

Update on nCTEQ PDFs

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WWU
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nCTEQ
nuclear parton distribution functions

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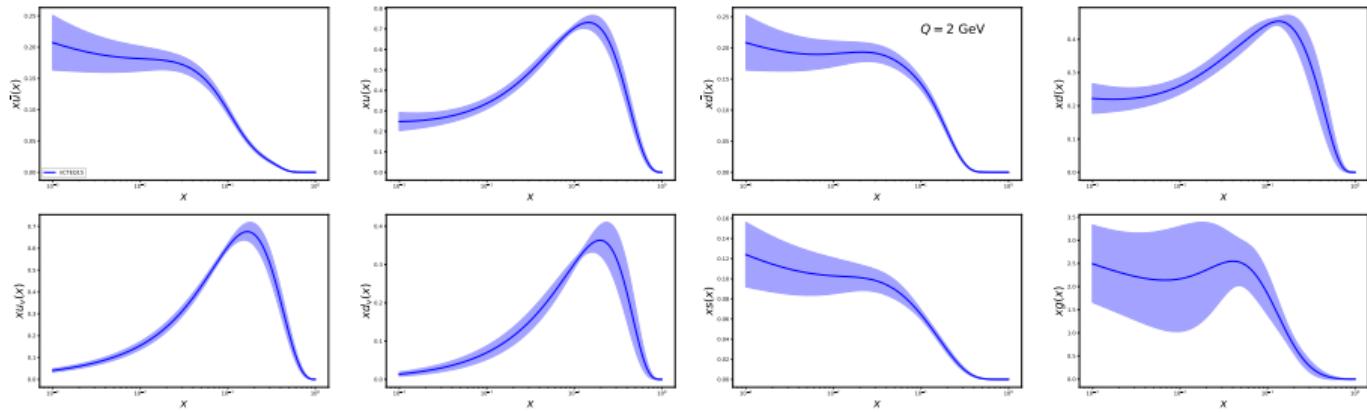
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Introduction

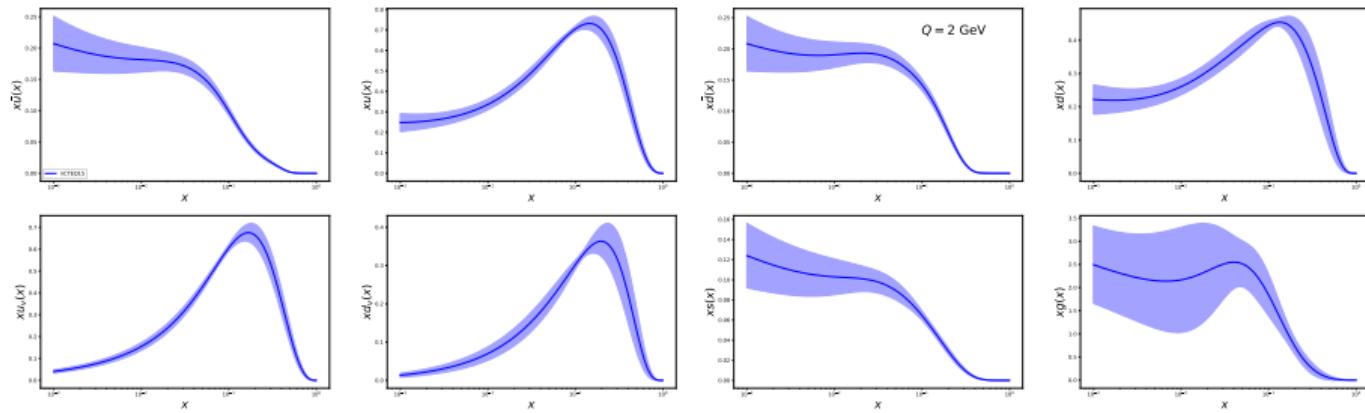
Introduction - Current status

Current main release: nCTEQ15



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Two long standing problems:

- ▶ Gluon
- ▶ Strange quark

PDF Fits - Parameterization

- The full nPDFs are parametrized in terms of the bound nucleon PDFs :

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

- Bound proton PDF parametrizations at $Q_0 = 1.3$ GeV :

$$x f_i^{p/A}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4 x})^{c_5}, \quad i = u_v, d_v, g, \bar{u} + \bar{d}, s + \bar{s}$$
$$\frac{\bar{d}}{\bar{u}} = c_0 x^{c_1} (1-x)^{c_2} + (1 + c_3 x) (1-x)^{c_4}$$

- The dependence of nPDFs on A, Z is parametrized as

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

- Open parameters:

$$\{a_1^{u_v}, a_2^{u_v}, a_4^{u_v}, a_5^{u_v}, a_1^{d_v}, a_2^{d_v}, a_5^{d_v}, a_1^{\bar{u}+\bar{d}}, a_5^{\bar{u}+\bar{d}}, a_1^g, a_4^g, a_5^g, b_0^g, b_1^g, b_4^g, b_5^g, a_0^{s+\bar{s}}, a_1^{s+\bar{s}}, a_2^{s+\bar{s}}\}$$

Recent updates to nCTEQ15

nCTEQ15: 740 data points

- ▶ Mainly DIS and DY data

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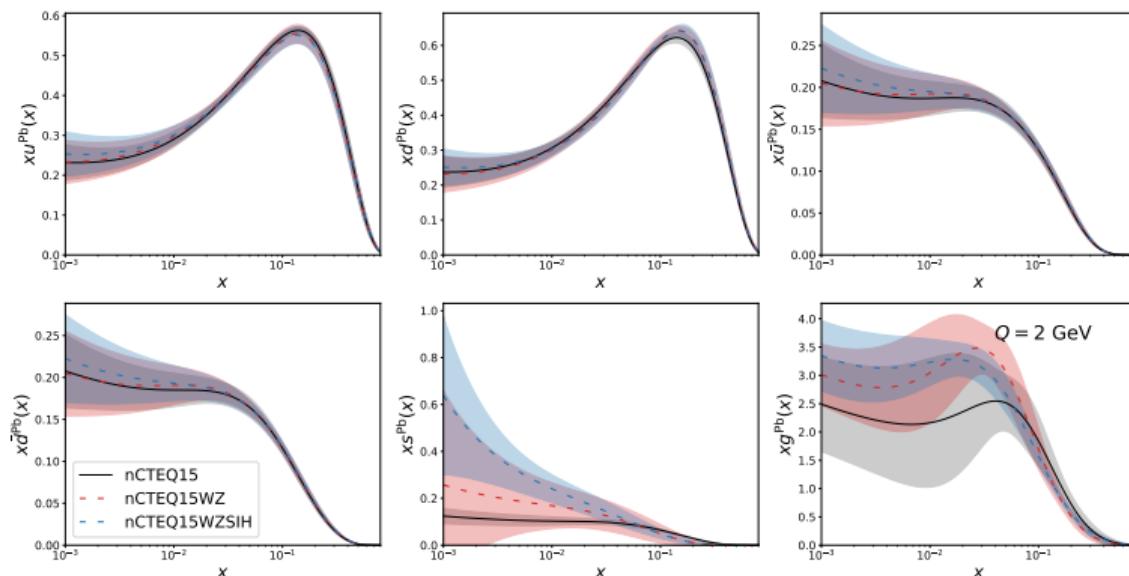
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PART I : Global Analysis with HQ and Quarkonium Data

Impact of heavy quark and quarkonium data on nuclear gluon PDFs

P. Duwentäster ,^{1,*} T. Ježo ,^{1,†} M. Klasen ,¹ K. Kovařík ,¹ A. Kusina ,²
K. F. Muzakka ,¹ F. I. Olness ,³ R. Ruiz ,² I. Schienbein ,⁴ and J. Y. Yu ,⁴

Duwentäster *et al.*, arXiv:2204.09982

Heavy Quarks - Motivation

Why are we interested in quarkonium (and open heavy-flavor meson) production data?

