nCTEQ Nuclear Parton Distribution Functions

Quarkonia as Tools 2021

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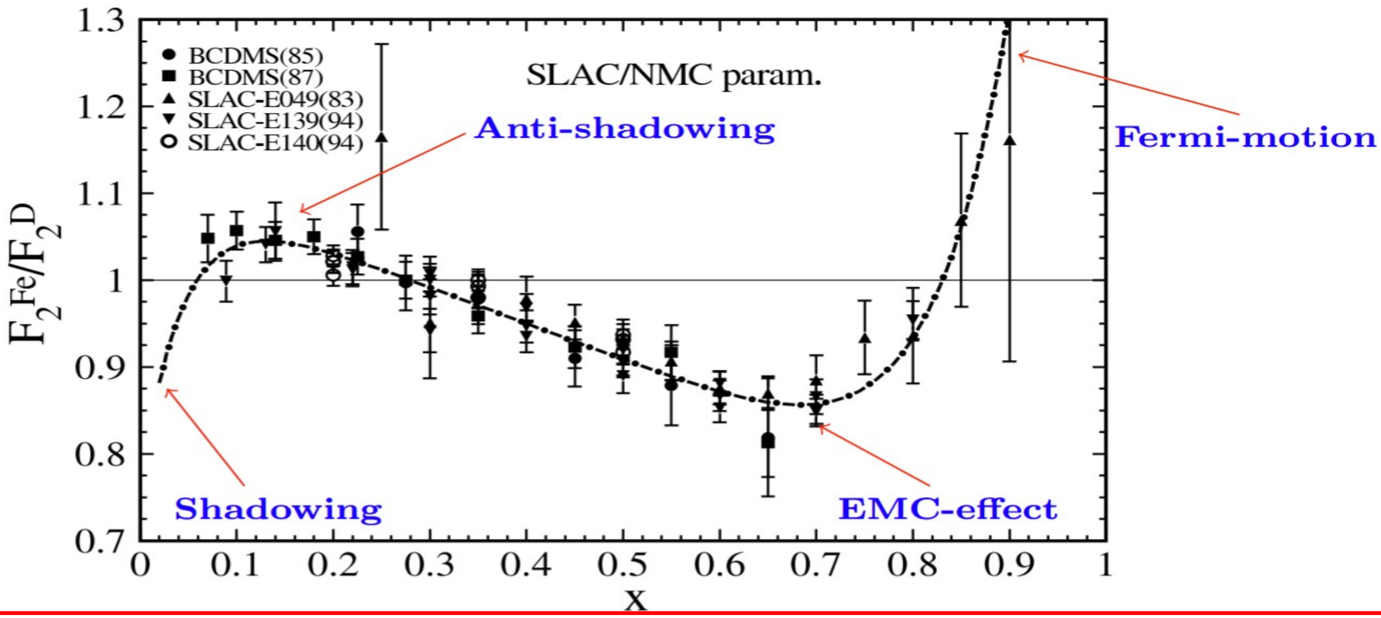
nCTEQ
nuclear parton distribution functions

WWU MÜNSTER

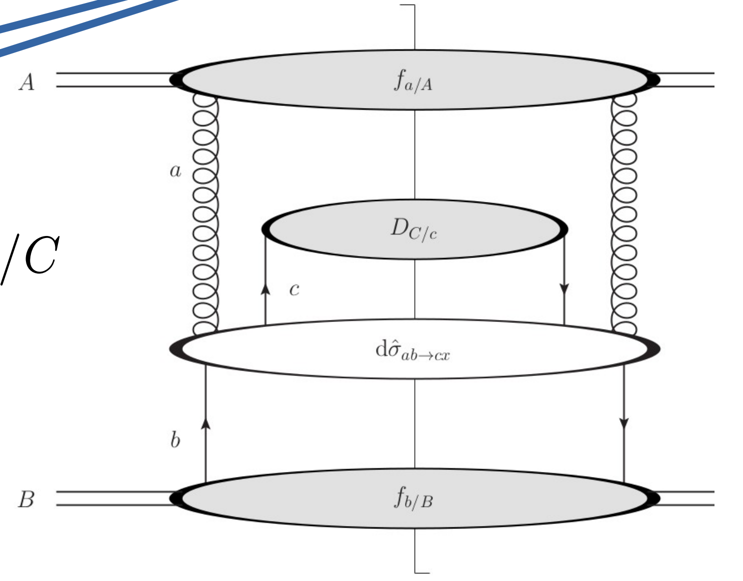
INTRODUCTION : nPDFs

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



Working assumption : Factorization ⟶ **nPDFs**

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



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:

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

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

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

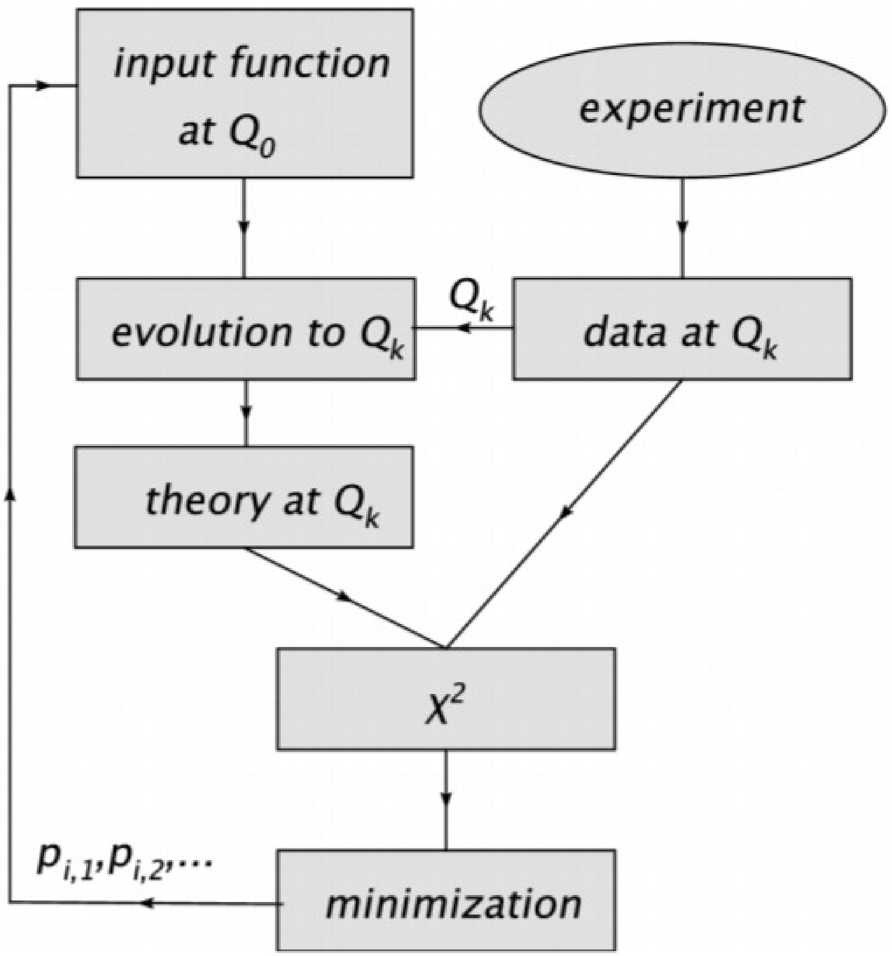
- **A-dependence :** $c_k(A) = c_{k,0} + c_{k,a}(1 - A^{-c_{k,b}})$

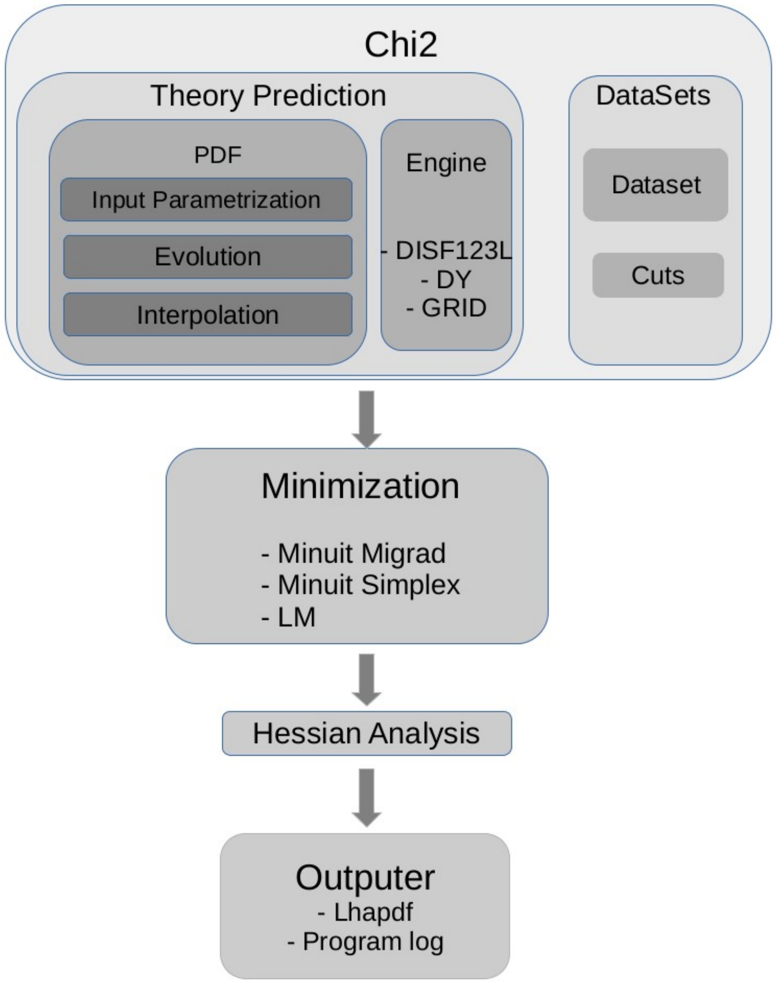
Proton PDF parameters from nCTEQ6M

- **Sum rules :**

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

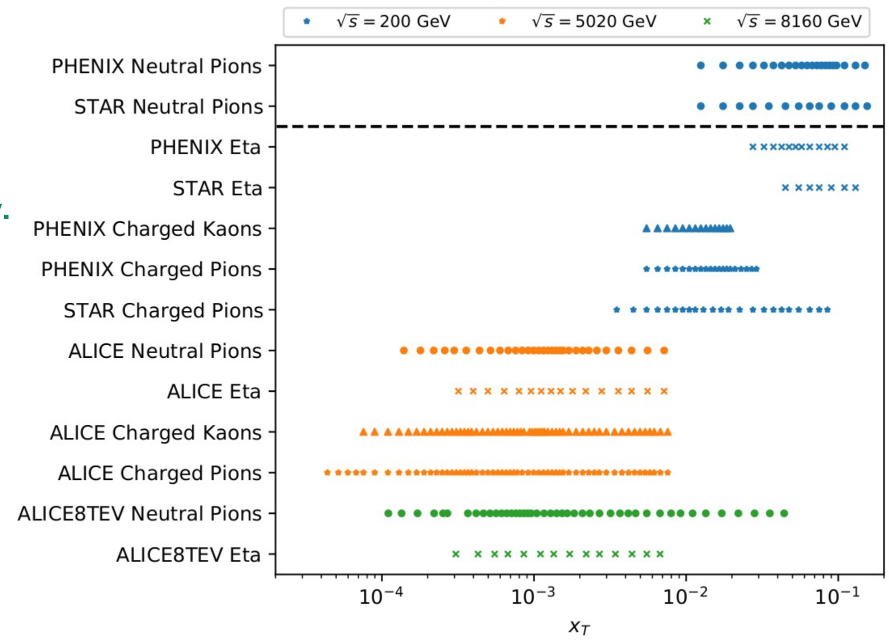
nPDF fitting with ncteq++





Current status from nCTEQ (2021)

