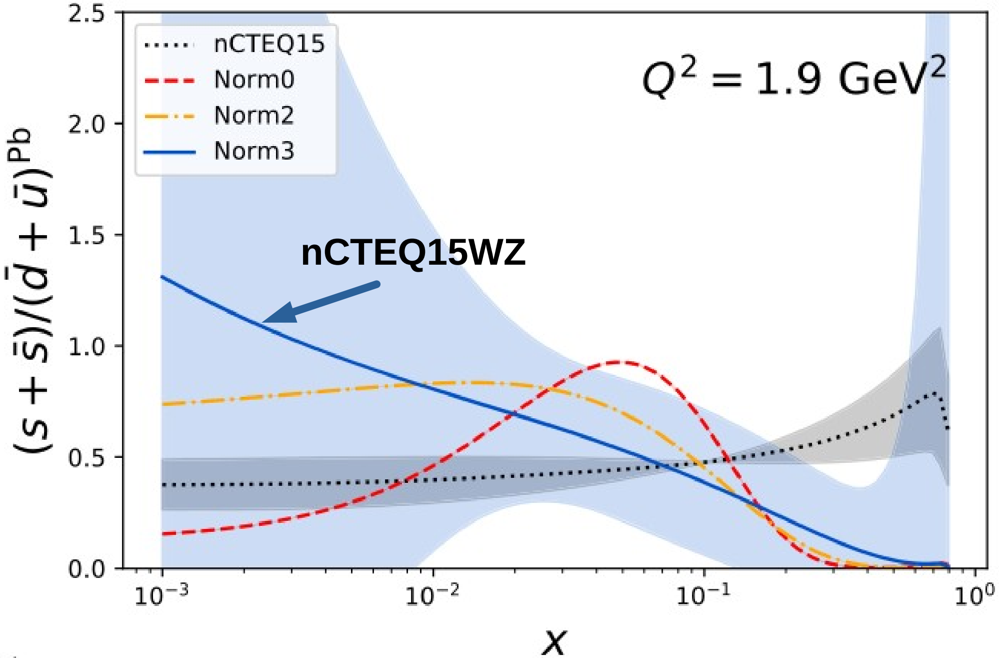
Larger uncertainty : more free parameters



improved constraints on gluon PDF

Strange sea ratio



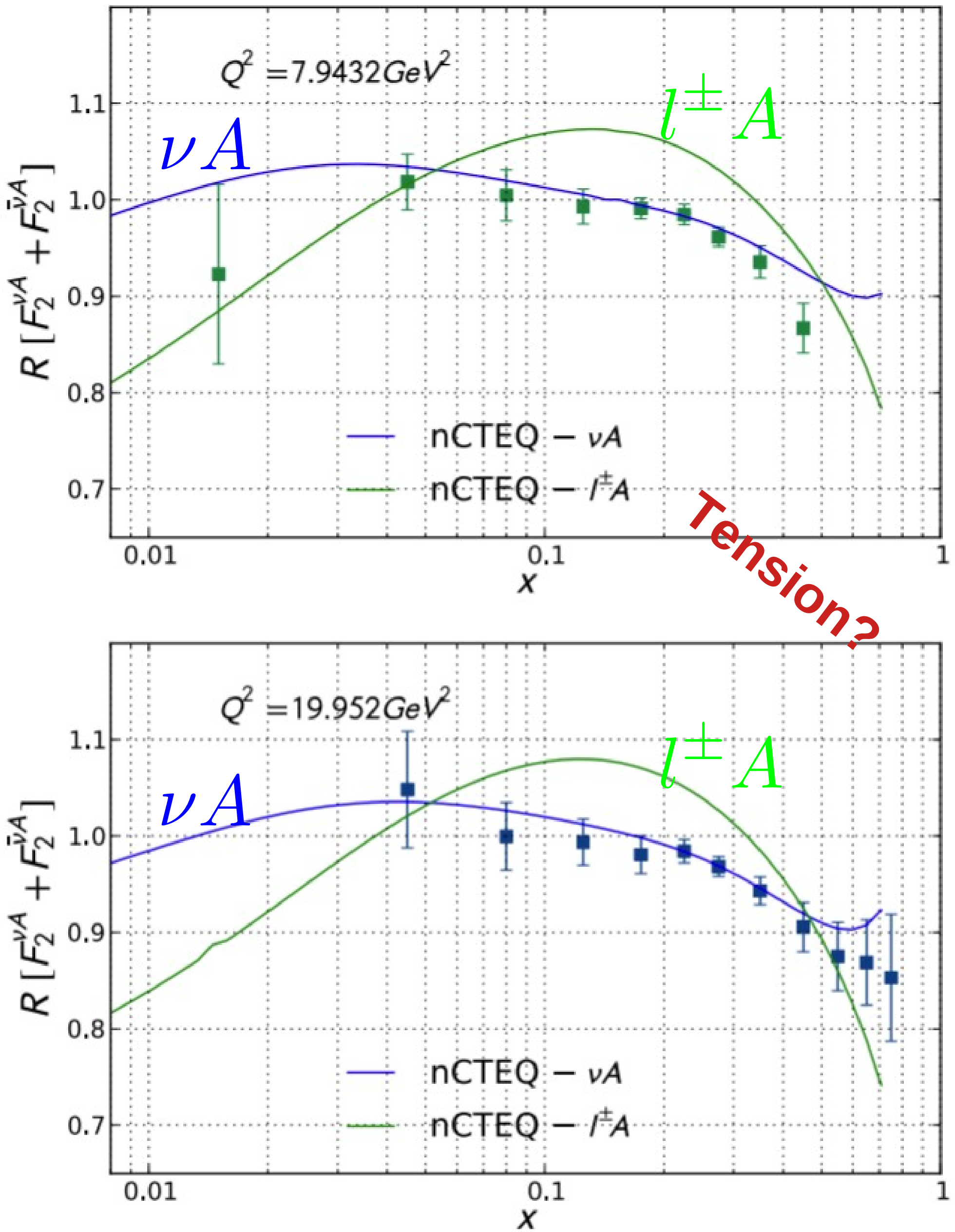


Is the elevated strange PDF what nature dictates or is it because of lacks of flavor separations?

Still open question. Need more data!

Neutrino DIS

- Important for flavor differentiation
- (More) sensitivity to strange PDF
- High statistics!
- Heavy target (Fe, Pb)
- Different nuclear correction ?
- Problem : Tension with charge lepton DIS data ?