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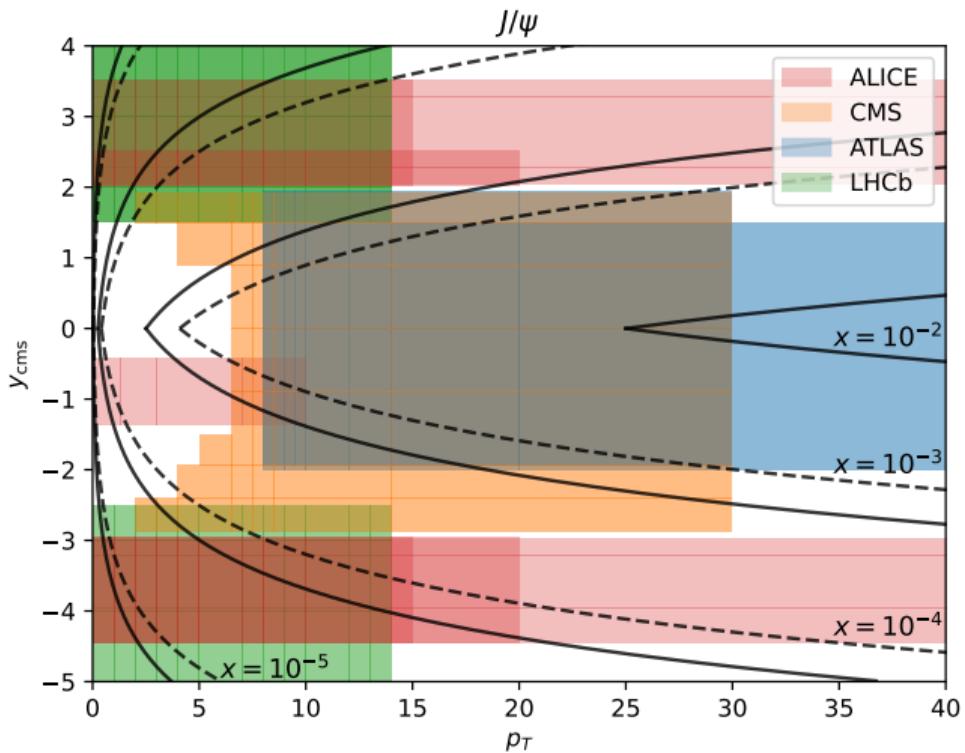
- ▶ Large available data sets from multiple LHC experiments
- ▶ Sensitivity to gluon PDFs down to very low x values ($x \lesssim 10^{-5}$)
- ▶ Interesting data-driven approach [A. Kusina et al., PRL 121 (2018) 052004; PRD 104 (2021) 014010]

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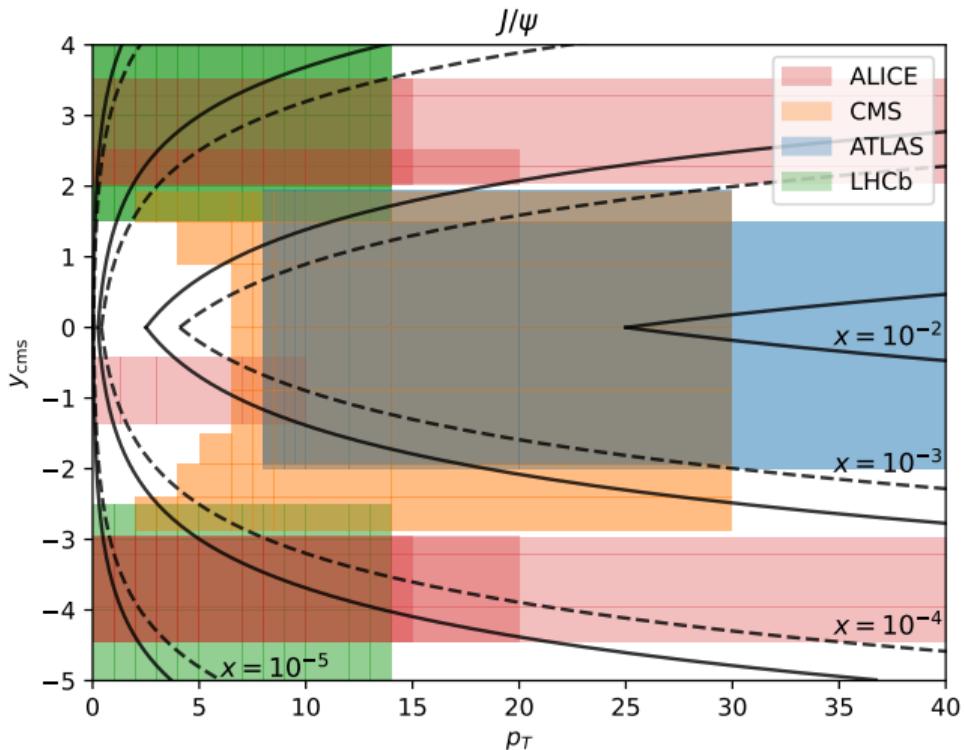
Why are we interested in quarkonium (and open heavy-flavor meson) production data?

- ▶ Large available data sets from multiple LHC experiments
- ▶ Sensitivity to gluon PDFs down to very low x values ($x \lesssim 10^{-5}$)
- ▶ Interesting data-driven approach [A. Kusina et al., PRL 121 (2018) 052004; PRD 104 (2021) 014010]
 - ▶ Understanding of quarkonium production in pQCD is limited
 - ▶ Fast calculation
 - ▶ Can quantify theory uncertainties
 - ▶ Potentially applicable for many single-inclusive particle production processes

Heavy Quarks - Data



Heavy Quarks - Data



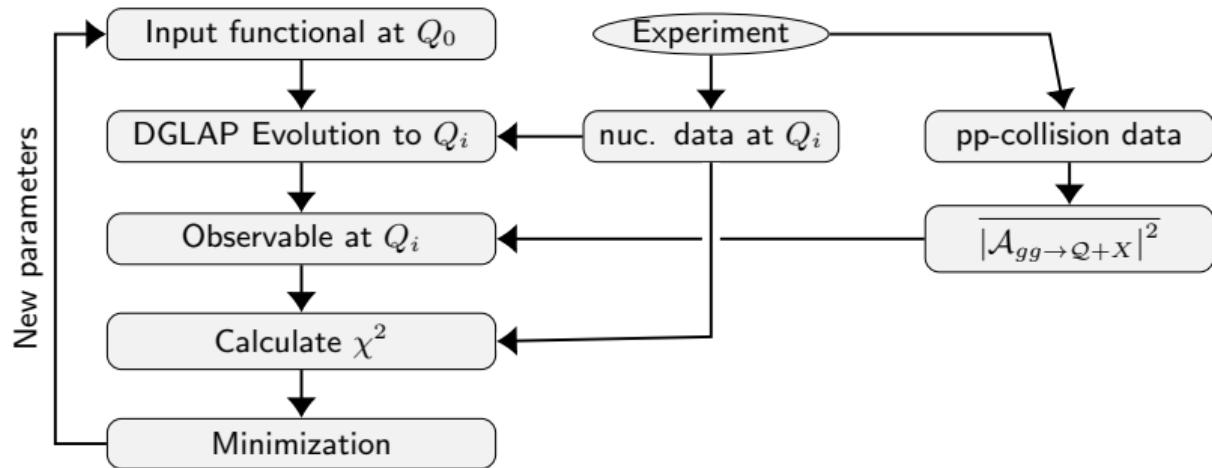
- ▶ Analysis also includes $\Upsilon(1S)$, $\psi(2S)$ and D^0 meson production

Data-driven Approach

$$\sigma(AB \rightarrow Q + X) = \int dx_1 \, dx_2 f_{1,g}(x_1) f_{2,g}(x_2) \frac{1}{2\hat{s}} |\overline{\mathcal{A}_{gg \rightarrow Q+X}}|^2 dPS$$