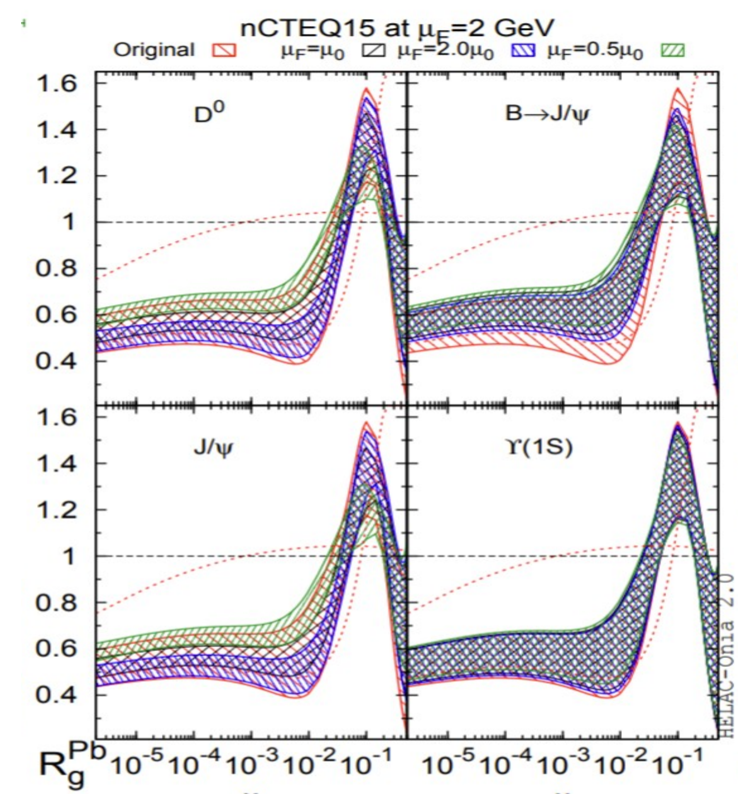
- **Tension between NC and CC DIS**
  - **nCTEQ Neutrino DIS study** [PRL106(2011)122301, Phys. Rev. D77, 054013 (2008)]
  - **Neutrino DIS revisited (ongoing)**



- **Better constrain for strange quark PDF**
  - **nCTEQ15WZ** EPJC 80, 968
  - **Neutrino DIS revisited**

- **Relaxing the kinematic cuts?**
  - **nCTEQ15HiX (under review)**

- **Better constrain on gluon PDF**
  - **HR with Heavy flavor production data** [PRL 121 2018]
  - **RHIC + ALICE SIH data ---> nCTEQ15SIH (ongoing)**
  - **Direct photon (ongoing)**
  - **Jets (to do)**



- **A-dependence**
  - **A-dependence overhaul (just started)**

→ **nCTEQ2x ?**

nCTEQ15HiX

nCTEQ15HIX — Extending nPDF Analyses into the High-x Region with New Jefferson Lab Data

E.P. Segarra,[1,*] T. Ježo,[2,†] A. Accardi,[3,4] P. Duwentäster,[5] O. Hen,[1] T .J. Hobbs,[6,4] C. Keppel,[4] M. Klasen,[5] K. Kovařík,[5] A. Kusina,[7] J.G. Morfín,[8] K.F. Muzakka,[5] F.I. Olness,[6,‡] I. Schienbein,[9] and J.Y. Yu.[9]

ArXiv : 2012.11566

nCTEQ15HiX : Data Sets

F_2^A/F_2^D : Observable	Experiment	ID	Ref.	# data	# data after cuts
D	NMC-97	5160	75	292	201/275
^{3}He/D	Hermes	5156	76	182	17/92
^{4}He/D	NMC-95,re	5124	77	18	12/16
	SLAC-E139	5141	26	18	3/17
Li/D	NMC-95	5115	78	24	11/15
Be/D	SLAC-E139	5138	26	17	3/16
C/D	FNAL-E665-95	5125	79	11	3/4
	SLAC-E139	5139	26	7	2/7
	EMC-88	5107	80	9	9/9
	EMC-90	5110	81	9	0/2
	NMC-95	5113	78	24	12/15
	NMC-95,re	5114	77	18	12/16
N/D	Hermes	5157	76	175	19/92
	BCDMS-85	5103	29	9	9/9
Al/D	SLAC-E049	5134	82	18	0/18
	SLAC-E139	5136	26	17	3/16
Ca/D	NMC-95,re	5121	77	18	12/15
	FNAL-E665-95	5126	79	11	3/4
	SLAC-E139	5140	26	7	2/7
	EMC-90	5109	81	9	0/2
Fe/D	SLAC-E049	5131	28	14	2/14
	SLAC-E139	5132	26	23	6/22
	SLAC-E140	5133	27	10	0/6
	BCDMS-87	5101	30	10	10/10
	BCDMS-85	5102	29	6	6/6
Cu/D	EMC-93	5104	55	10	9/10
	EMC-93(chariot)	5105	55	9	9/9
	EMC-88	5106	80	9	9/9
Kr/D	Hermes	5158	76	167	12/84
Ag/D	SLAC-E139	5135	26	7	2/7
Sn/D	EMC-88	5108	80	8	8/8
Xe/D	FNAL-E665-92	5127	83	10	2/4
Au/D	SLAC-E139	5137	26	18	3/17
Pb/D	FNAL-E665-95	5129	79	11	3/4
Total:				1205	414/857

$F_2^A/F_2^{A'}$: Observable	Experiment	ID	Ref.	# data	# data after cuts
C/Li	NMC-95,re	5123	77	25	7/20
Ca/Li	NMC-95,re	5122	77	25	7/20
Be/C	NMC-96	5112	84	15	14/15
Al/C	NMC-96	5111	84	15	14/15
Ca/C	NMC-95,re	5120	77	25	7/20
	NMC-96	5119	84	15	14/15
Fe/C	NMC-96	5143	84	15	14/15
Sn/C	NMC-96	5159	85	146	111/144
Pb/C	NMC-96	5116	84	15	14/15
Total:				296	202/279

$\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$: Observable	Experiment	ID	Ref.	# data	# data after cuts
C/D	FNAL-E772-90	5203	86	9	9/9
Ca/D	FNAL-E772-90	5204	86	9	9/9
Fe/D	FNAL-E772-90	5205	86	9	9/9
W/D	FNAL-E772-90	5206	86	9	9/9
Fe/Be	FNAL-E886-99	5201	87	28	28/28
W/Be	FNAL-E886-99	5202	87	28	28/28
Total:				92	92/92

New Jlab data

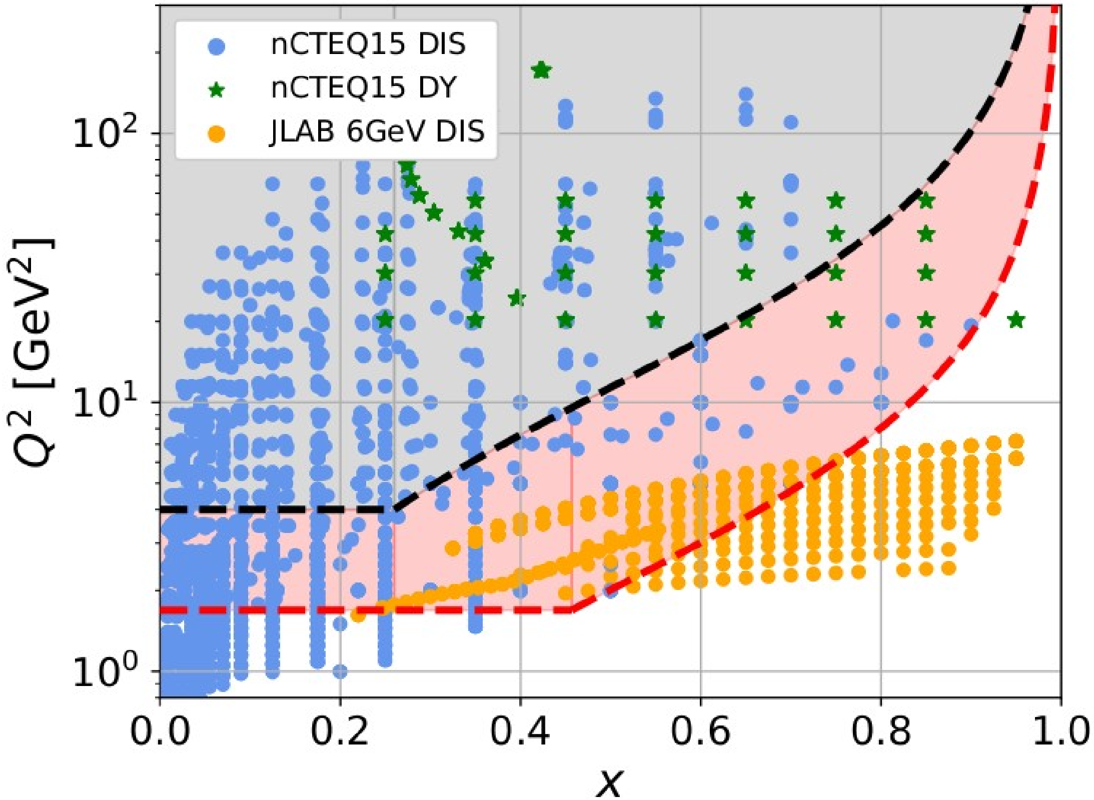
F_2^A/F_2^D : Observable	Experiment	ID	Ref.	# data	#data after cuts
^{208}Pb/D	CLAS	9976	35	25	24
^{56}Fe/D	CLAS	9977	35	25	24
^{27}Al/D	CLAS	9978	35	25	24
^{12}C/D	CLAS	9979	35	25	24
^{4}He/D	Hall C	9980	58	25	17
		9981	58	26	16
^{3}He/D	Hall C	9982	58	25	17
		9983	58	26	16
^{64}Cu/D	Hall C	9984	58	25	17
		9985	58	26	16
^{9}Be/D	Hall C	9986	58	25	17
		9987	58	26	16
^{197}Au/D	Hall C	9988	58	24	17
		9989	58	26	16
^{12}C/D	Hall C	9990	58	25	17
		9991	58	17	7
		9992	58	26	16
		9993	58	18	6
		9994	58	17	7
		9995	58	15	2
		9996	58	19	7
		9997	58	16	2
		9998	58	21	8
		9999	58	18	3
Total				546	336

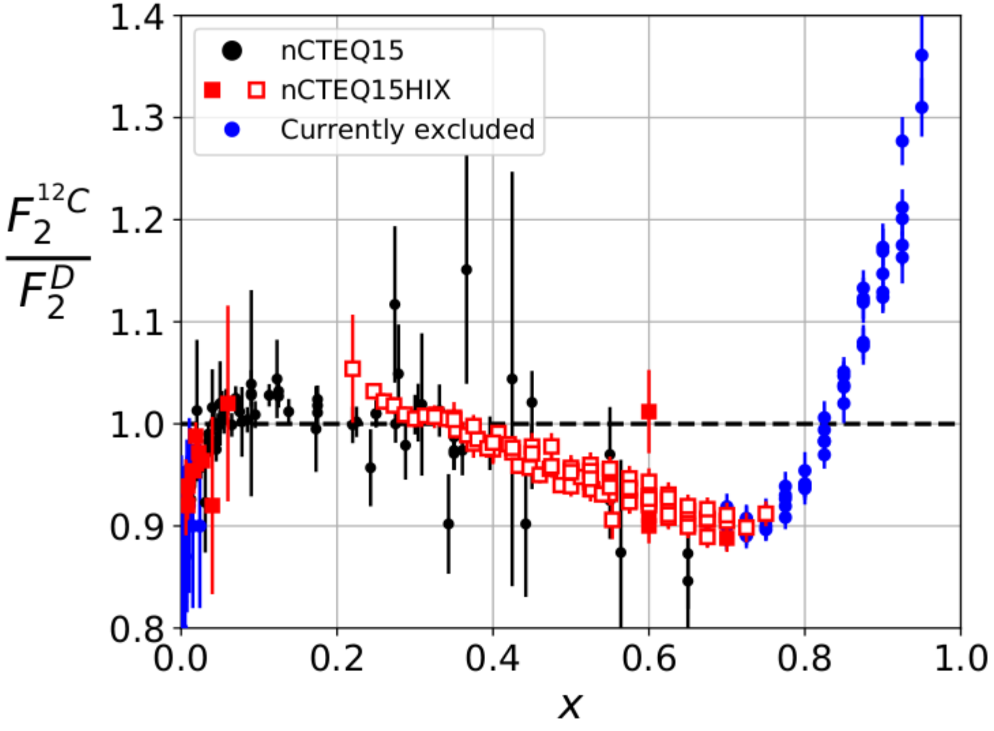
nCTEQ15HiX : Kinematic Cuts

Q^2_{cut}	Q_{cut}	W_{cut} No Cut	W_{cut} 1.3	W_{cut} 1.7	W_{cut} 2.2	W_{cut} 3.5
1.3	$\sqrt{1.3}$	1906	1839	1697	1430	1109
1.69	1.3	1773	1706	1564	1307	1024
2	$\sqrt{2}$	1606	1539	1402	1161	943
4	2	1088	1042	952	817	708

