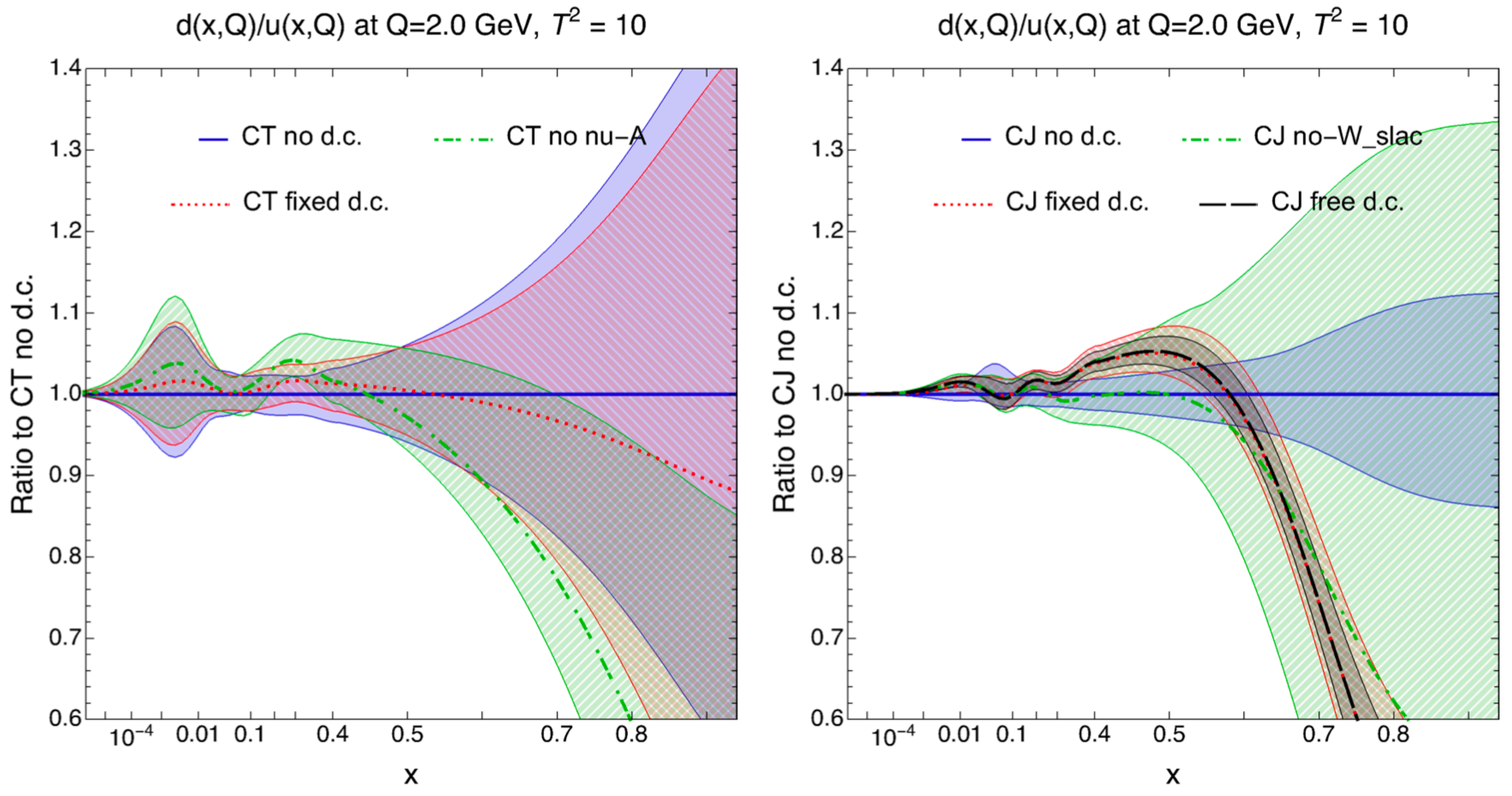
Deuteron Scattering Experiments in CTEQ-JLab and CTEQ-TEA Global QCD Analyses