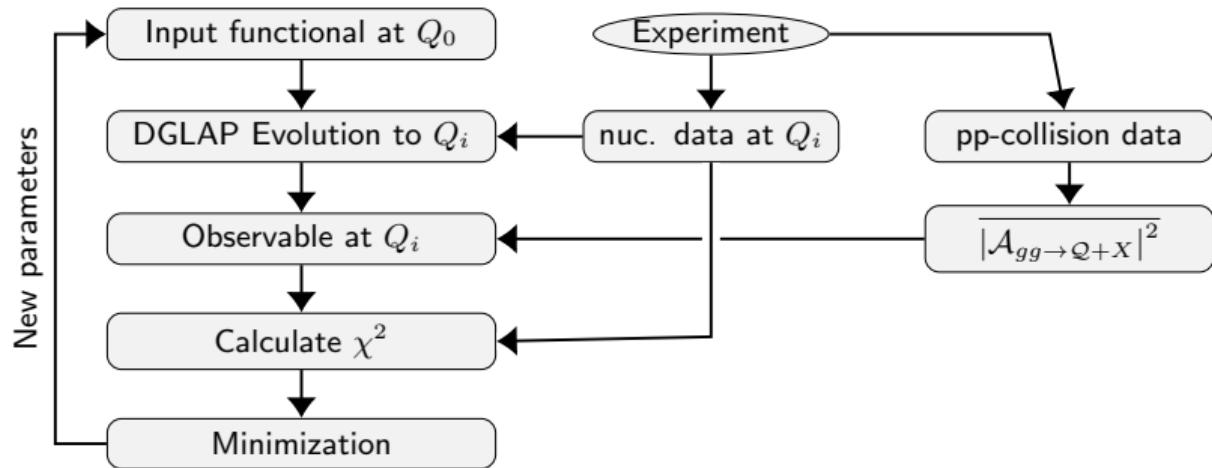
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Data-driven Approach

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$$\frac{|\bar{\mathcal{A}}_{gg \rightarrow Q+X}|^2}{M_Q^2} = \begin{cases} \frac{\lambda^2 \kappa \hat{s}}{M_Q^2} \exp\left(-\kappa \frac{p_T^2}{M_Q^2} + a|y|\right) & \text{if } p_T \leq \langle p_T \rangle \\ \frac{\lambda^2 \kappa \hat{s}}{M_Q^2} \exp\left(-\kappa \frac{\langle p_T \rangle^2}{M_Q^2} + a|y|\right) \left(1 + \frac{\kappa}{n} \frac{p_T^2 - \langle p_T \rangle^2}{M_Q^2}\right)^{-n} & \text{if } p_T > \langle p_T \rangle \end{cases}$$

Proton-proton baseline

- ▶ Impose cuts to remove data with $p_T < 3 \text{ GeV}$ and outside of $-4 \leq y_{\text{c.m.s.}} \leq 4$

Proton-proton baseline

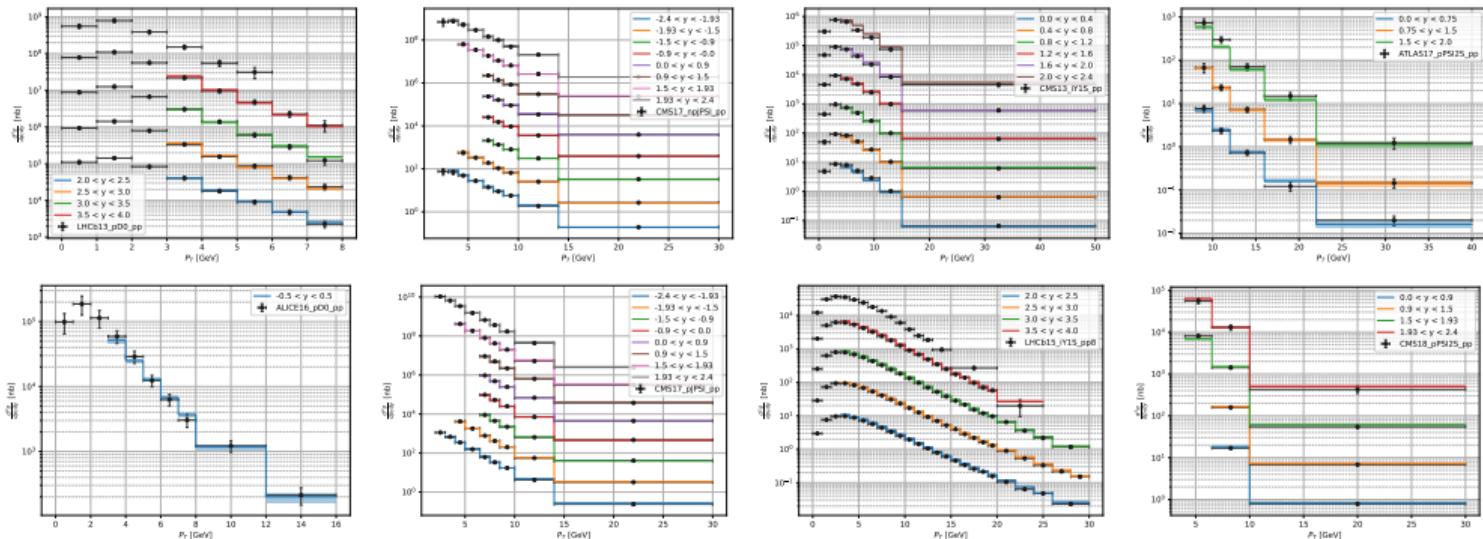
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	D^0	J/ψ	$B \rightarrow J/\psi$	$\Upsilon(1S)$	$\psi(2S)$	$B \rightarrow \psi(2S)$
N_{points}	34		501	375		55
χ^2/N_{dof}	0.25		0.88	0.92		0.77

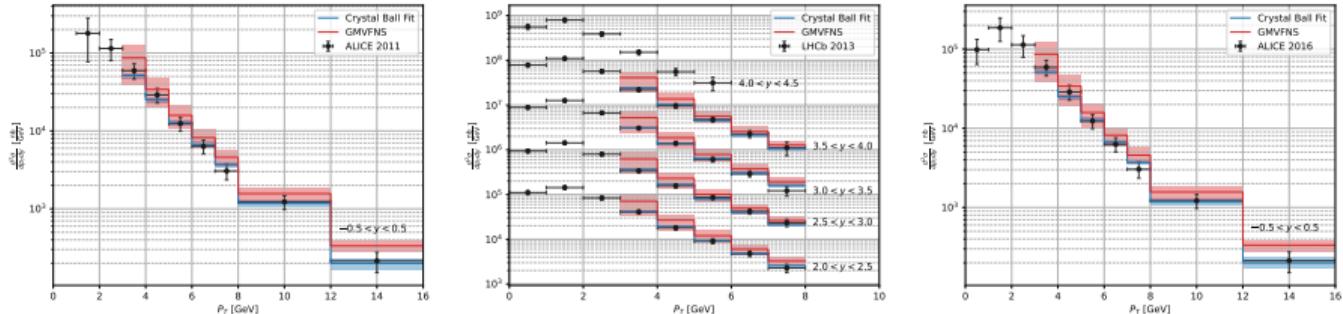
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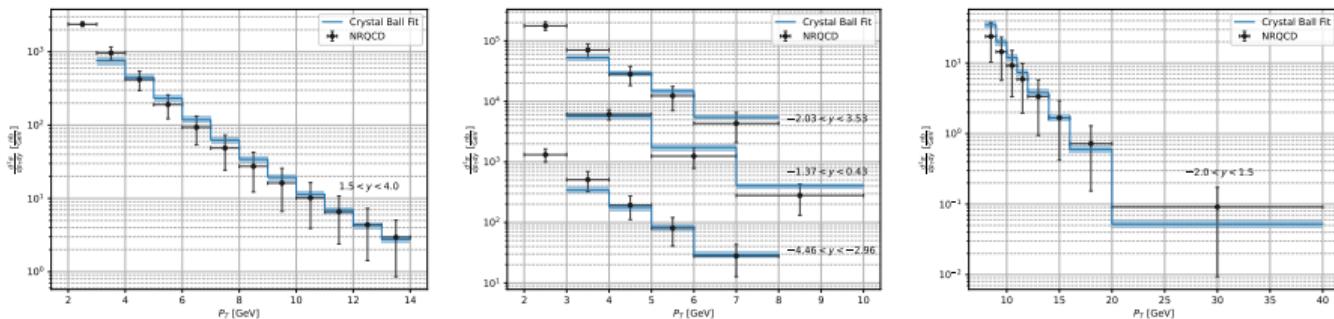
Baseline - comparison with GMVFNS