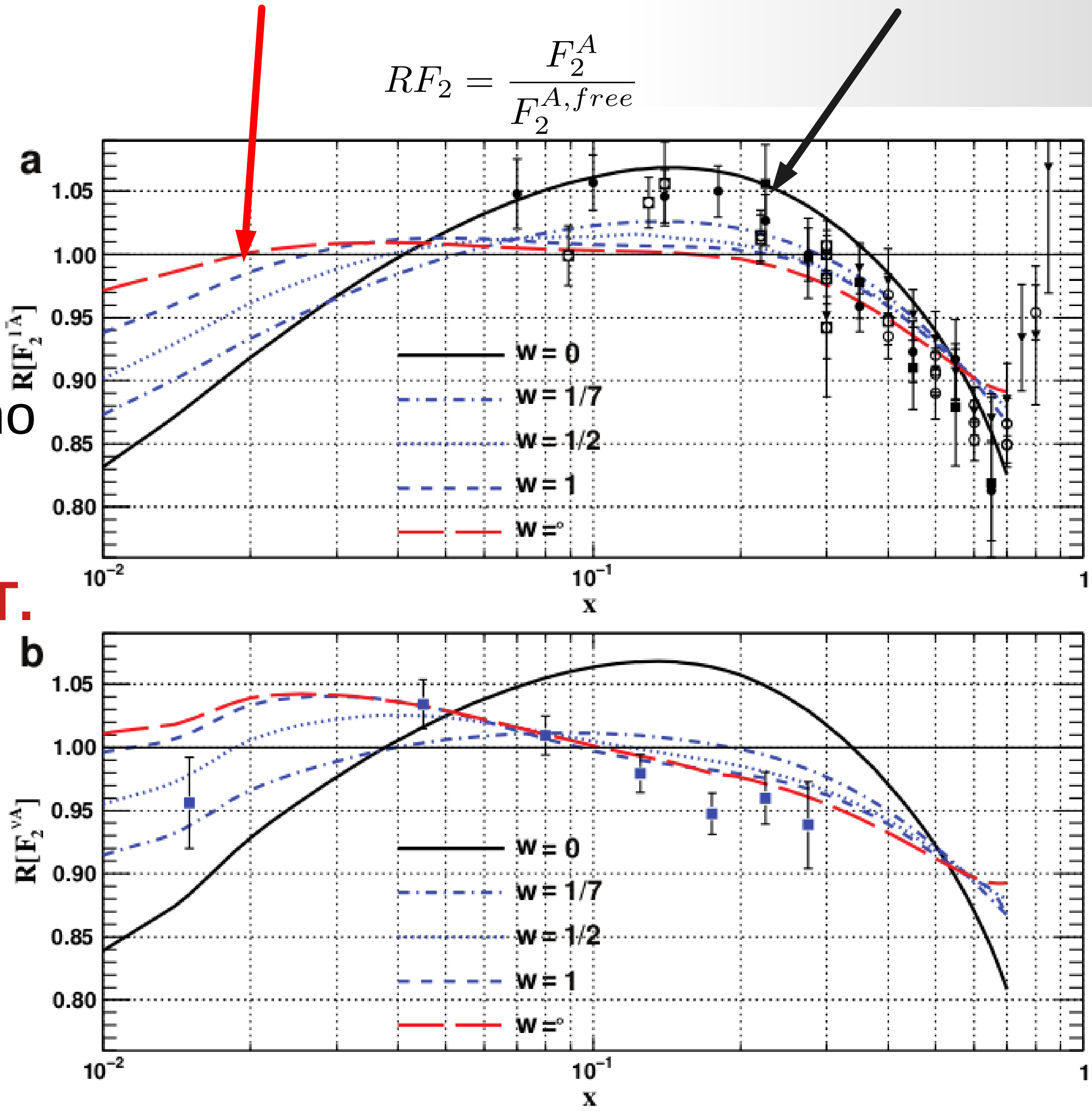


nCTEQ Study

Dimuon + Chorus+ NuTeV vs $l^{\pm}A + DY$

$$RF_2 = \frac{F_2^A}{F_2^{A,free}}$$

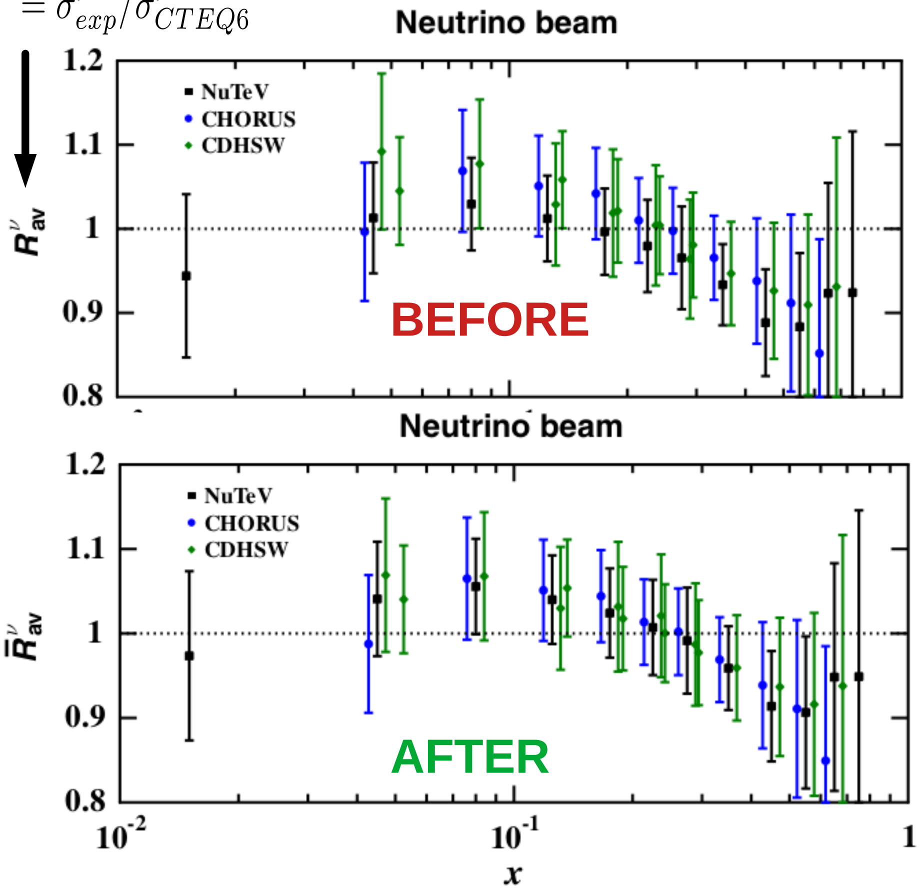
- Use NuTeV's point-by-point correlated systematic uncertainties.
- Different weights *w* for the neutrino DIS data.
- χ^2- test **: NO COMPROMISE FIT.**
- **Using NuTeV uncorrelated seems to lower the tension, but NOT ENOUGH!**