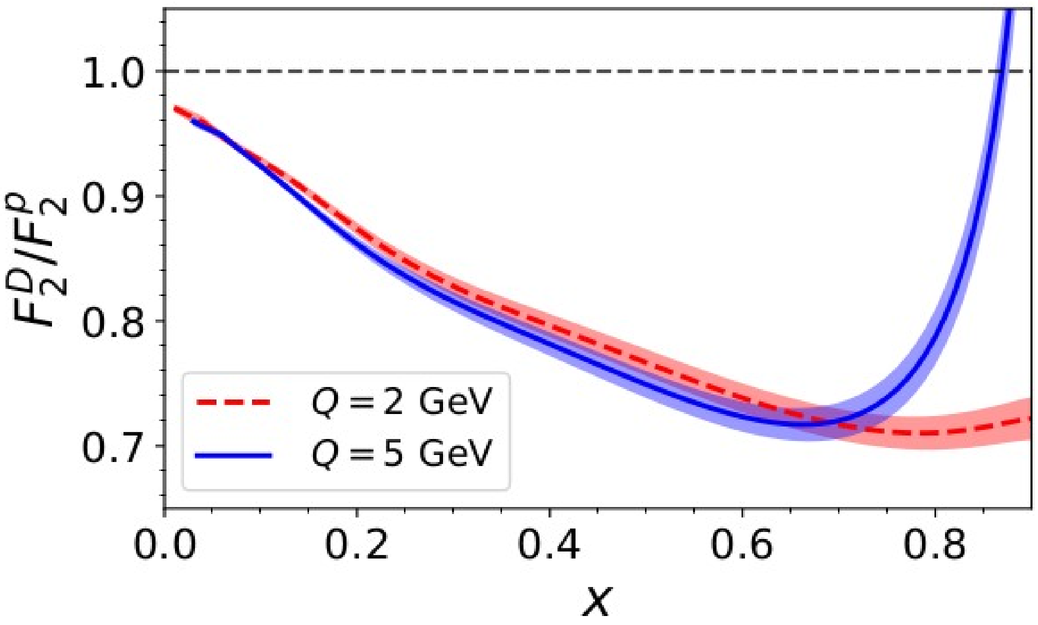
nCTEQ15HiX kinematic cuts

nCTEQ15 kinematic cuts





Corrections



- **Isoscalar correction**

$$F_2^A \to F_2^A \times \frac{F_2^p + F_2^n}{ZF_2^p + NF_2^n}$$

UNDONE.

- **Deuteron Correction**

$$F_2^D \to F_2^p = F_2^D \times \left(F_2^p/F_2^D\right)_{CJ15}$$

$\left(F_2^p/F_2^D\right)_{CJ15}$ **taken from [Accardi *et al, Phys. Rev. D 93 11 (2016) 114017*]**

- **TMC correction**

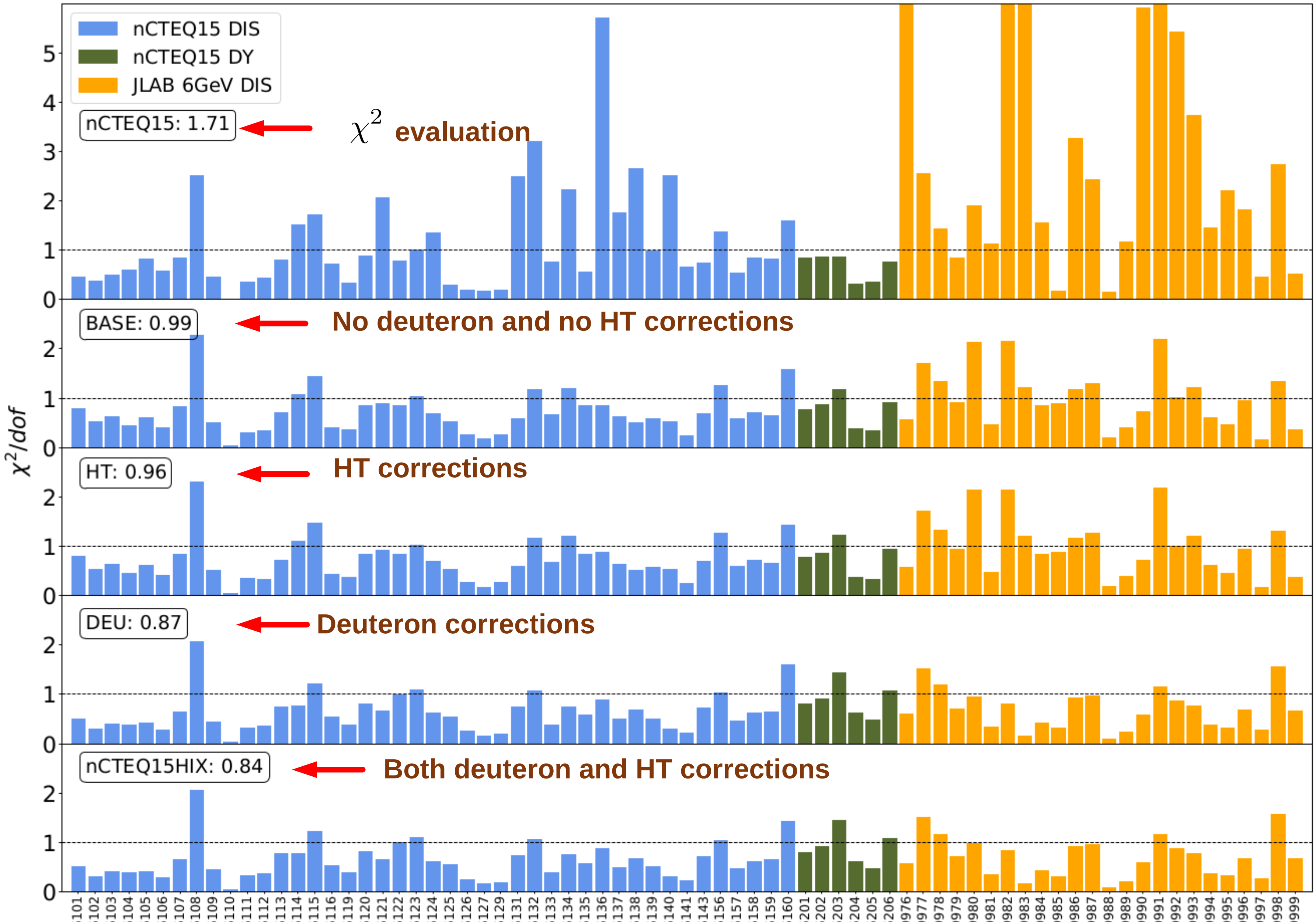
$$\frac{F_2^{A,\mathrm{TMC}}(x,Q)}{F_2^{D,\mathrm{TMC}}(x,Q)} \simeq \frac{F_2^{A,\,\substack{\text{leading}\\ \text{TMC}}}(x,Q)}{F_2^{D,\,\substack{\text{leading}\\ \text{TMC}}}(x,Q)} = \frac{F_2^{A,(0)}(\xi,Q)}{F_2^{D,(0)}(\xi,Q)}$$

- **HT correction**

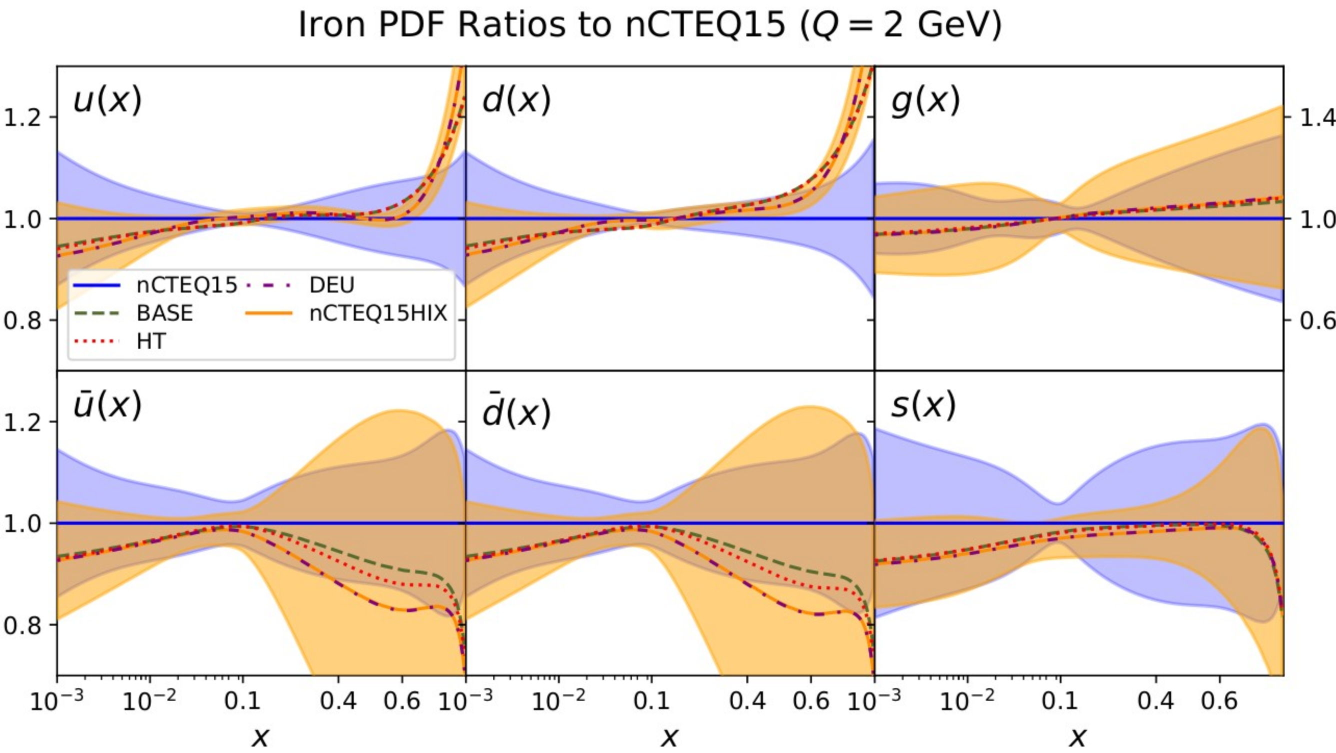
$$F_2^A(x,Q) \to F_2^A(x,Q)\left[1 + \frac{C_{HT}(x,A)}{Q^2}\right]$$