- ▶ KKKS08 fragmentation functions
- ▶ Base scale $\mu_r = \mu_i = \mu_f = \sqrt{p_T^2 + 4m_c^2}$
- ▶ Uncertainties due to individual scale variations by factor 2 or $\frac{1}{2}$

Baseline - comparison with NRQCD

Calculations by Mathias Butenschoen, Bernd Kniehl [M. Butenschoen et al., Nucl.Phys.B Proc.Suppl. 222-224 (2012) 151-161]



- ▶ Base scale $\mu_{r,0} = \mu_{f,0} = \sqrt{p_T^2 + 4m_c^2}$ and $m_{\text{NRQCD},0} = m_c$
- ▶ NRQCD Uncertainties due to scale variations:
 $1/2 < \mu_r / \mu_{r,0} = \mu_f / \mu_{f,0} = \mu_{\text{NRQCD}} / \mu_{\text{NRQCD},0} < 2$

PDF Fits - Data selection and settings

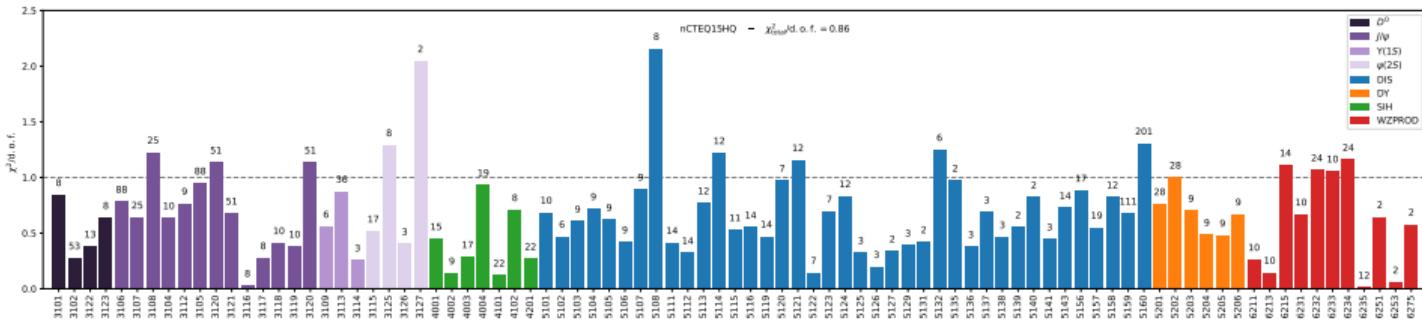
- ▶ Include all data from nCTEQ15WZ+SIH
- ▶ Use the same open parameters as nCTEQ15WZ+SIH

PDF Fits - Data selection and settings

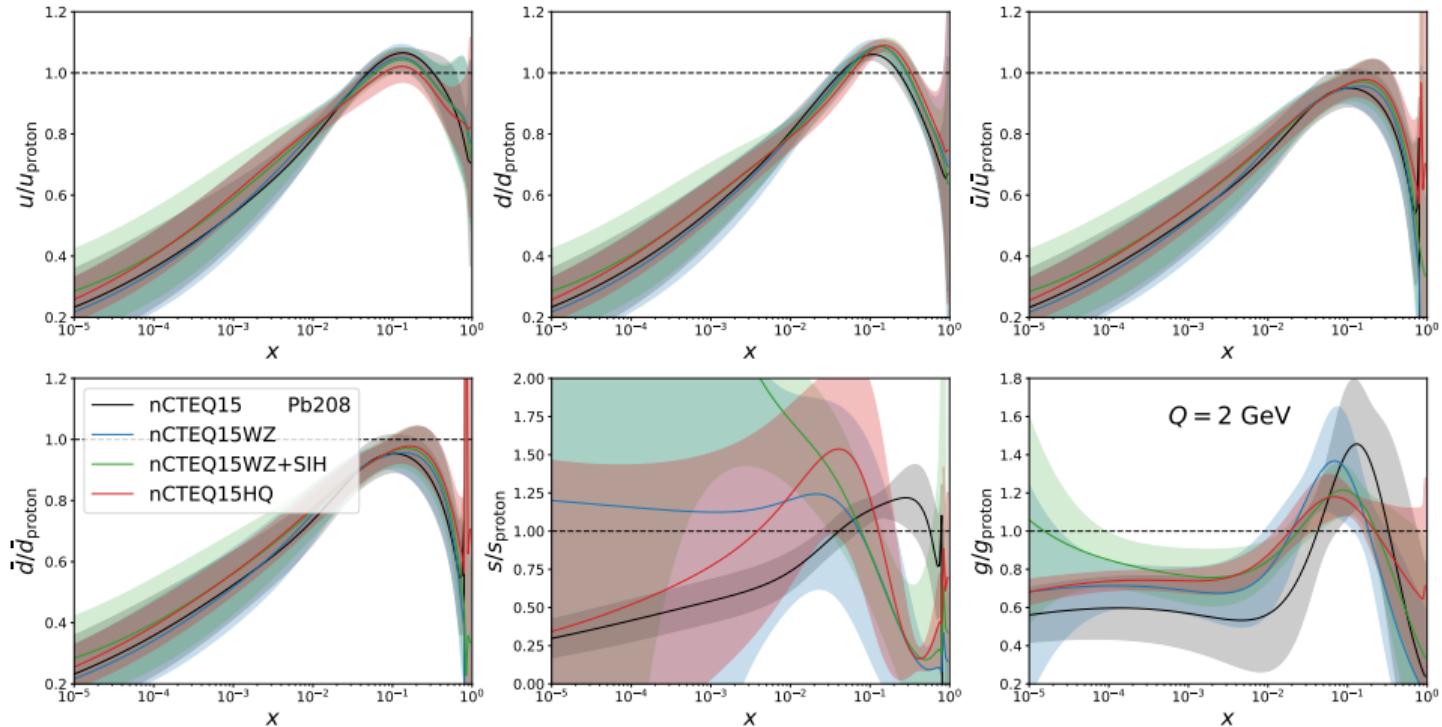
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- ▶ Cut HQ data below $p_T < 3.0 \text{ GeV}$ and outside $-4 \leq y_{\text{c.m.s.}} \leq 4$
 - ▶ Same as proton-proton baseline.
 - ▶ 548 new data points
 - ▶ Add Crystal Ball uncertainty to data systematics