Kovarik *et al PRL106(2011)122301*

EPPS

$R^{\nu} = \sigma^{\nu}_{exp}/\sigma^{\nu}_{CTEQ6}$



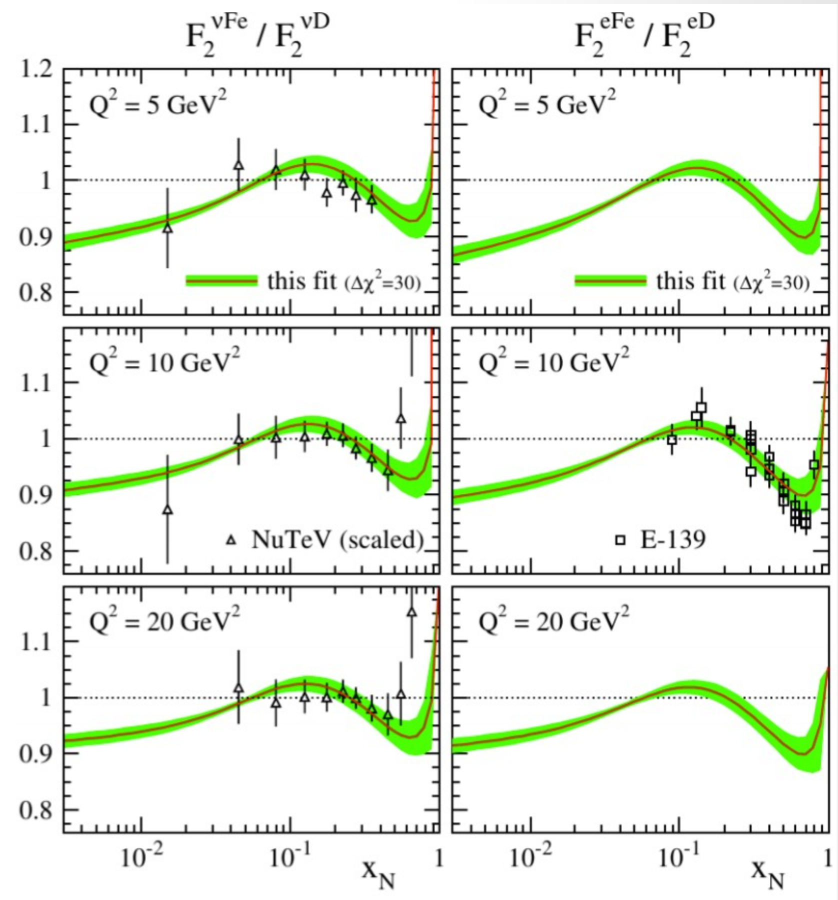
- **Correlation is ignored**
- **Normalization procedure :**

$$\bar{R}^{\nu}(x,y,E) = \frac{\sigma^{\nu}_{exp}/I^{\nu}_{exp}(E)}{\sigma^{\nu}_{CTEQ6}/I^{\nu}_{CTEQ6}(E)}$$

- **NO nPDF fits, used Hessian reweighting**
- **With normalization procedure : OK**

Paukunen & Salgado PRL110(2013)212301

DSSZ



- **Global nPDF fit : charge lepton DIS, DY, pion production, and $F_{2,3}$ NuTeV, Chorus, CDHSW.**
- **MSTW2008 proton PDF as base -- → NuTeV is already included.**
- **Correlation is IGNORED**
- **NO NOTICEABLE TENSION**

de Florian *et al Phys.Rev.D85,074028(2012)*

The ANALYSIS

BASE : nCTEQ15WZ

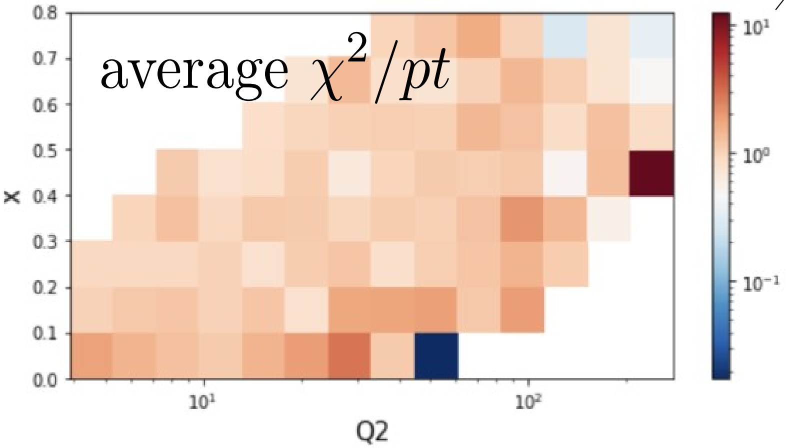
- **Data :** DIS+ DY+ pion + WZ LHC
- **Number of data : 853 pts**
  - NC DIS : 616
  - DY : 92
  - Pion : 25
  - WZ LHC : 120

VS

DimuNeu

- **Data :** Dimu CCFR & NuTeV + NuTeV + CDHSW+ Chorus
- **Total number of data : 4063 pts**
  - NuTeV : 2136 pts
  - Chorus : 824 pts
  - CDHSW : 929 pts
- **Proper treatment of normalization uncertainty**
- **CORRELATIONs from NuTeV and Chorus are taken into account**

DimuNeu Fit



χ^2 for the i-th data point :

$$\tilde{\chi}_i^2 = \frac{1}{\sigma_i^2}\left(D_i - rT_i - \sum_\alpha \bar{\sigma}_{i\alpha}\bar{r}_\alpha\right)^2 + \frac{1}{N}\sum_\alpha \bar{r}_\alpha^2$$