$$C_{HT}(x,A) = h_0 x^{h_1}(1 + h_2 x)\ A^{1/3}$$

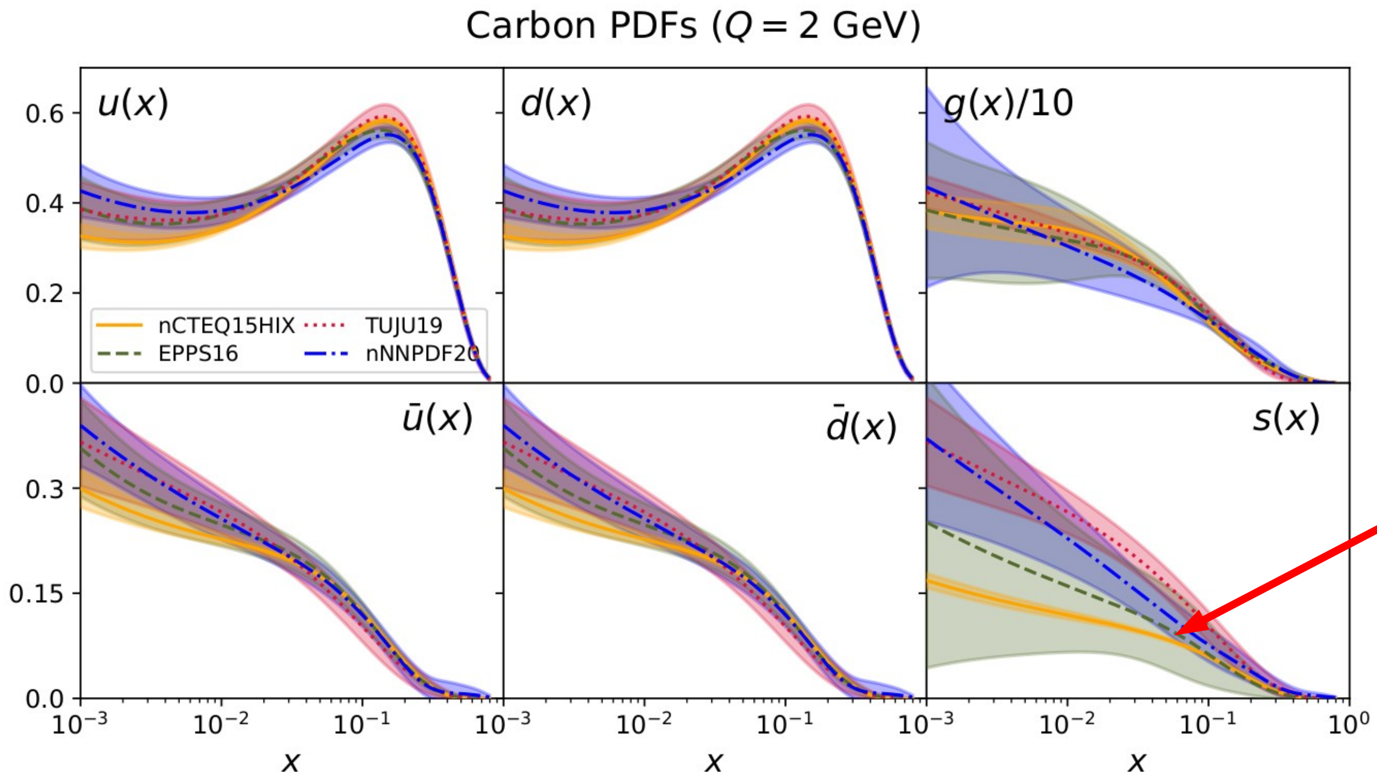
Goodness-of-fits



nCTEQ15HiX : nPDFs



Different large *x* and low *x* behavior compared to nCTEQ15



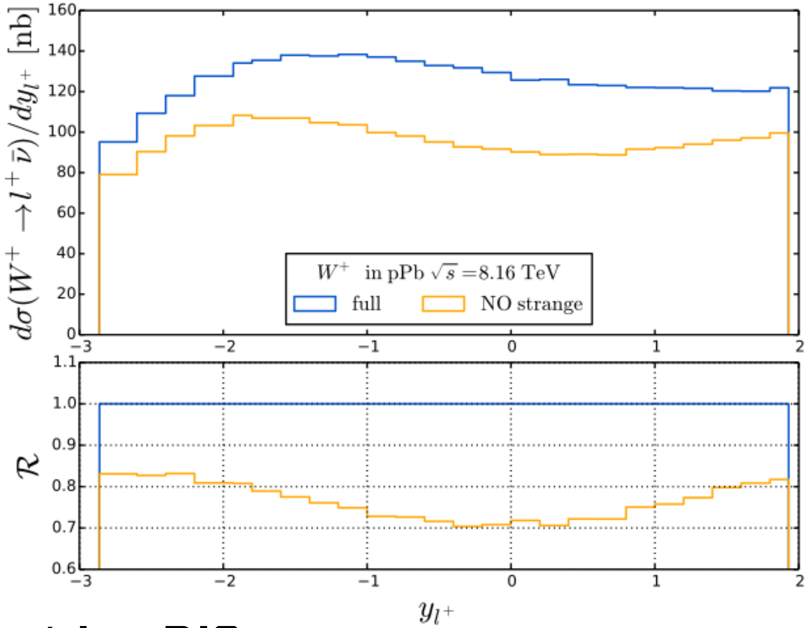
Small error band : strange PDF parameters are fixed. Vary through momentum sum rule.

nCTEQ15WZ

[EPJC 80, 968]

Constraining Strange PDF

Drell-Yan W and Z boson production

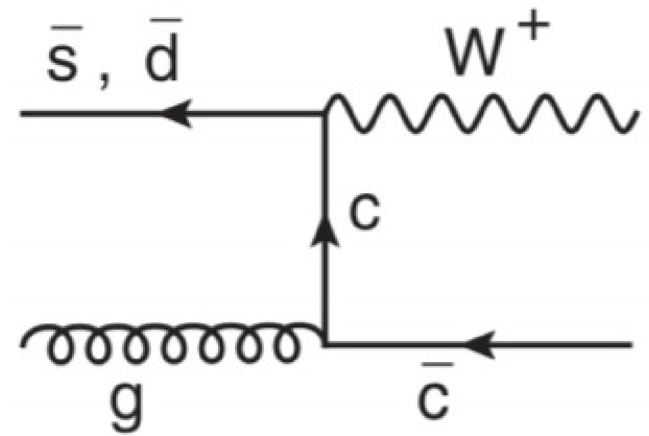


Neutrino DIS

$$F_2^{\nu} \sim \left[d + s + \bar{u} + \bar{c}\right]$$
$$F_2^{\bar{\nu}} \sim \left[\bar{d} + \bar{s} + u + c\right]$$
$$F_3^{\nu} \sim 2\left[d + s - \bar{u} - \bar{c}\right]$$
$$F_3^{\bar{\nu}} \sim 2\left[u + c - \bar{d} - \bar{s}\right]$$

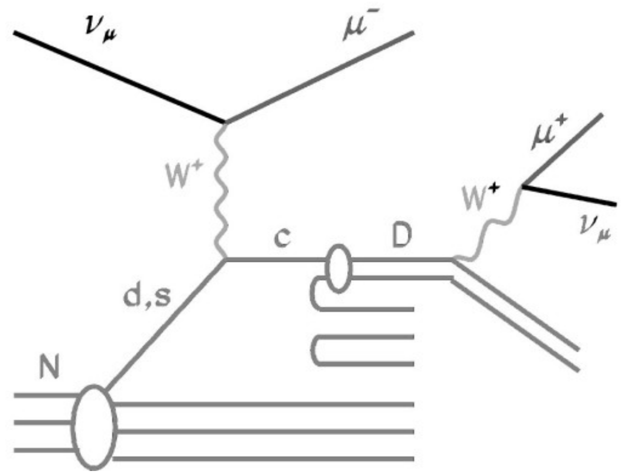
High statistics cross-section data !

W+c associated production



Direct constrain already at LO, but NO nuclear data.

Dimuon production



Direct constrain at LO, but beware of uncertainty in the charm fragmentation function.

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

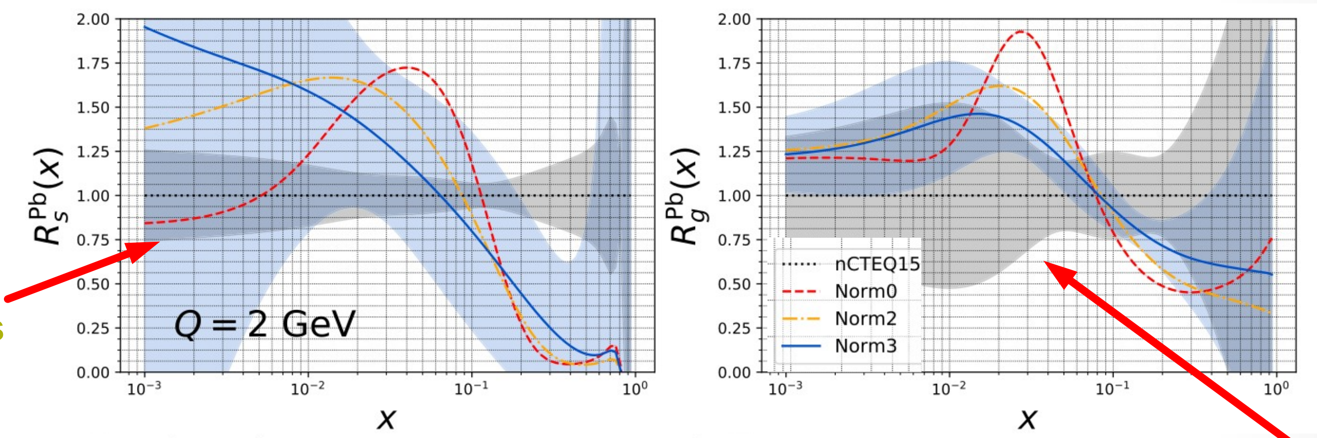
- **Number Free Parameters : 19+2+3: 7 gluon, 7 valence, 2 ub+db, 3 s+sb, 2 norm pion, 3 norm WZ.**
- **Error analysis : Hessian method, with**

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

- **Error analysis : Use Lanczos derivative to reduce numerical noise.**

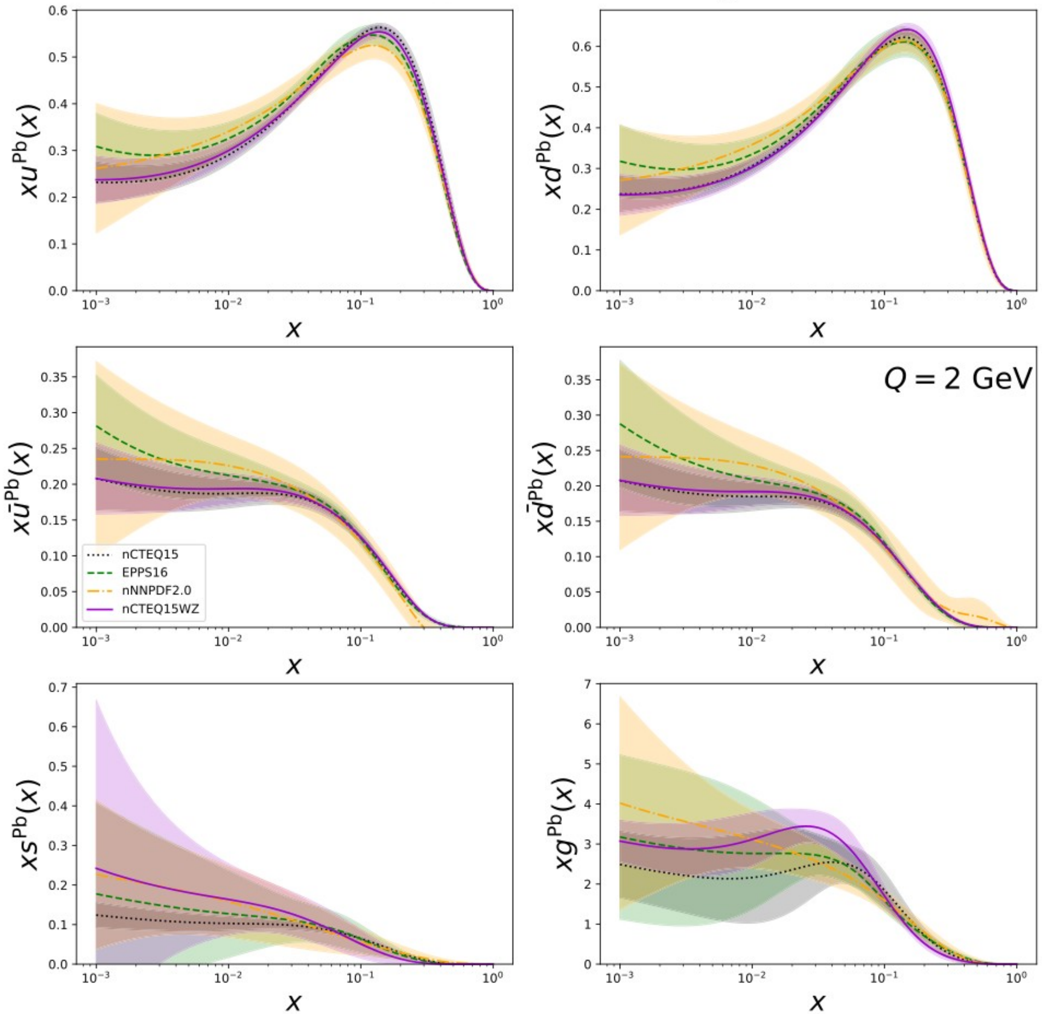
			$\sqrt{s_{NN}}$ [TeV]	σ_{norm} (%)	No points
Data overview					
ATLAS	Run I	$W^\pm$	5.02	2.7	10+10
ATLAS	Run I	Z	5.02	2.7	14
CMS	Run I	$W^\pm$	5.02	3.5	10+10
CMS	Run I	Z	5.02	3.5	12
CMS	Run II	$W^\pm$	8.16	3.5	24+24
ALICE	Run I	$W^\pm$	5.02	2.0	2+2
LHCb	Run I	Z	5.02	2.0	2