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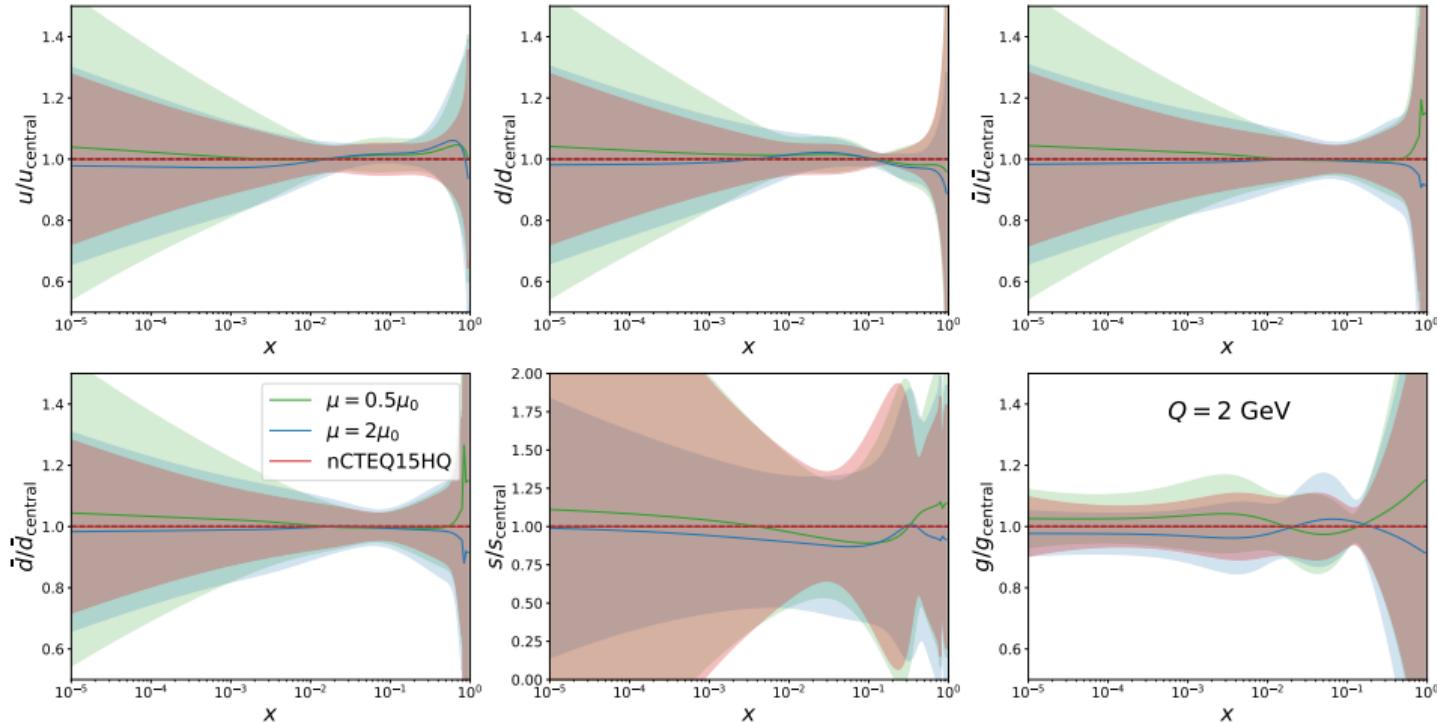
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nCTEQ15HQ PDFs



nCTEQ15HQ PDFs - scale variation



Summary Part I

- ▶ **New data driven approach**

- ▶ Good description of proton-proton data
- ▶ Compatible with predictions from NRQCD and GMVFNS
- ▶ Controlled uncertainties

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- ▶ **New global nPDF fit - nCTEQ15HQ**
 - ▶ Good description of new and old data
 - ▶ Strong new constraints on the gluon PDF, particularly at low x
 - ▶ No strong scale dependence

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- ▶ **New data driven approach**
 - ▶ Good description of proton-proton data
 - ▶ Compatible with predictions from NRQCD and GMVFNS
 - ▶ Controlled uncertainties
- ▶ **New global nPDF fit - nCTEQ15HQ**
 - ▶ Good description of new and old data
 - ▶ Strong new constraints on the gluon PDF, particularly at low x
 - ▶ No strong scale dependence
- ▶ **Strange quark uncertainty is still very large**
 - ▶ Neutrino data is required

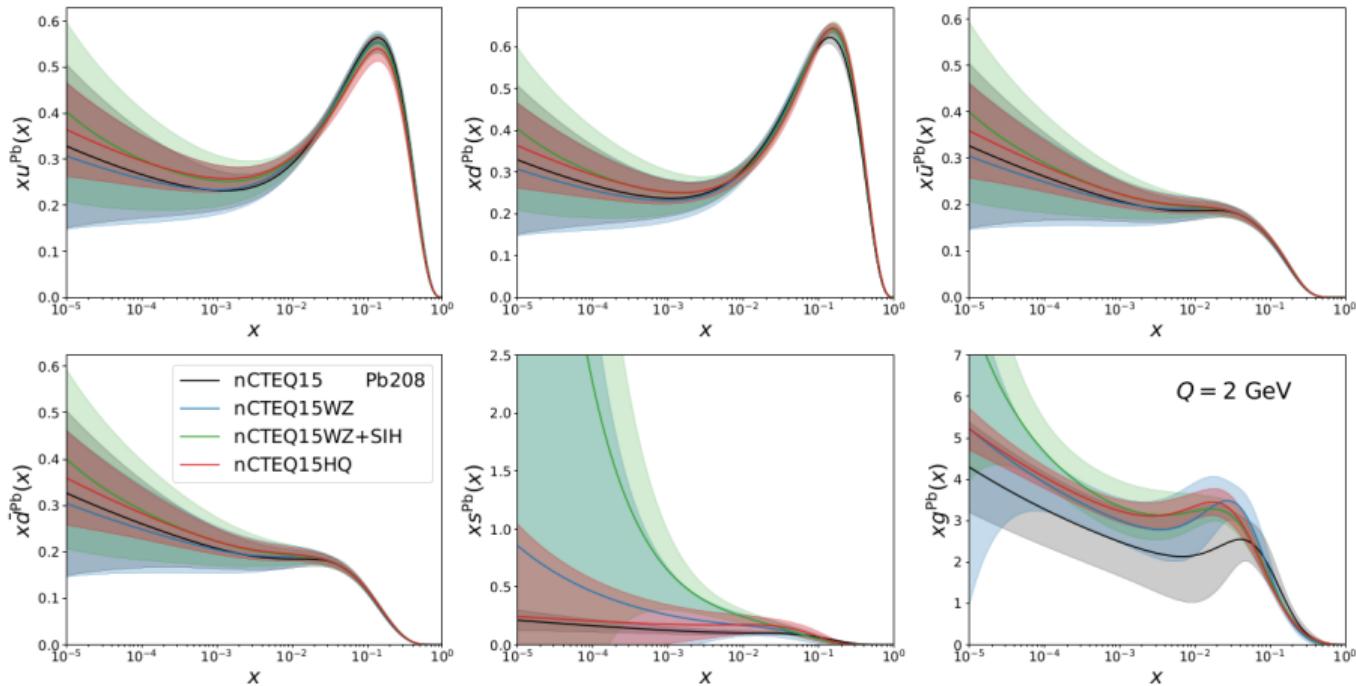
PART II : Global Analysis with Neutrino DIS data

Compatibility of neutrino DIS data and its impact on nuclear parton distribution functions

K.F. Muzakka ,^{1,*} P. Duwentäster ,¹ T.J. Hobbs,^{2,3} T. Ježo ,¹ M. Klasen ,¹ K. Kovařík ,^{1,†}
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Muzakka *et al*, arXiv:2204.13157

Large Uncertainty of the Strange Quark PDF

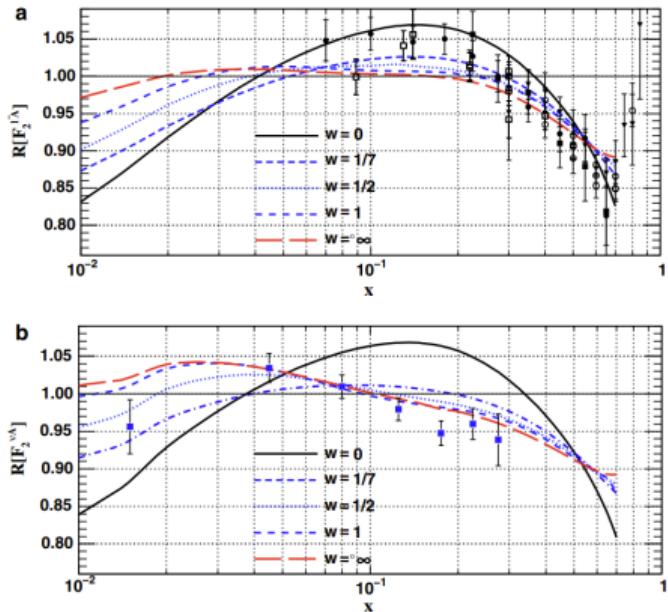


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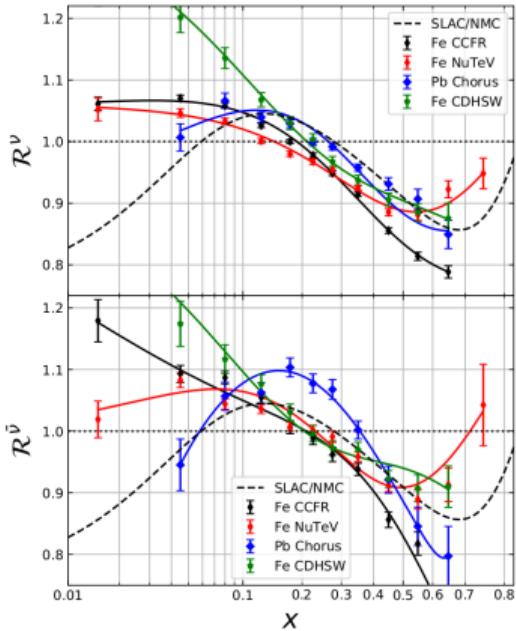
→ need to include neutrino data.