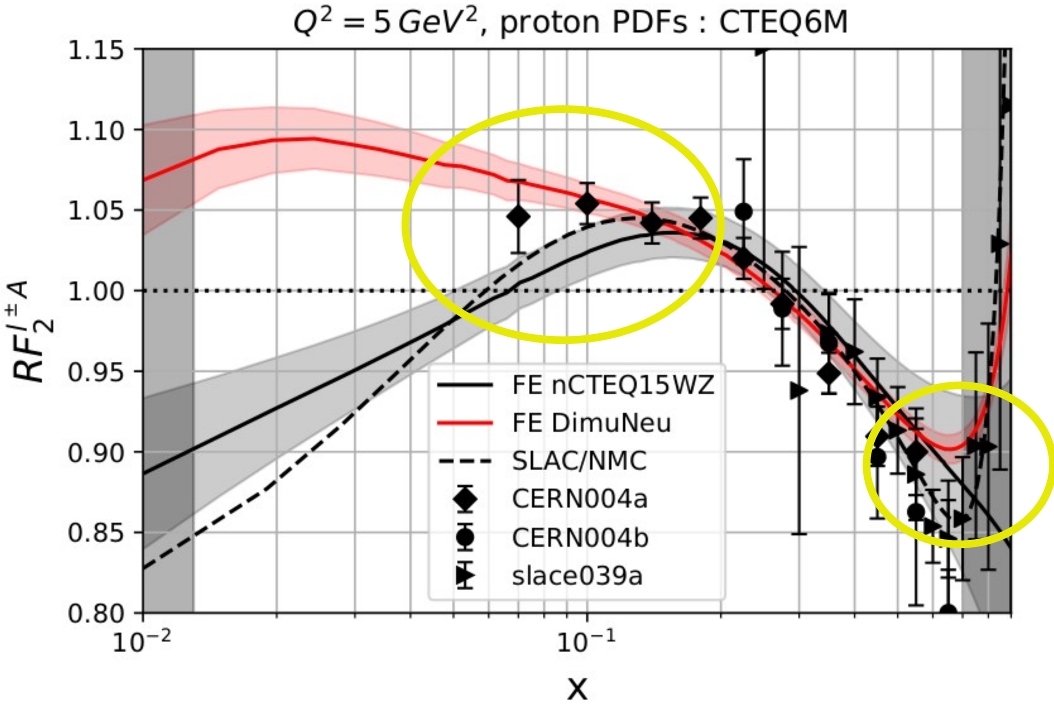
Tension at low x

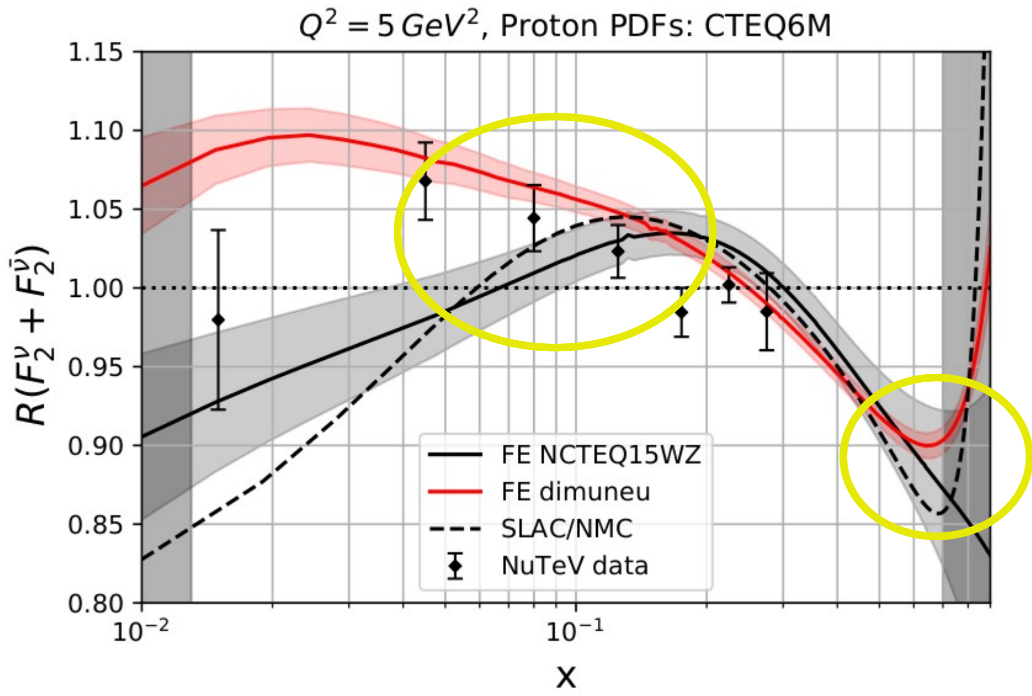
x	NuTeV	Chorus	CDHSW	All
0.015	2.51	-	3.85	2.56
0.045	1.37	1.90	1.35	1.44
0.08	1.72	1.24	0.87	1.49
0.125	1.83	1.15	0.48	1.41
0.175	1.30	1.10	0.50	1.07
0.225	1.19	0.90	0.68	1.04
0.275	1.20	1.26	0.73	1.00
0.35	1.40	1.18	0.59	1.16
0.45	1.17	1.23	0.67	1.03
0.55	1.29	1.44	0.61	1.08
0.65	1.04	1.16	0.61	1.02
0.75	1.01	-	-	1.01

- **DimuNeu : Dimuon+ CDHSW+Chorus+NuTeV**
- **Total χ^2/pt :**
  Dimuon : 1.27
  NuTeV neu, antineu : 1.50 , 1.23
  Chorus neu, antineu : 1.27 , 1.09
  CDHSW neu, antineu : 0.60 , 0.72
  ALL : 1.17
- **TENSION between neutrino data sets at low x!**

Prediction Comparisons with nCTEQ15WZ

$$RF_2 = \frac{F_2^A}{F_2^{A,free}} \qquad f_i^{A,free} = \frac{Z}{A} f_i^p + \frac{N}{A} f_i^n$$





Tensions with nCTEQ15WZ predictions at $x \leq 0.1$ and $x \sim 0.6$

Statistical Tests

BASE (S) vs Neutrino ($\bar{S}$)

$\bar{S}$	$\Delta\chi^2_S$	Percentile $\bar{S}$ (%)	$\chi^2_{\bar{S}}/pt$	Compatible?
Chorus	17	83.8	1.18	YES
CDHSW	44	**100**	0.66	YES
NuTeV	**92**	**93.5**	**1.42**	**NO**
DimuNeu	**106**	**99.2**	**1.23**	**NO**

Compatibility criteria :

$$\Delta\chi^2_S \leq 45 \text{ and } (p_{\bar{S}} \leq 90\% \text{ or } \chi^2_{\bar{S}}/pt \leq 1.0)$$

The BaseChorus & BaseCDHSW fits seems to describe both the data quite well. But …. still have large χ^2/pt at low x!

x	BaseNuTeV	BaseChorus	BaseCDHSW	All
0.015	2.50	-	5.69	3.05
0.045	1.54	1.84	1.67	1.89
0.08	1.78	1.72	0.72	1.55
0.125	1.82	1.07	0.40	1.43
0.175	1.29	1.11	0.47	1.11
0.225	1.20	1.10	0.63	1.04
0.275	1.19	0.84	0.70	0.97
0.35	1.33	1.26	0.51	1.15
0.45	1.19	1.08	0.62	1.01
0.55	1.29	1.14	0.57	1.07
0.65	0.99	1.16	0.58	1.02
0.75	1.01	-	-	1.05