NCTEQ15WZ nPDFs



Larger uncertainty : more free parameters

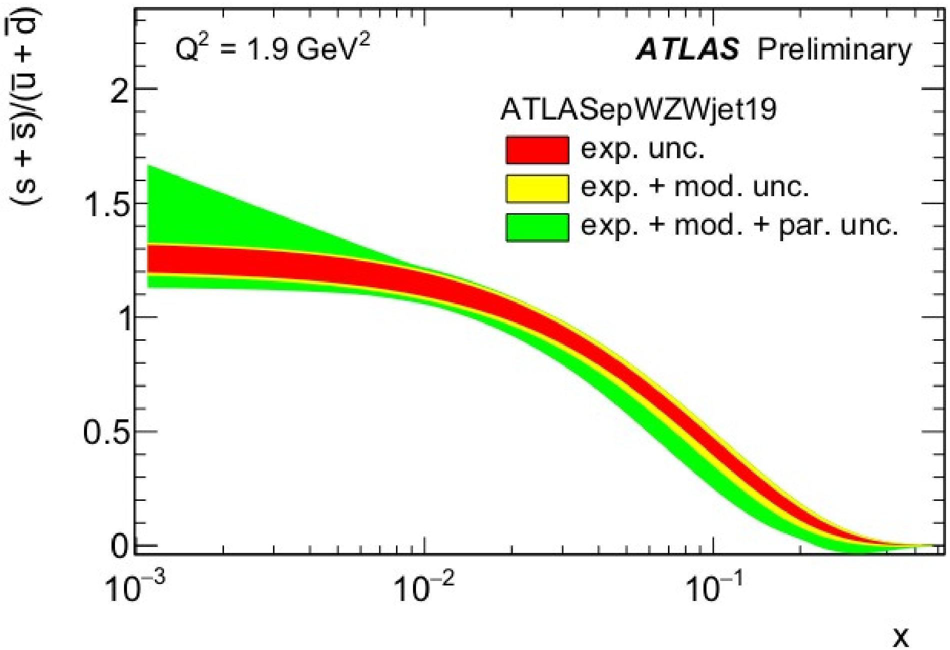
Better constrain on gluon PDF

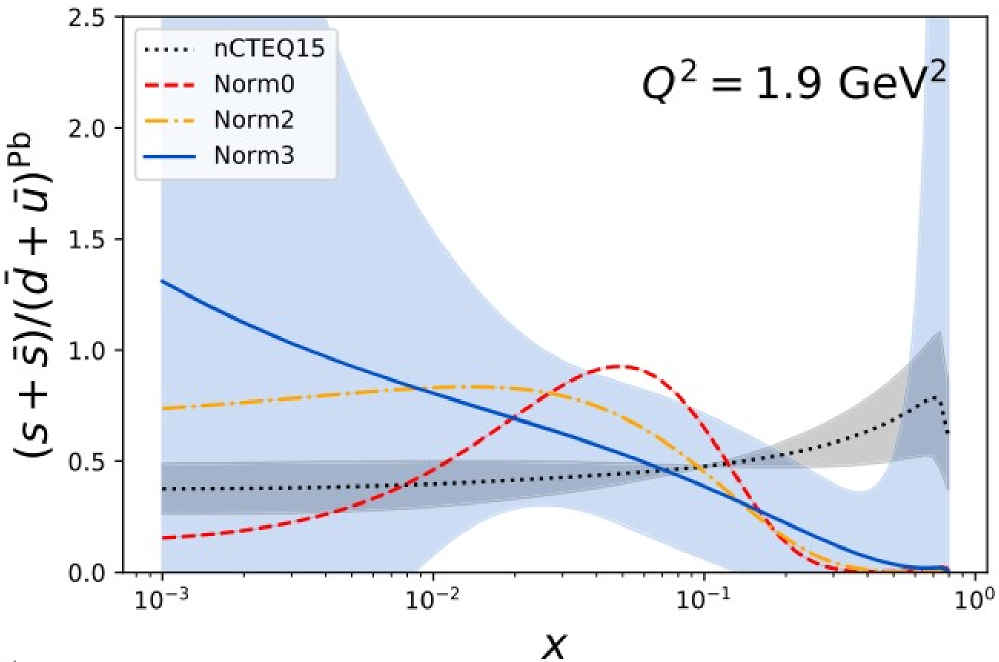


Low x and high CM energy

→ Constrain on gluon PDF!

Strange sea ratio





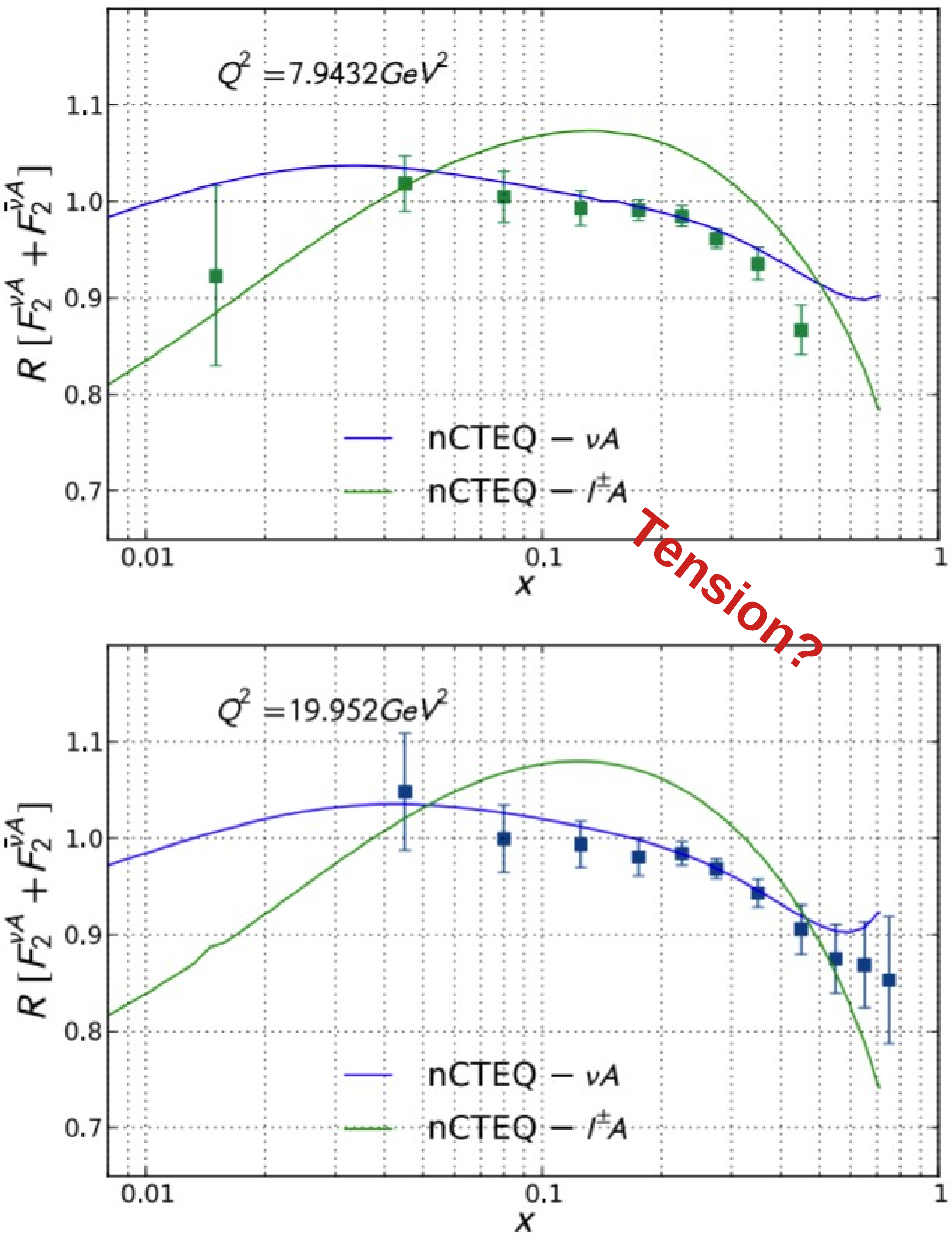
Does the elevated strange PDF is what nature dictates, or is it because lack of flavor separation ?

Still open question. Need more data!

Neutrino DIS Revisited

Neutrino DIS

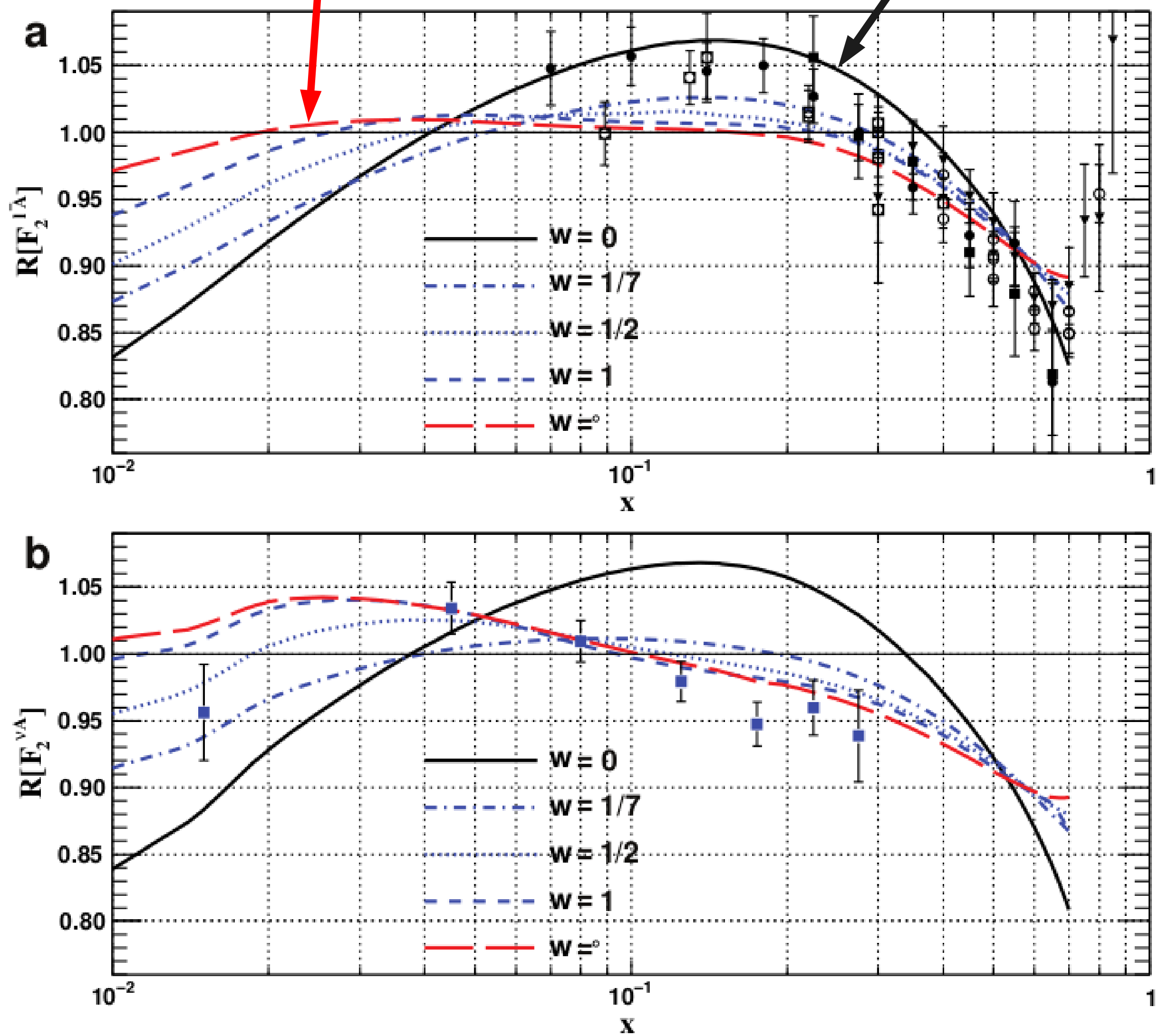
- **Important for flavor differentiation**
- **(More) sensitivity to strange PDF.**
- **High statistics!**
- **Heavy target (FE, PB), but usually used in proton PDF fit.**
- **Different nuclear correction ?**
- **Problem : Tension with charge lepton DIS data ?**