Challenge : Tension Between l^\pm DIS and ν DIS

nCTEQ-study [Phys.Rev.Lett.106(2011)122301]:



Weighted average :



$$R[F] = \frac{F[f^A]}{F[f_{free}^A]}, \quad f^{A,\text{free}} = \frac{Z}{A} f^p + \frac{A-Z}{A} f^n.$$

$$\mathcal{R}(x) = \sum_i w_i R_i, \quad w_i = \left(\sum_j \frac{1}{(\Delta R_j)^2} \right)^{-1} \frac{1}{(\Delta R_i)^2}$$

Neutrino Analysis Revisited (2022)

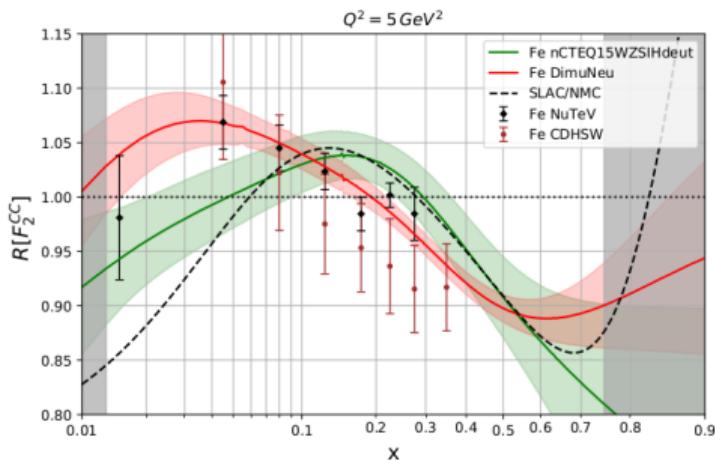
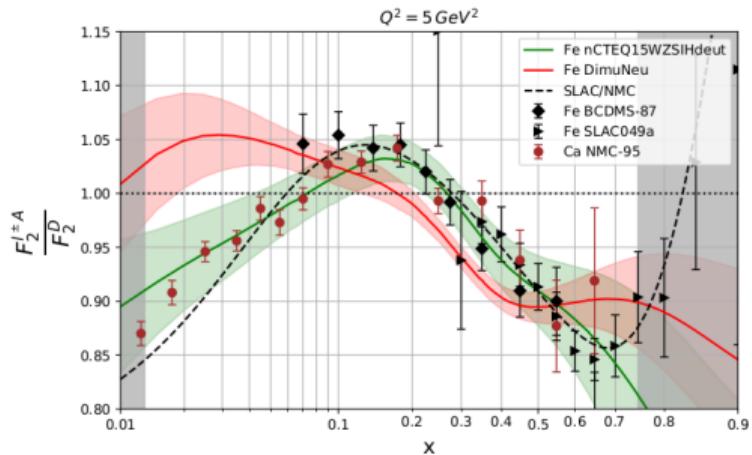
What's new?

- ▶ Full treatment of normalization uncertainties.
- ▶ Deuteron correction from CJ15 analysis.
- ▶ More PDF parameters to fit.
- ▶ SIH, W, and Z data from LHC are now included.
- ▶ CCFR and CDHSW differential cross section data are now included.

Neutrino Data used in this analysis:

Data set	Nucleus	#pts	Corr.sys.
CDHSW ν	Fe	465	No
CDHSW $\bar{\nu}$		464	
CCFR ν	Fe	1109	No
CCFR $\bar{\nu}$		1098	
NuTeV ν	Fe	1170	Yes
NuTeV $\bar{\nu}$		966	
Chorus ν	Pb	412	Yes
Chorus $\bar{\nu}$		412	
CCFR dimuon ν	Fe	40	No
CCFR dimuon $\bar{\nu}$		38	
NuTeV dimuon ν	Fe	38	No
NuTeV dimuon $\bar{\nu}$		34	

Base Fits



- ▶ **nCTEQ15WZSIHdeut** : l^\pm DIS+DY+SIH+WZ (940 pts, 27 parameters)
- ▶ **DimuNeu** : ν DIS+Dimuon (5689 pts, 20 parameters)

Compatibility Analysis S vs \bar{S}

Definition ($\Delta\chi_S^2$ -compatibility)

$$\chi_S^2(\text{after}) - \chi_S^2(\text{before}) \leq \Delta\chi_S^2$$

Definition (χ^2 -compatibility)

$$p_S \leq 0.9 \quad \text{and} \quad p_{\bar{S}} \leq 0.9$$

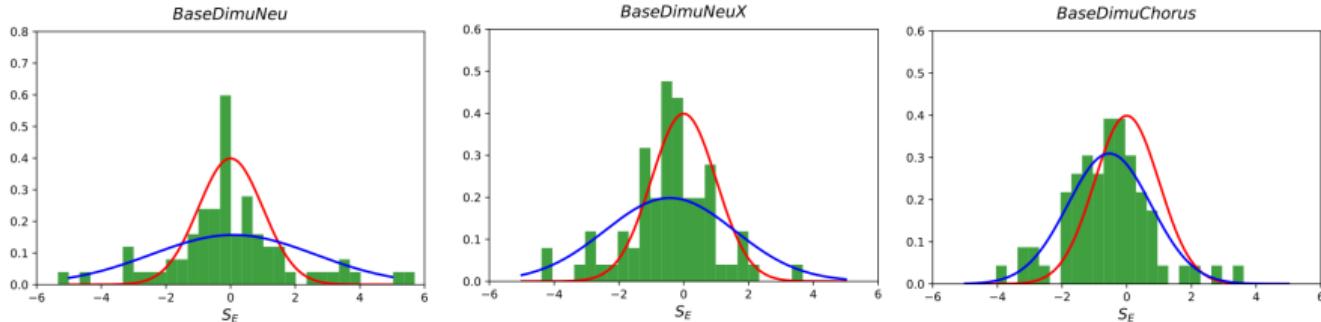
$$p_S = \int_0^{\chi_S^2} P(\chi^2, N_S) d\chi^2$$

Definition (S_E -compatibility)