- **Tension at low x between neutrino data and the Base**
- **Incomplete theory?**
- **What if we cut low *x* data?**

Neutrino Data with x ≤ 0.1 cut (x>0.1 data points are kept)

$\bar{S}$	$\Delta\chi^2_S$	Percentile $\bar{S}$ (%)	$\chi^2_{\bar{S}}/pt$	Compatible?
Chorus	9	81.7	1.09	YES
CDHSW	26	**99.2**	0.59	YES
NuTeV	17	74.6	**1.30**	YES
DimuNeu	28	66.0	**1.10**	YES

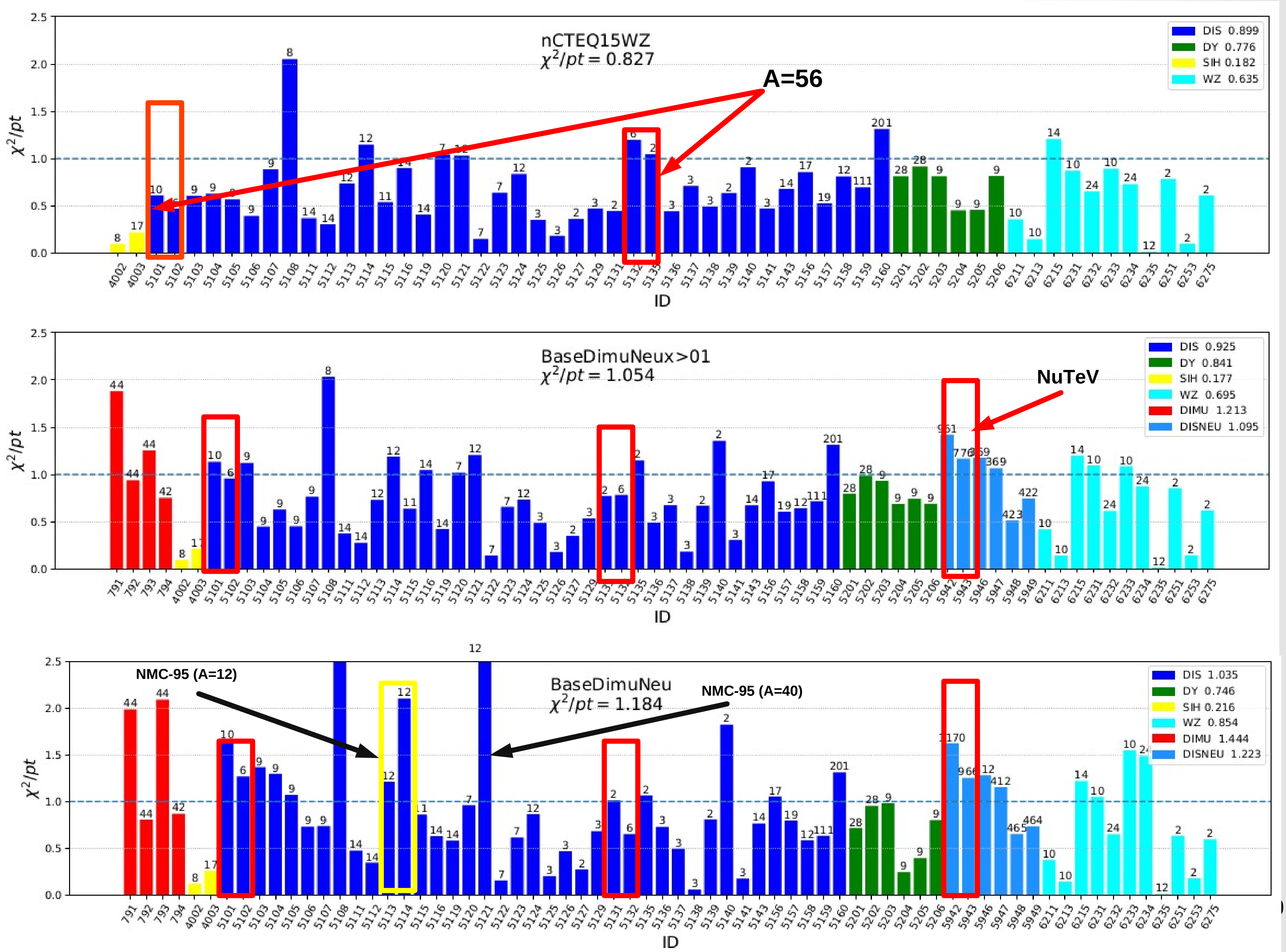
The tensions are now gone!

The Combined Fit : DIS + DY+ PION+ WZ+DIMU+NEUTRINO

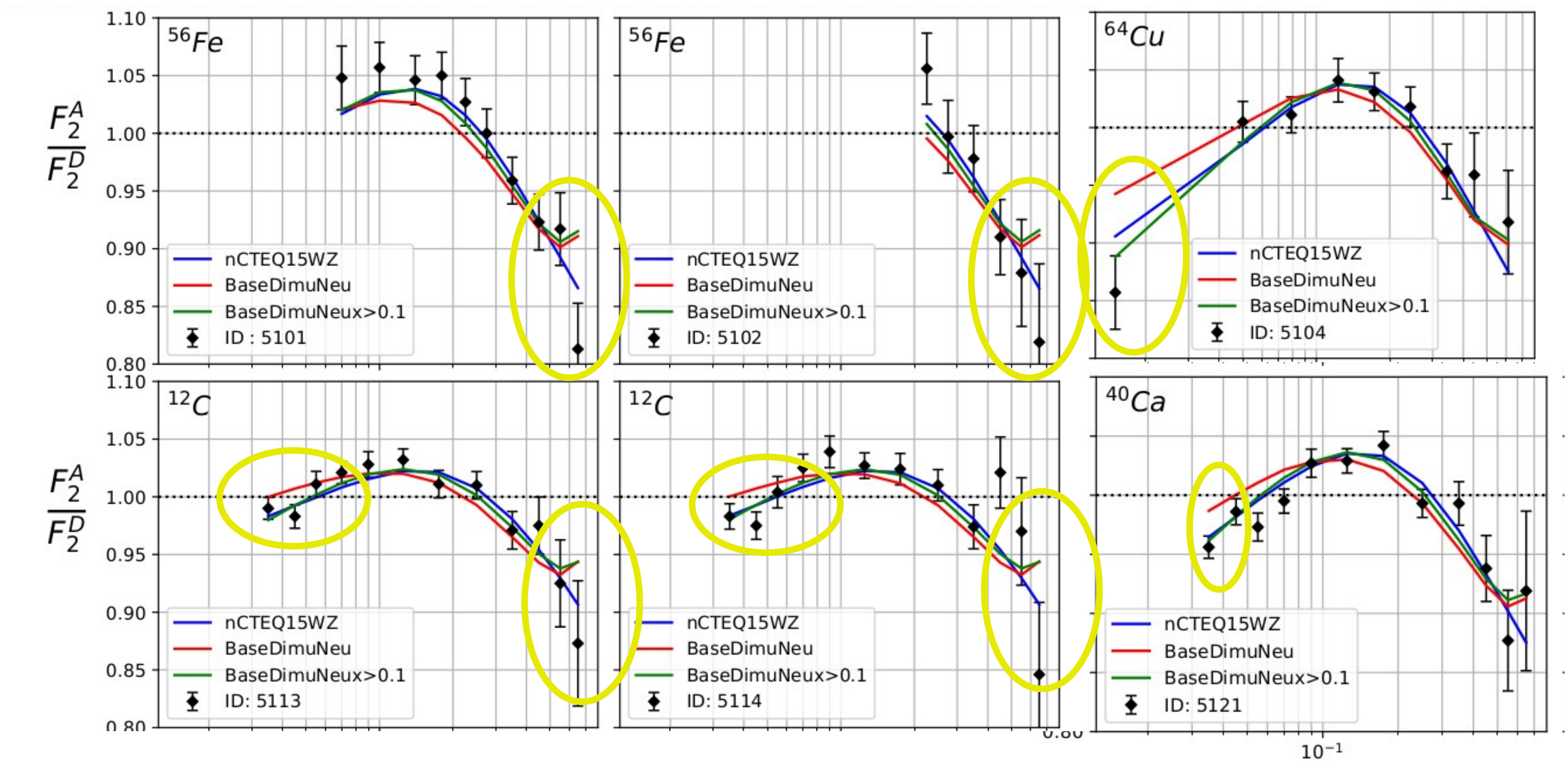
- **BaseDimuNeu** :
  - No low x cuts for the Neutrino data
  - Number of data points : 4916
  - Does not pass our compatibility criteria