nCTEQ Study

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

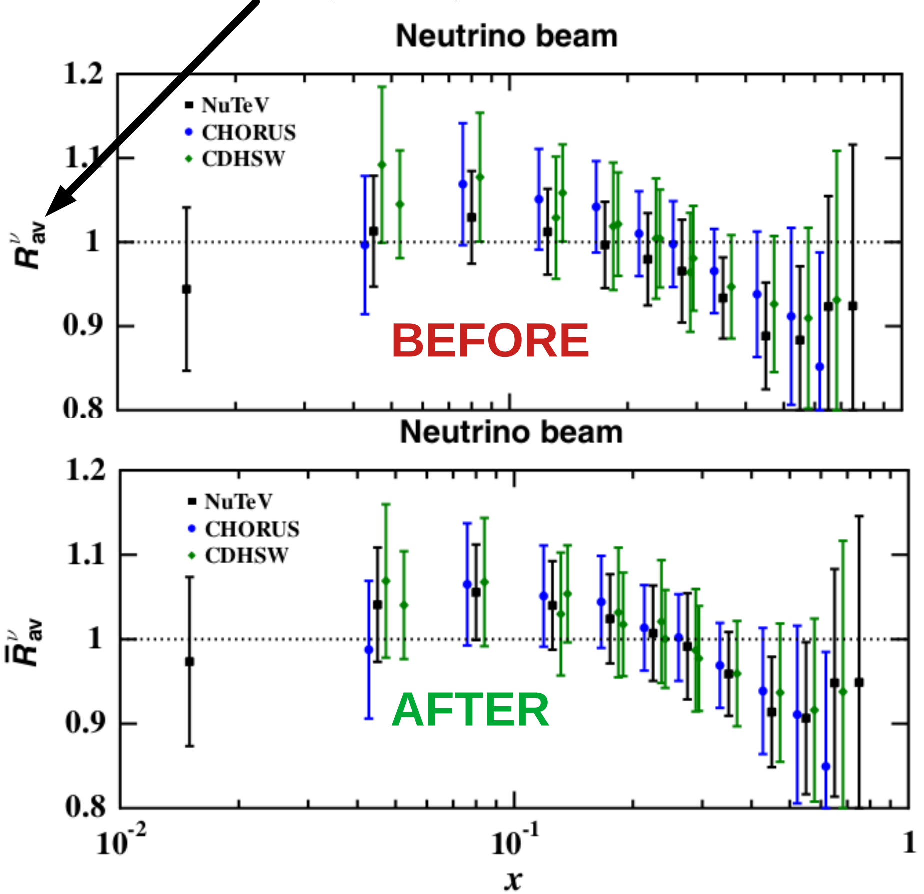
- **USE** NuTeV's point-by-point correlated systematic uncertainties.
- Different weights ***w*** for the neutrino DIS data.
- χ^2- **Hypothesis test : NO COMPROMISE FIT**
- **Ignoring NuTeV correlation seems to lower the tension, but NOT ENOUGH!**



Kovarik *et al PRL106(2011)122301*

EPPS

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

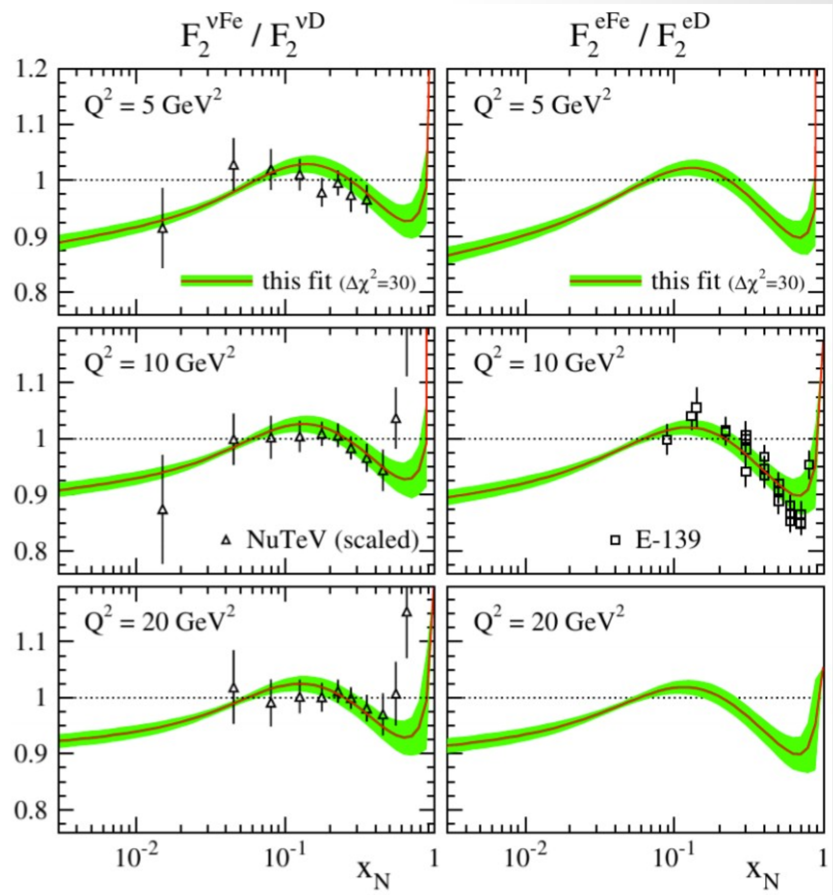


Normalization : $$\bar{R}^{\nu}(x,y,E) = \frac{\sigma^{\nu}_{exp}/I^{\nu}_{exp}(E)}{\sigma^{\nu}_{CTEQ6}/I^{\nu}_{CTEQ6}(E)}$$

Hessian Reweighting → $\Delta\chi^2 < \Delta\chi^2_{EPS09}$

Paukunen & Salgado PRL110(2013)212301

DSSZ



- **Global nPDF fit : charge lepton DIS, DY, pion production, and F2,3 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 : nCTEQ15WZdeut

- **Data : DIS+ DY+ pion + WZ LHC**
- **Number of data : 859 pts**
- **Iso-scalar corrections are undone.**
- **Deuteron correction :**

$$F_2^D \to F_2^p = F_2^D \times \left(F_2^p / F_2^D\right)_{CJ15}$$

$\left(F_2^p / F_2^D\right)_{CJ15}$ **taken from (Accardi *et al* *Phys. Rev. D 93 11 (2016) 114017*)**

VS

DimuNeu

- **Data : Dimu CCFR & NuTeV + NuTeV + CDHSW+ Chorus**
- **Number of data : 4063 pts**
- **Proper treatment of normalization uncertainty**
- **CORRELATIONs from NuTeV and Chorus are taken into account!**

Statistical Tests

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

$\bar{S}$	$\Delta\chi^2_S$	P-value	Compatible?
CDHSW	**49**	(6.6e-02, **9.4e-08**)	NO
Chorus	6	(0.4199, 0.0568)	YES
NuTeV	**58**	(0.038, 0.258)	NO
DimuNeu	**79**	(**0.0086**, **0.0069**)	NO

Compatibility criteria : $\Delta\chi^2_S \leq 35 \ \& \ P \geq 0.01$

The BaseChorus fit seems to describe both the data quite well. But ….

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

Poor agreement at low x!

- **Low x neutrino data disagree with each other and with the BASE.**
- **Incomplete theory?**
- **What if we cut low *x* data?**

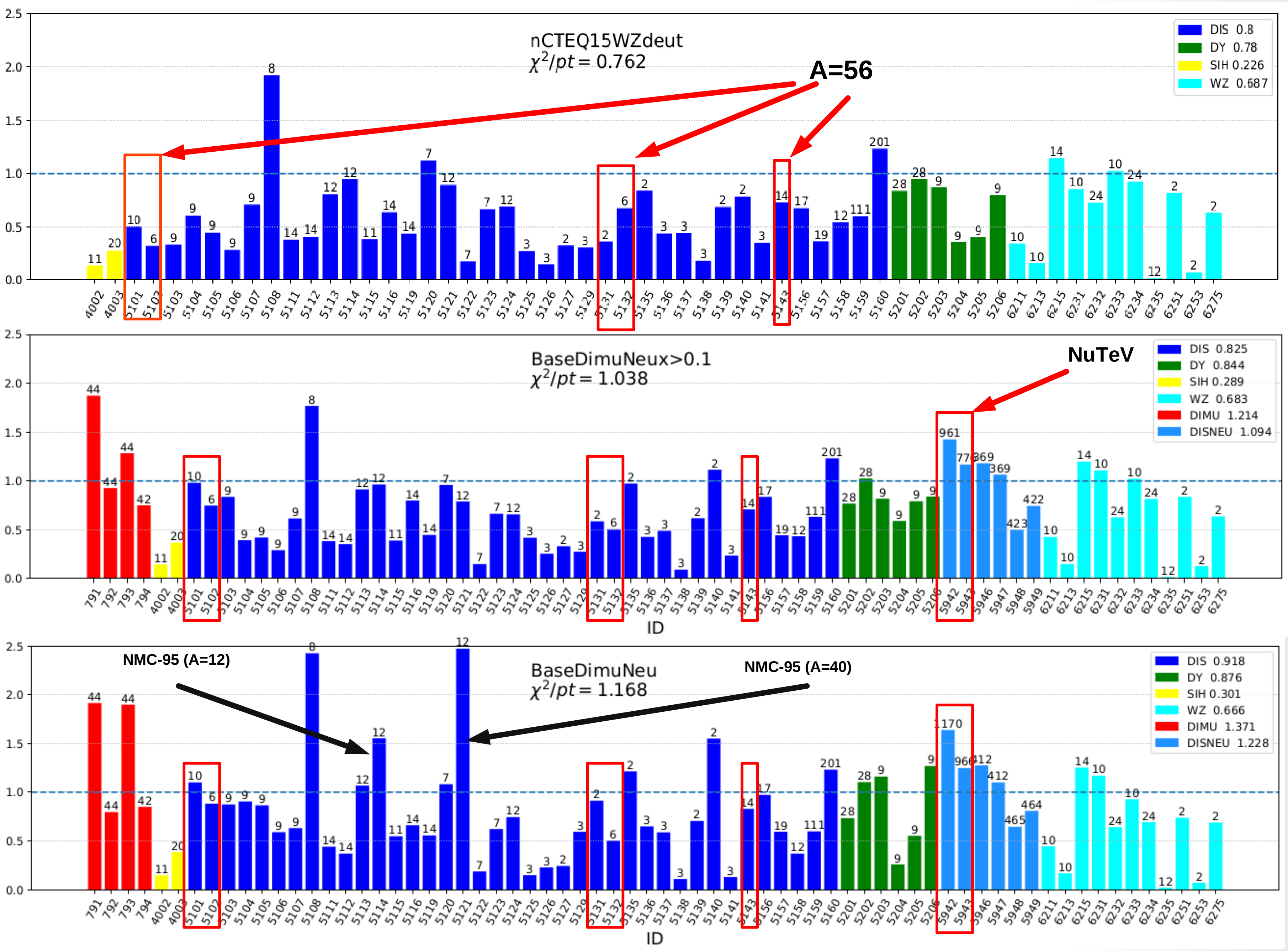
NuTeV : minimal tension at $x \geq 0.175$