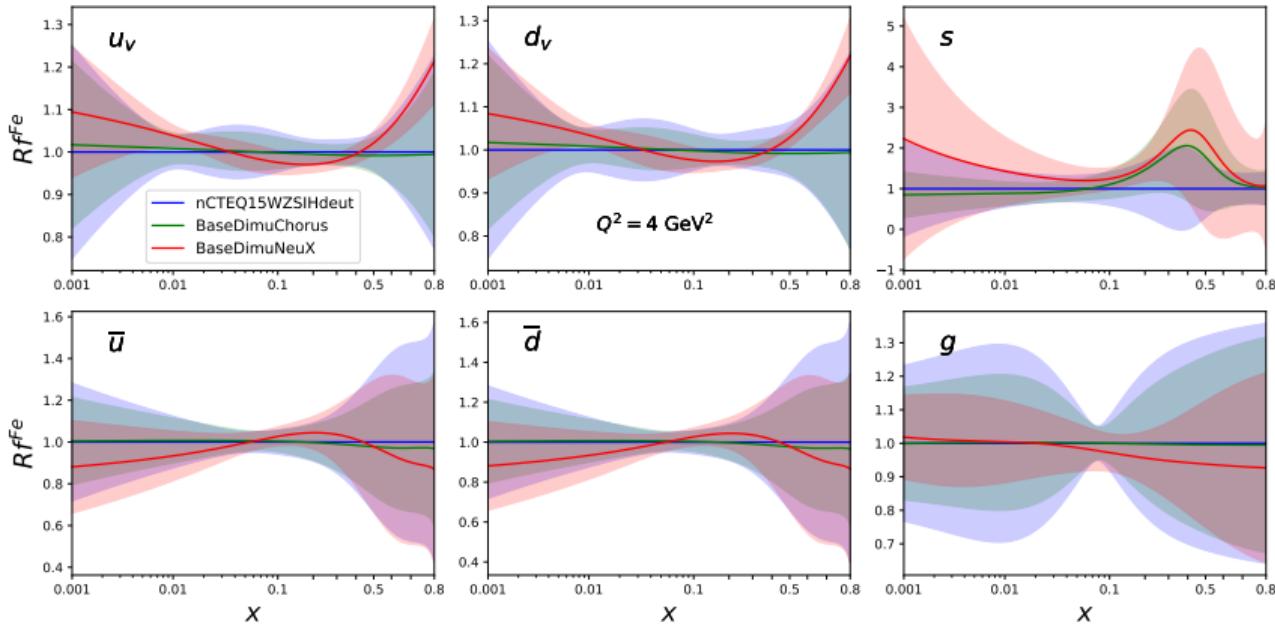
$$S_E = \sqrt{2\chi_E^2(N)} - \sqrt{2N-1} \sim \mathcal{N}(0, 1)$$

Compatibility Assessment (S =Base= nCTEQ15WZSIHdeut, \bar{S} = Neutrino data)

Analysis name	χ^2_S/pt	$\chi^2_{\bar{S}}/pt$	$\Delta\chi^2_S$	$\Delta\chi^2_{\bar{S}}$	$p_S/p_{\bar{S}}$
nCTEQ15WZSIHdeut	0.78	-	0	-	0.500 / -
DimuNeu	-	1.12	-	0	- / 0.500
DimuChorus	-	1.09	-	0	- / 0.500
BaseChorus	0.78	1.18	2	-	0.530 / -
BaseCDHSW	0.83	0.63	43	-	0.895 / -
BaseCCFR	0.87	0.96	80	-	0.989 / -
BaseNuTeV	0.86	1.43	72	-	0.981 / -
BaseNuTeVU	0.84	0.93	52	-	0.933 / -
BaseDimuNeu	0.92	1.17	131	283	0.99987 / 0.990
BaseDimuNeuU	0.92	0.98	126	-	0.99978 / -
BaseDimuNeuX	0.83	1.08	46	-	0.908 / -
BaseDimuChorus	0.79	1.15	5	58	0.559 / 0.885

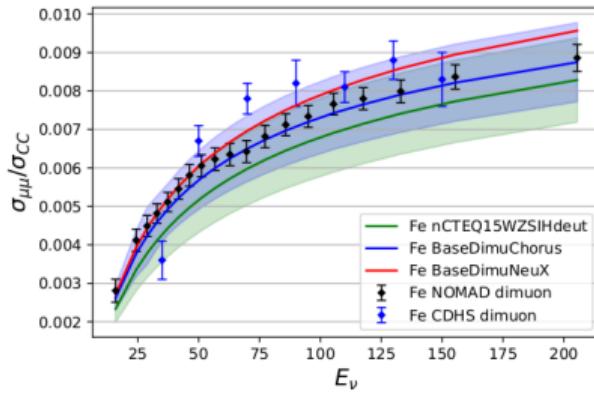
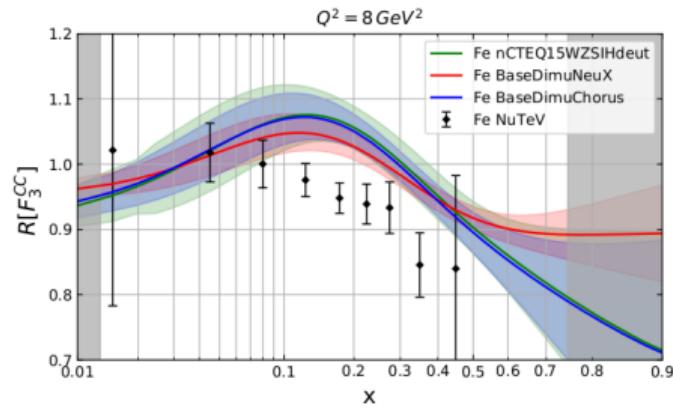
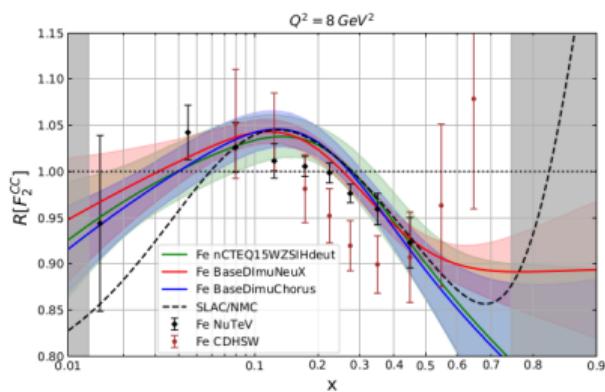
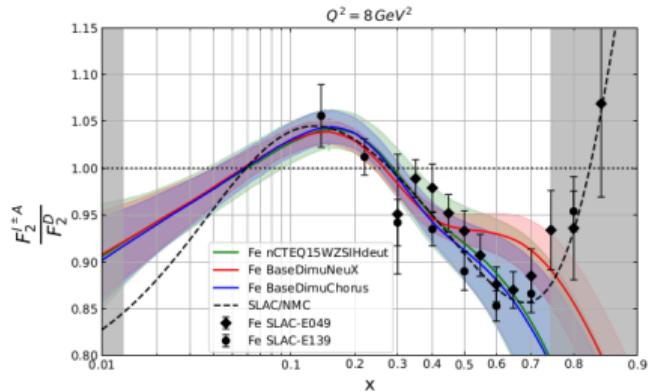


Combined fits



- ▶ nCTEQ15WZSIHdeut = Base : l^\pm DIS+DY+SIH+WZ (940 pts)
- ▶ BaseDimuNeuX : Base + Dimuon + Neutrino, with $x \leq 0.1$ data are removed from the dimuon and neutrino data (5584 pts)
- ▶ BaseDimuChorus : Base + Dimuon + Chorus (1914 pts)