- **BaseDimuNeux>0.1** :
- - x≤0.1 cuts applied for the neutrino data
  - Number of data points : 4347
  - Pass our compatibility criteria

The Combined Fit : BaseDimuNeu vs BaseDimuNeux>0.1



Data – Theory Comparison : charge lepton DIS



- **Low x tensions largely disappear in BaseDimuNeux>0.1 fit.**
- **Tensions at x~0.6 are still there in BaseDimuNeux>0.1 fit.**

Data – Theory Comparison : neutrino DIS

Nuclear Ratio :

$$R = \frac{\sigma(x,y,E)}{\sigma_{free}(x,y,E)}$$

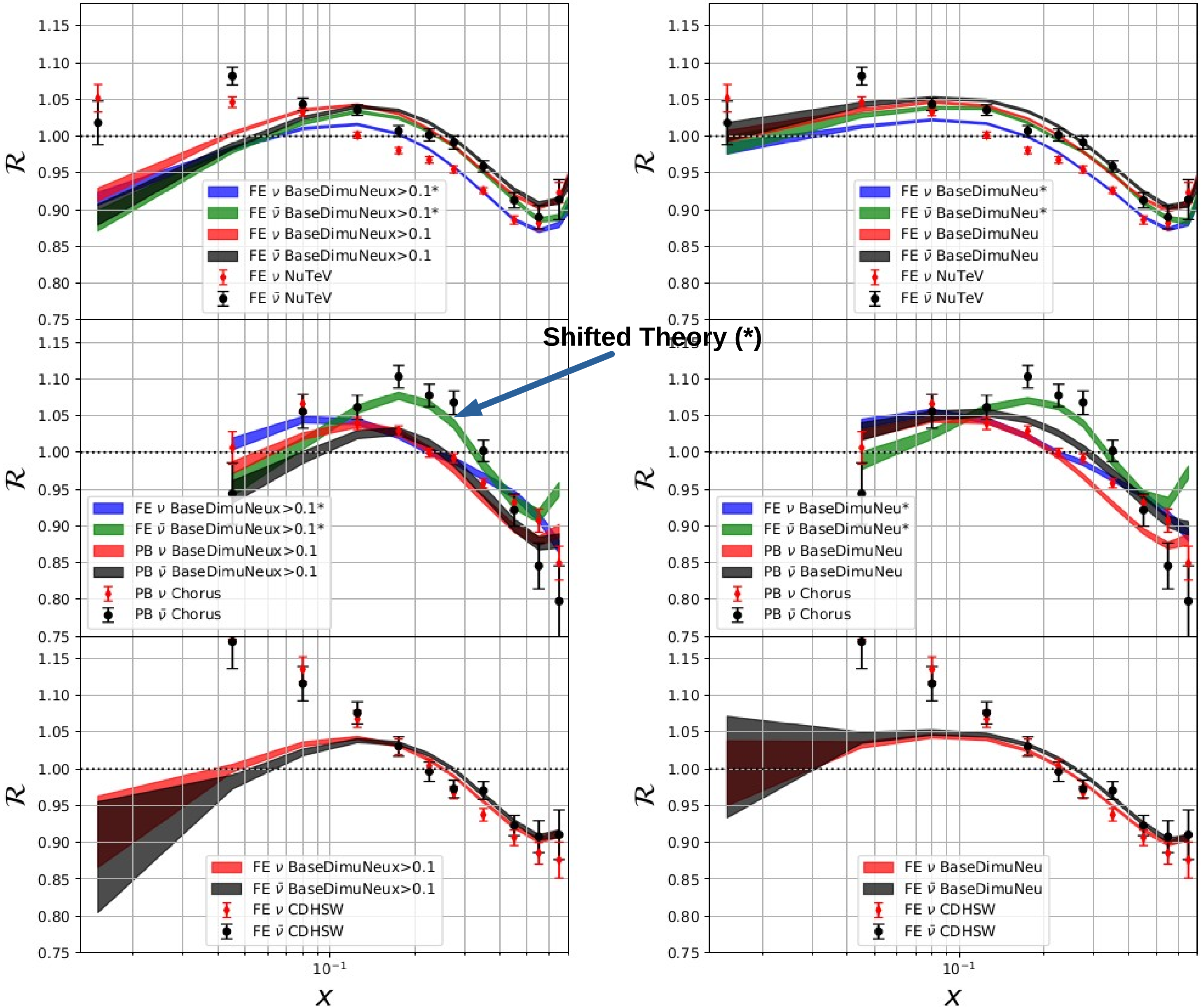
Weighted average :