Neutrino Data with $x \leq 0.1$ Cut

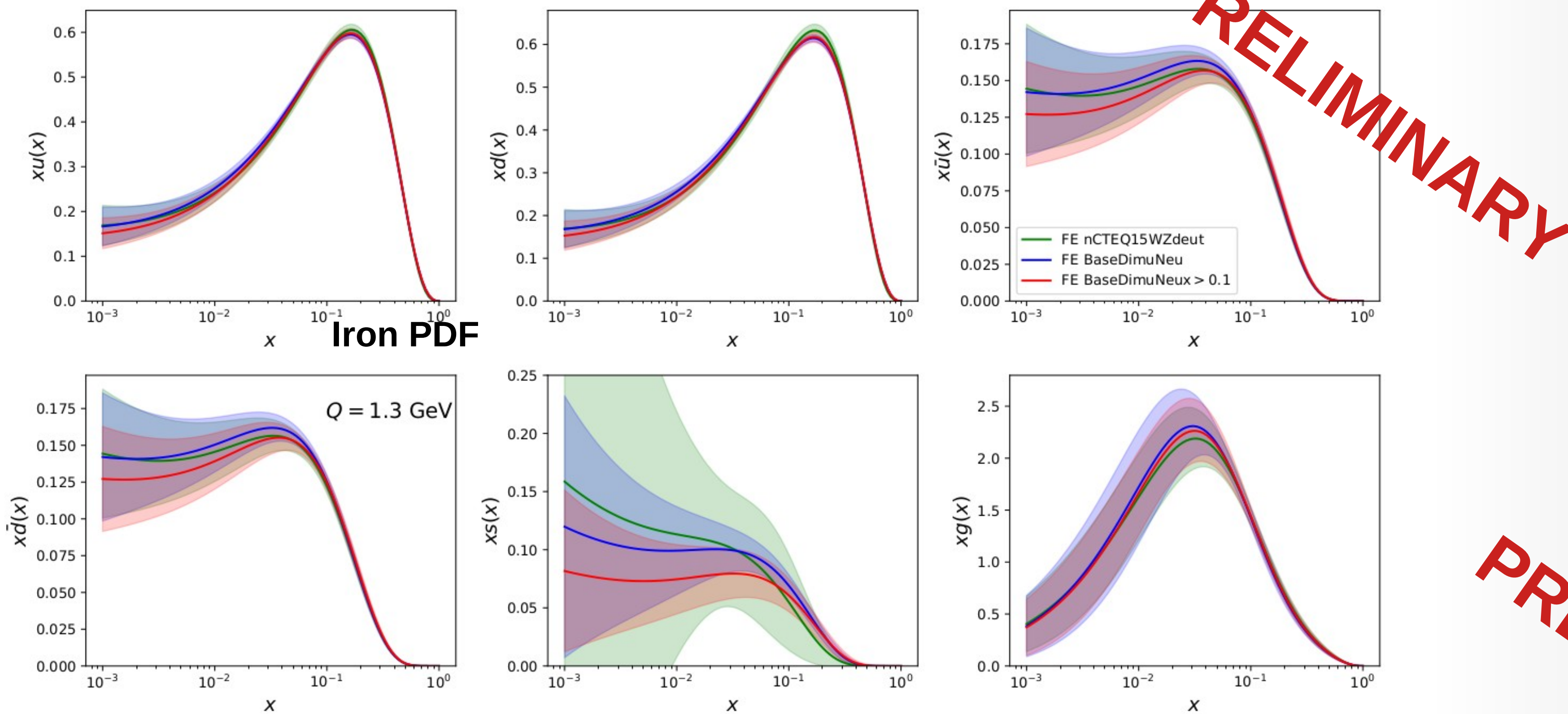
$\bar{S}$	$\Delta\chi^2_S$	P-value	Compatible?
CDHSW	19	(0.2737, 0.0376)	YES
Chorus	5	(0.4320, 0.2084)	YES
NuTeV	29	(0.1826, 0.2499)	YES
DimuNeu	23	(0.2346, 0.3522)	YES

The tensions are now gone!

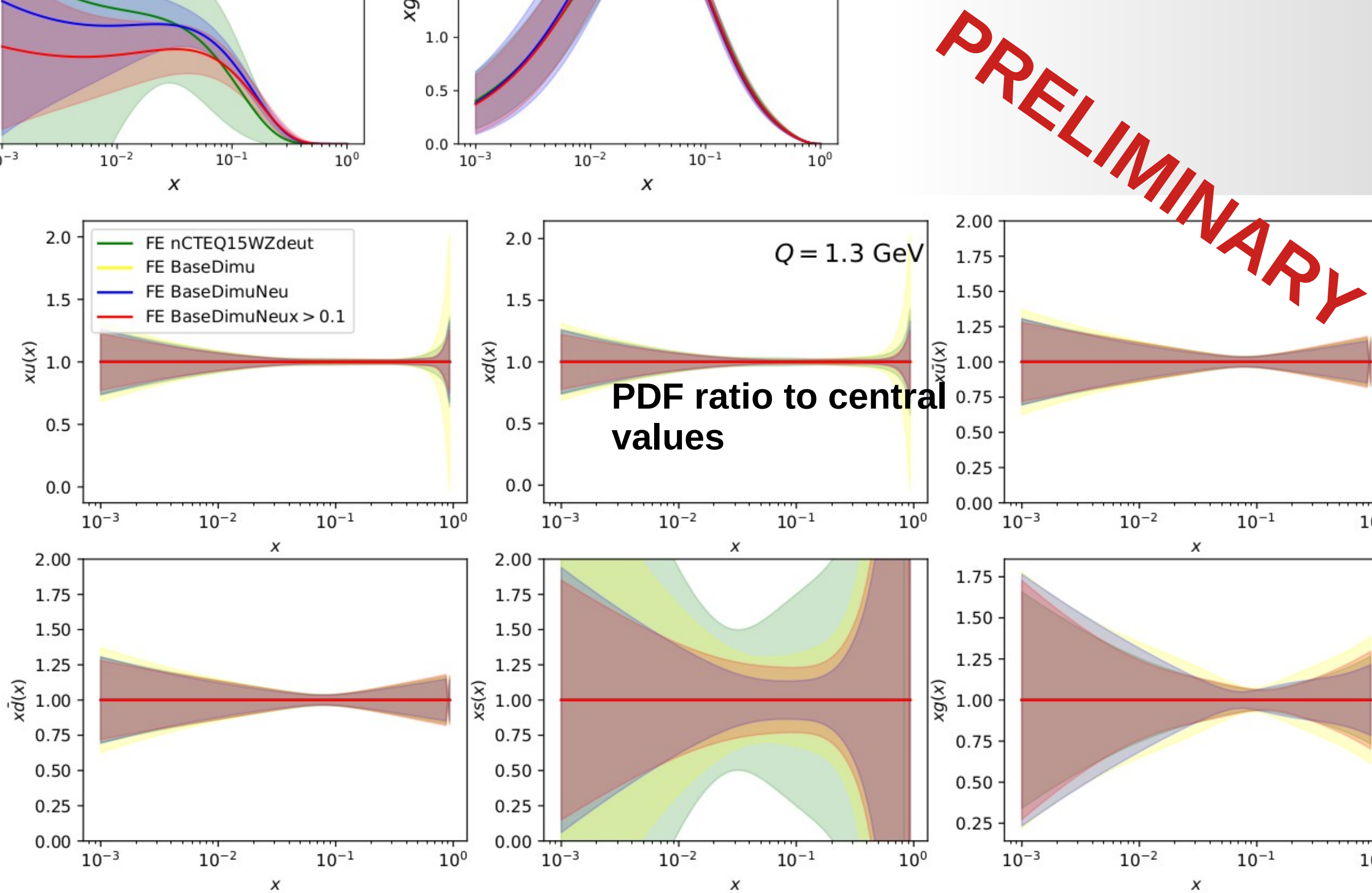
The Combined Fit : BaseDimuNeu vs BaseDimuNeux>0.1



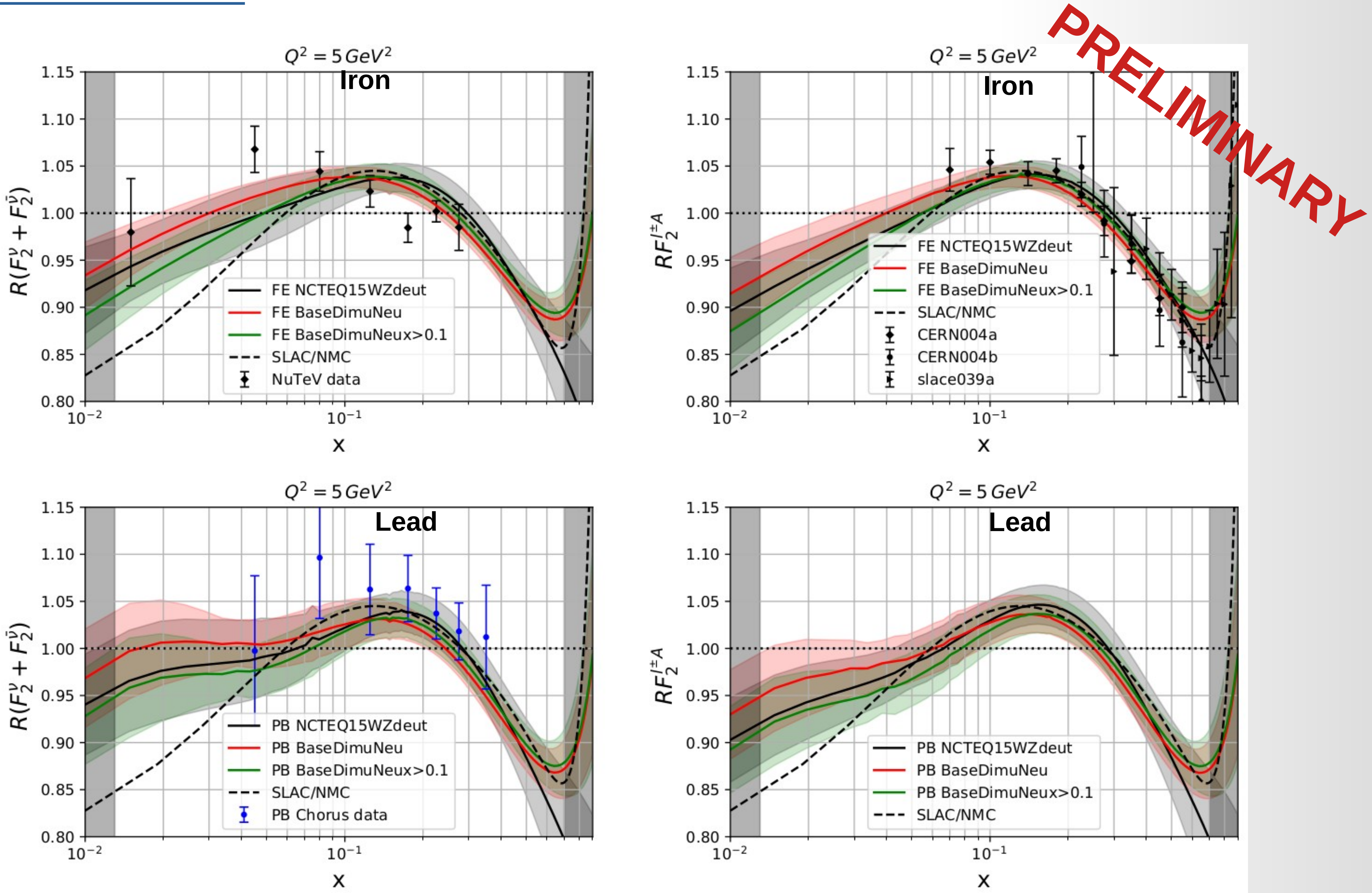
Impact on nPDFs



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



RF2 Predictions



Summary

- **New data sets that are specifically sensitive to strange and gluon PDFs have been analyzed for their impact on nPDFs.**

- **Relaxing Q and W cuts is reasonable if theory uncertainties are taken into account.**

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

- **Tension with some charge lepton DIS data needs to be addressed.**

- **The tensions dominantly happen at low x , cutting neutrino data at low x $\longrightarrow$ *agreement*. Still needs to understand why the tension happen at low x.**

Thank you

	EPPS16	nNNPDF2.0	nCTEQ15WZ	nNNPDF1.0	TuJu19	KSASG20
Order in α_s	NLO	NLO	NLO	NNLO	NNLO	NNLO
lA NC DIS	✓	✓	✓	✓	✓	✓
νA CC DIS	✓	✓			✓	✓
pA DY	✓		✓			
πA DY	✓					
RHIC dAu/pp π	✓		✓			
LHC pPb W, Z	✓	✓	✓			
LHC pPb jets	✓					
Q cut in DIS	1.3 GeV	1.87 GeV	2 GeV	1.87 GeV	1.87 GeV	1.3 GeV
Data points	1811	1467	828	451	2336	4525
Free parameters	20	256	19	183	16	9
Error analysis	Hessian	Monte Carlo	Hessian	Monte Carlo	Hessian	Hessian
Error tolerance $\Delta\chi^2$	52	N/A	35	N/A	50	10
Free-proton PDFs	CT14	NNPDF3.1	~CTEQ6M	NNPDF3.1	own fit	CT18
HQ treatment	GM-VFNS	GM-VFNS	GM-VFNS	GM-VFNS	GM-VFNS	GM-VFNS
Indep. flavours	6	6	5	3	4	3
Year	2016	2020	2020	2019	2019	2020
Reference	EPJC 77, 163	JHEP 09, 183	EPJC 80, 968	EPJC 79, 471	PRD 100, 096015	arXiv:2010.00555

Strange Quark PDF

- **Strange PDF has much larger uncertainty : limited flavor differentiation.**

- **Important for cross section computation and our understanding on hadron structure.**