Comparisons with l^\pm , ν DIS data and NOMAD Dimuon data



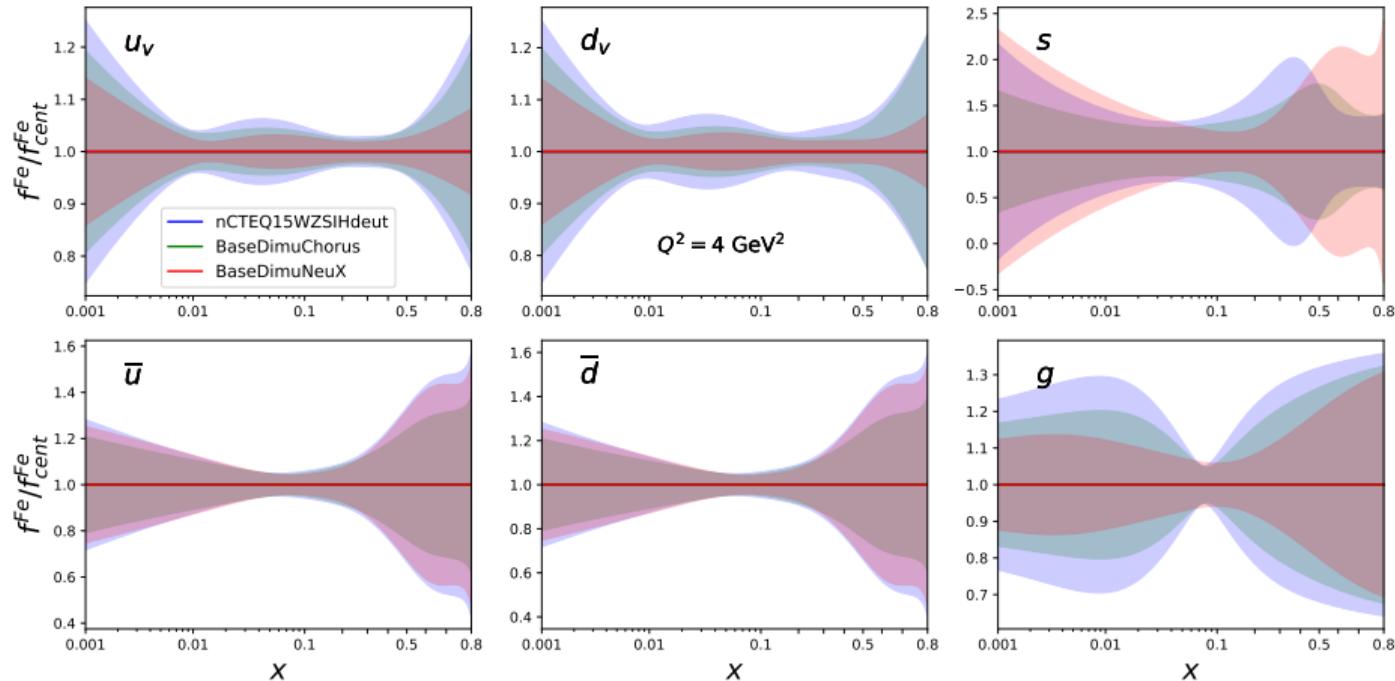
Summary Part II

- ▶ Neutrino DIS data is needed to further constrain the strange quark PDF.
- ▶ Tensions between the neutrino DIS and charged lepton DIS data are most severe in the shadowing region ($x \leq 0.1$).
- ▶ Two strategies : BaseDimuNeuX and BaseDimuChorus
- ▶ BaseDimuNeuX PDFs yield better description to the F_2 and F_3 data from NuTeV, while BaseDimuChorus predictions are in a good agreement with the dimuon data from NOMAD.
- ▶ New neutrino DIS data is most welcome to help solve the tension issue.

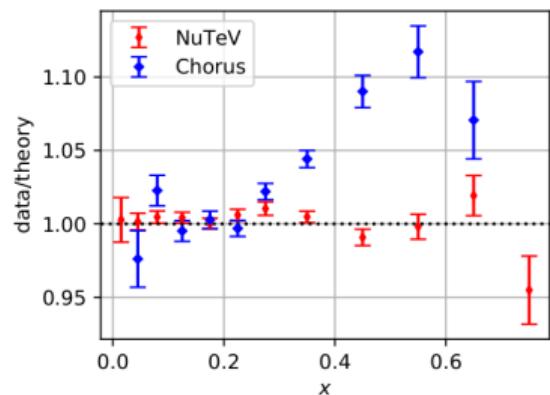
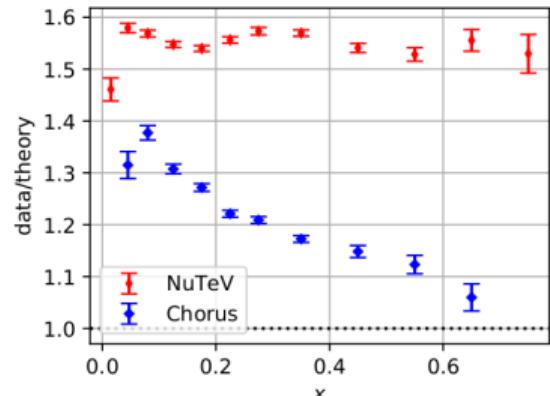
Thank You

Backup Slides

Combined fits : PDF uncertainties



Treatment of Normalization Parameters



- ▶ The old way to include normalization uncertainties :
 $\chi^2 = (D - T)^T C_D^{-1} (D - T)$,
 $C_{D,ij} = C_{ij} + \sigma_{norm}^2 D_i D_j$ lead to d' Agostini bias.
- ▶ Standard solution :

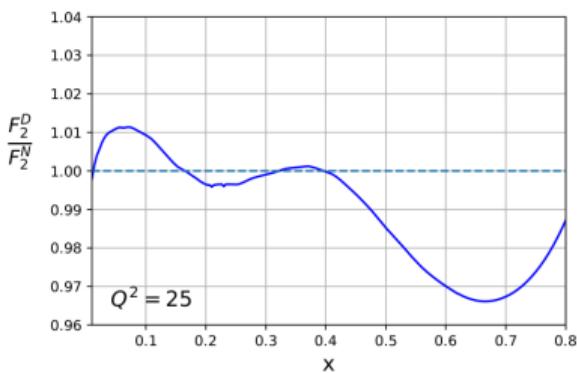
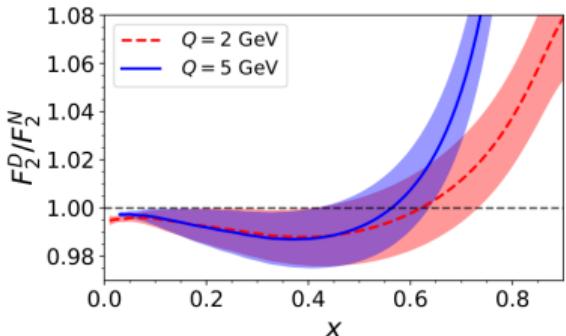
$$\chi^2 = (D - T/r)^T C^{-1} (D - T/r) + \frac{(1 - r)^2}{\sigma_{norm}^2}$$

- ▶ Drawbacks : (1) Additional fitting parameters. (2) Must be taken into account in the Hessian error analysis.
- ▶ Another solution :

$$\chi^2 = (D - rT)^T C_{-1} (D - rT) + \frac{(1 - r)^2}{\sigma_{norm}^2}$$

Advantages : (1) No additional open parameters as the optimal r can be calculated analytically. (2) The Hessian method automatically includes the contribution from r .

Treatment of Deuteron Correction



- ▶ Without deuteron correction, F_2^D is computed as : $F_2^D = F_2^p + F_2^n \equiv F_2^N$.
- ▶ However, $F_2^D \neq F_2^N$.
- ▶ How we compute F_2^D :

$$F_2^D = F_2^{p,CTEQ} \times \frac{F_2^{D,CJ}}{F_2^{p,CJ}}$$

where $F_2^{D,CJ}$, $F_2^{p,CJ}$ comes from CJ15 analysis [Accardi et al, Phys.Rev.D93 11,(2016) 114017].

Open Parameters in Neutrino Fits

$$\begin{aligned} & a_1^{u_v}, \ a_2^{u_v}, \ a_4^{u_v}, \ a_5^{u_v}, \ b_1^{u_v}, \ b_2^{u_v}, \\ & a_1^{d_v}, \ a_2^{d_v}, \ a_4^{d_v}, \ a_5^{d_v}, \ b_1^{d_v}, \ b_2^{d_v}, \\ & a_1^{\bar{u}+\bar{d}}, \ a_2^{\bar{u}+\bar{d}}, \ a_5^{\bar{u}+\bar{d}}, \\ & a_1^g, \ a_4^g, \ a_5^g, \ b_0^g, \ b_1^g, b_4^g, b_5^g, \\ & a_0^{s+\bar{s}}, \ a_1^{s+\bar{s}}, \ a_2^{s+\bar{s}}, \ b_0^{s+\bar{s}}, \ b_2^{s+\bar{s}} \end{aligned}$$

Combined Fit?

- ▶ **Important question** : issue with the data or incomplete understanding of neutrino interactions in nuclear environment?
- ▶ Need new neutrino DIS data.
- ▶ In the mean time, three strategies :
 - ▶ Issue with experimental uncertainties → Ignore correlations, Weight variation, etc.
 - ▶ Issue with possibly different shadowing mechanism → Restricting Kinematic region → BaseDimuNeuX.
 - ▶ Select data sets that pass the compatibility criteria → BaseDimuChorus.