$$\mathcal{R} = \sum_i w_i R_i$$

$$w_i = \left(\sum_j \frac{1}{\sigma_j^2}\right)^{-1} \frac{1}{\sigma_i^2}$$

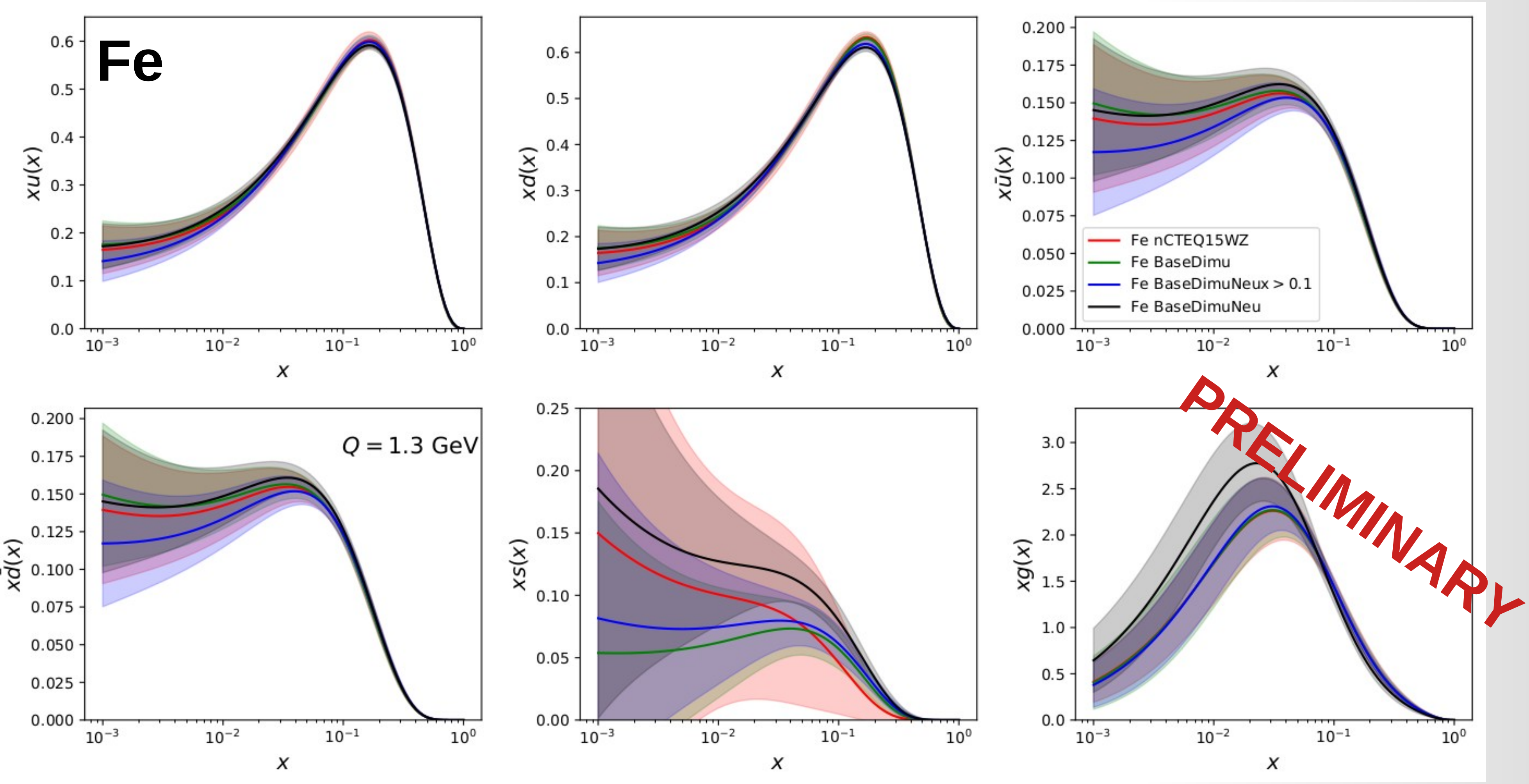
Shifted theory :

$$T_i^* = T_i + \sum_\alpha \bar{\sigma}_{i\alpha} r_\alpha$$



Milder shadowng if low x neutrino data is included.