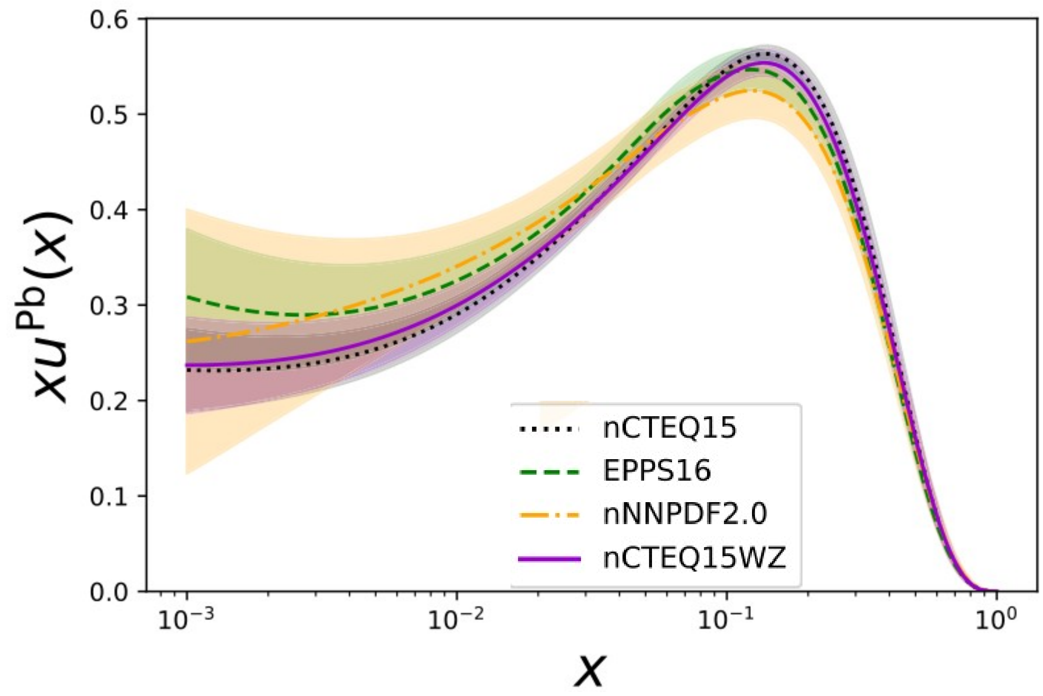
- **CC ang NC DIS constrain :**

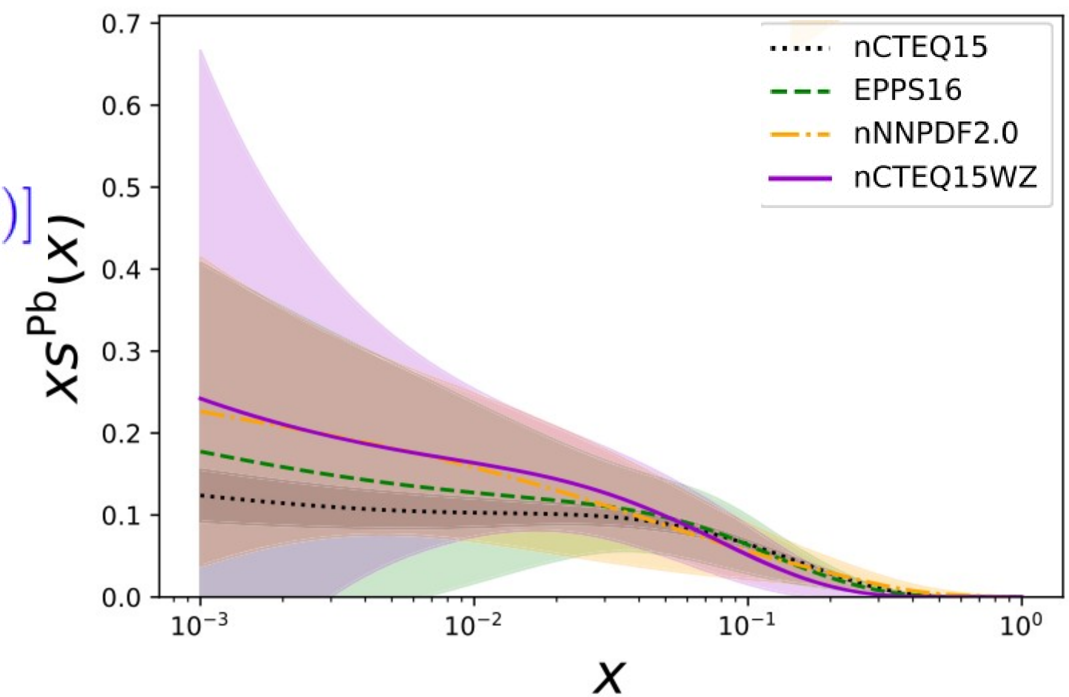
$$\Delta F_2 = \frac{5}{18} F_2^{CC} - F_2^{NC} \sim \frac{x}{6}[s(x) + \bar{s}(x)]$$

assumption :

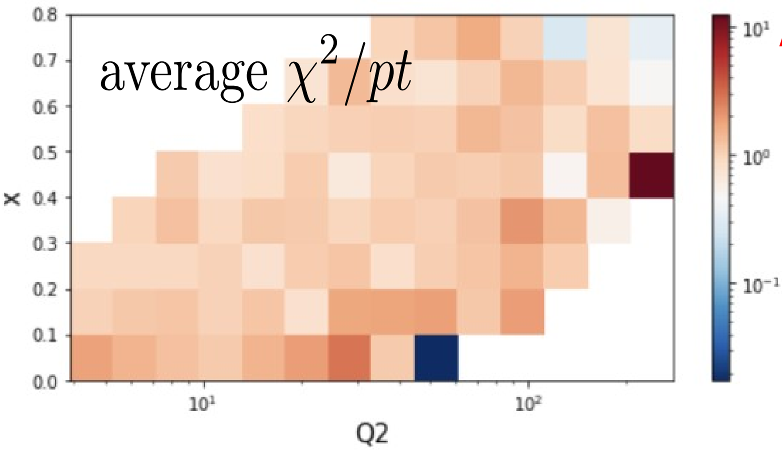
$$s(x) = \bar{s}(x) \sim \kappa \frac{\bar{u}(x) + \bar{d}(x)}{2}$$

→ **Underestimation of uncertainty!**





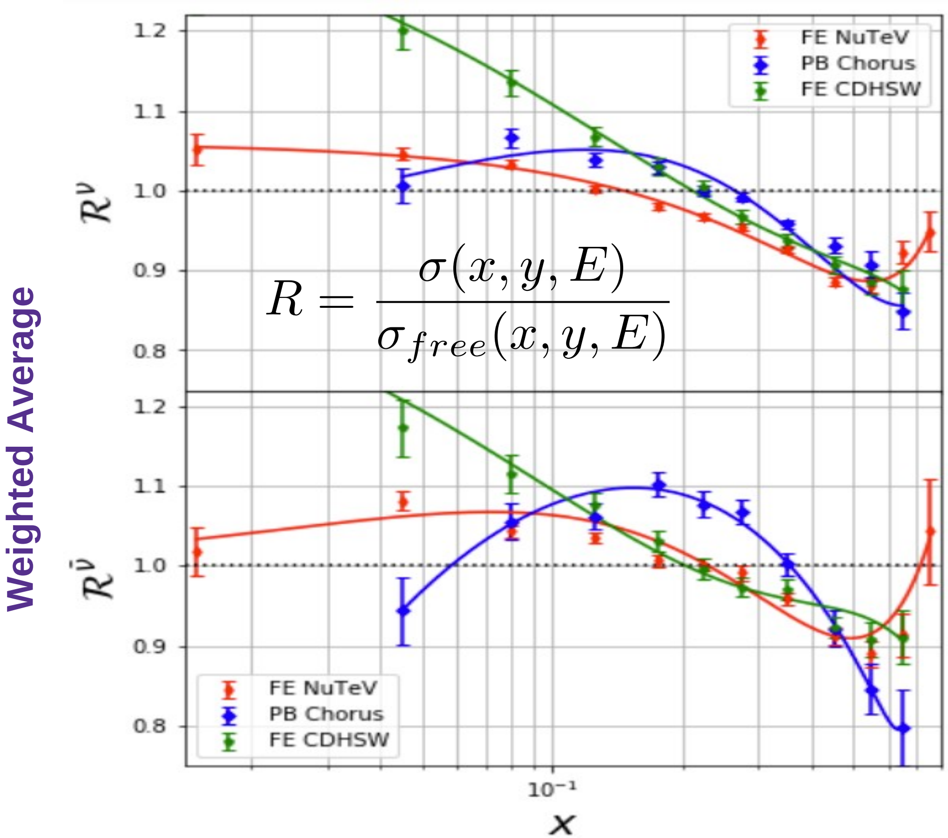
DimuNeu Fit



Higher x
better χ^2/pt

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

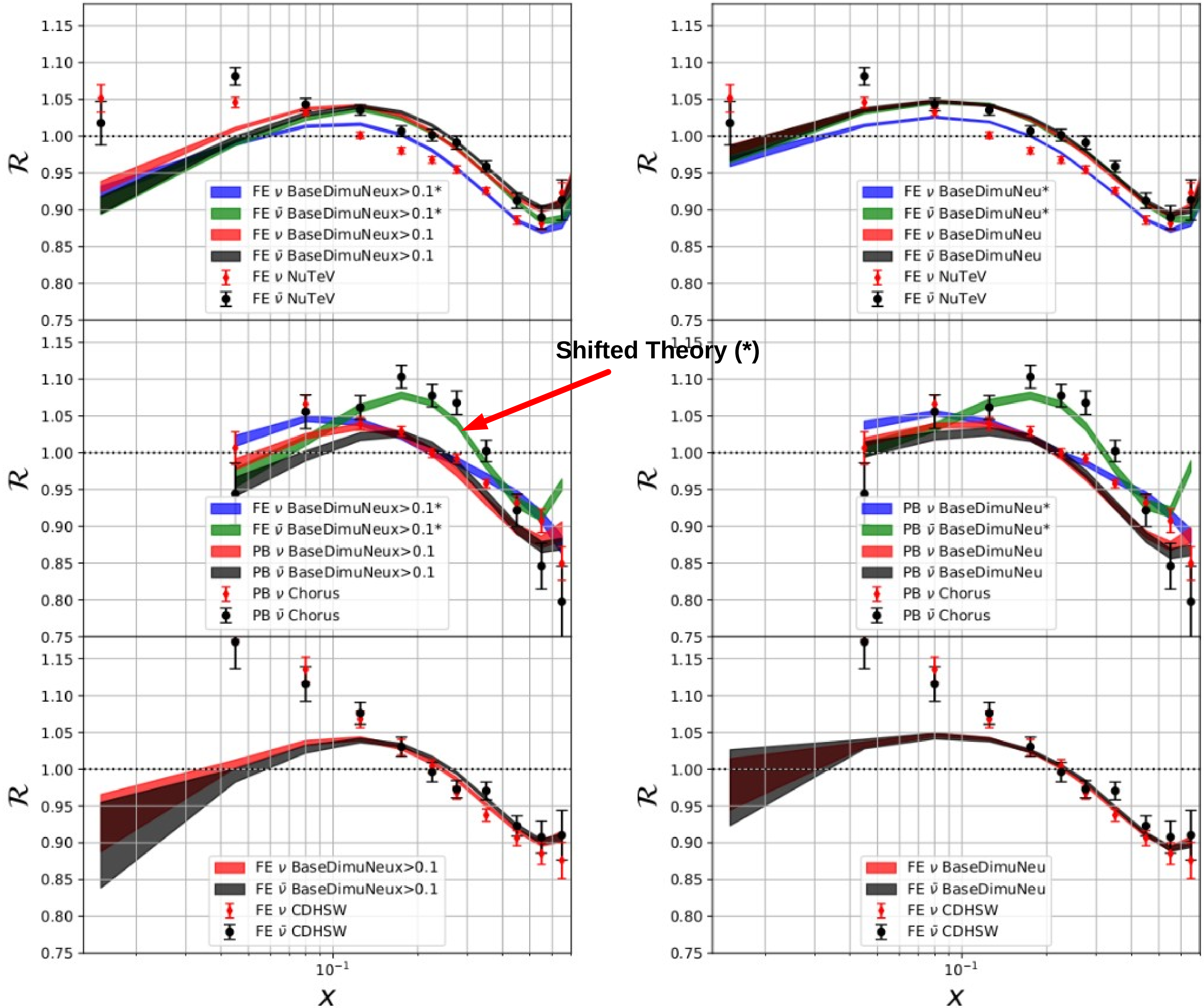
- χ^2/pt :
  Dimuon : 1.27
  NuTeV : [1.50 , 1.23]
  Chorus : [1.27 , 1.09]
  CDHSW : [0.60 , 0.72]
  ALL : 1.17
- **Higher x --> better agreement.**
- **TENSION between neutrino data sets at low x!**



Data – Theory Comparison

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

Weighted average over *E* and *y*



Milder shadowng if low *x* neutrino data is included.