Impact on nPDFs

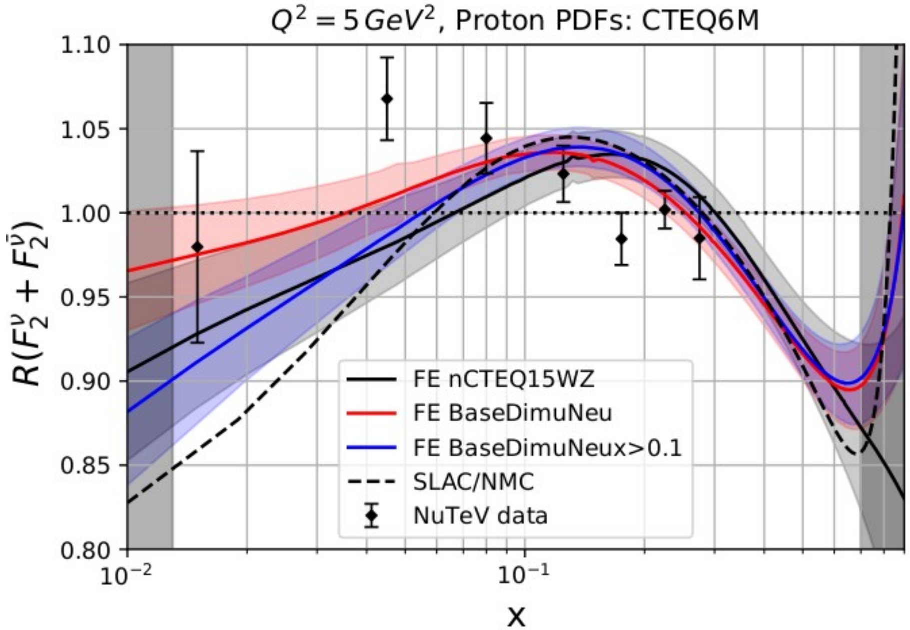


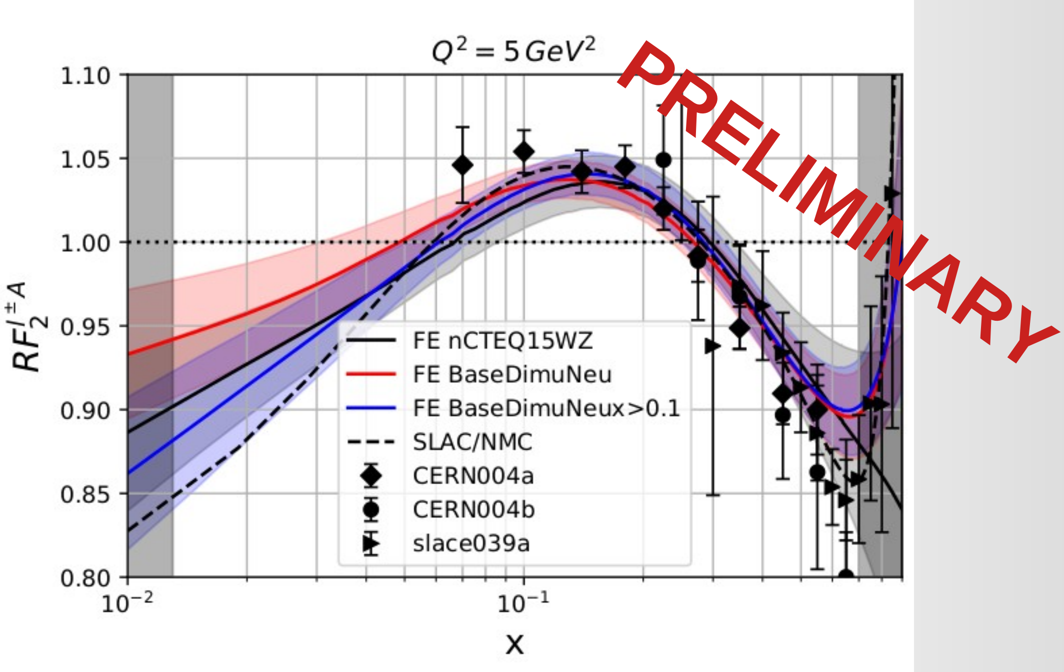
- **Including low x neutrino data pulls the strange PDF up.**
- **Smaller uncertainties as we add more neutrino data.**

RF₂ Predictions

$$RF_2 = \frac{F_2^A}{F_2^{A,free}}$$

$$f_i^{A,free} = \frac{Z}{A} f_i^p + \frac{N}{A} f_i^n$$





BaseDimuNeu predictions agree more with NuTeV data, especially at low x.

Summary

- **Still large uncertainties for strange PDF even after including W & Z data from LHC. An improved constraint for gluon PDF from WZ data.**

- **The nCTEQ15WZ fit prefers higher strange sea ratio**

- **Tensions between the predictions extracted from nCTEQ15WZ and neutrino data. The tension seems to be maximal at $x \leq 0.1$ and x~0.6.**

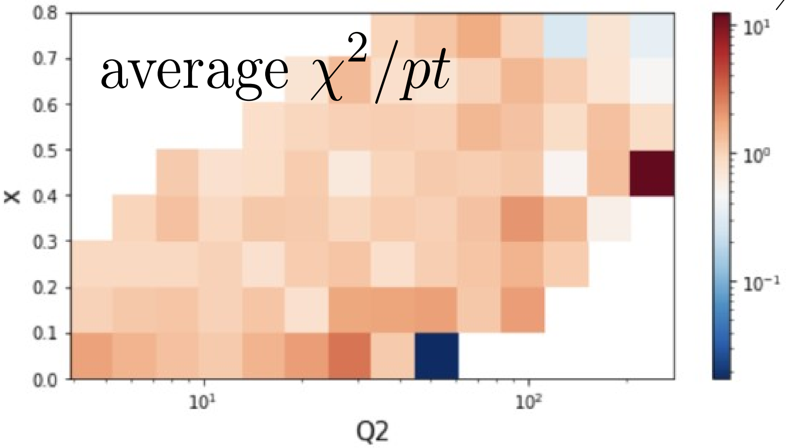
- **Applying the cut $x \leq 0.1$ relaxes the tensions and makes the combined fit, BaseDimuNeux>0.1, pass our compatibility criteria.**

- **Tensions at x~0.6 do not disappear in BaseDimuNeux>0.1 fit. The tension is small enough such that BaseDimuNeux>0.1 pass our compatibility criteria.**

- **Still need to determine the sources of the tensions at low x and x~0.6.**

Thank you

DimuNeu Fit



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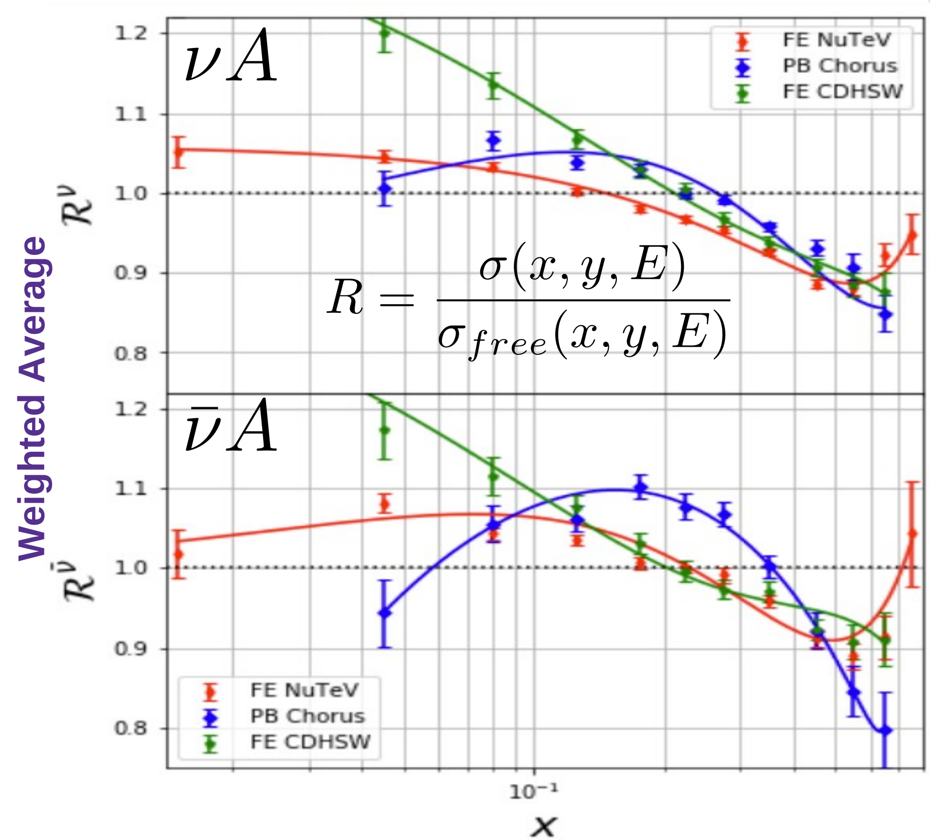

$$\mathcal{R}(x) = a_1 + a_2 x + a_3 e^{a_4 x} + a_5 x^{a_6}$$