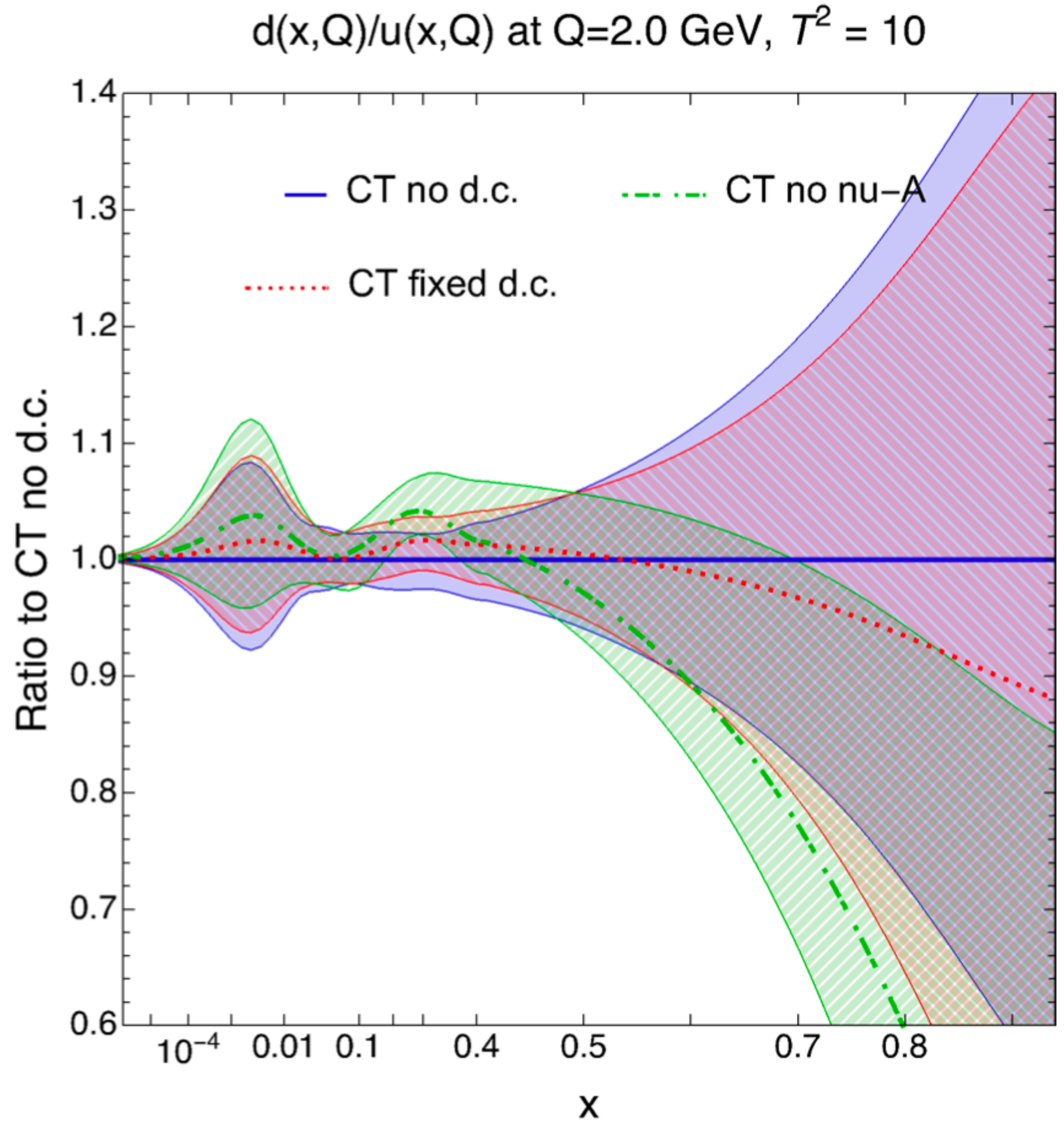


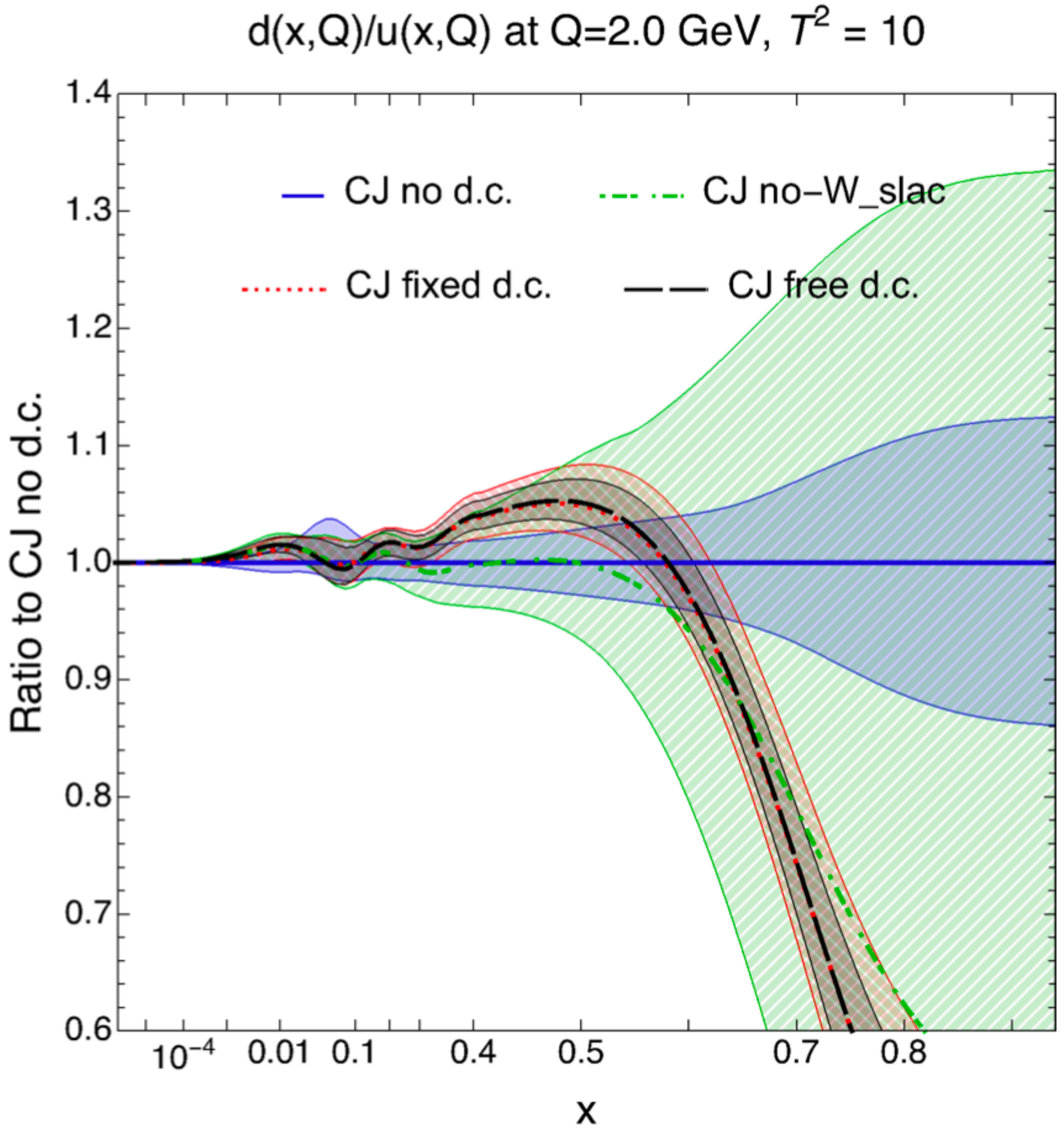
arXiv: 2102.01107 [hep-ph]

Work with: A.Accardi
Tim Hobbs
Pavel Nadolsky

CTEQ

Xiaoxian Jing, Southern Methodist University, DIS-2021, 2021-04-13

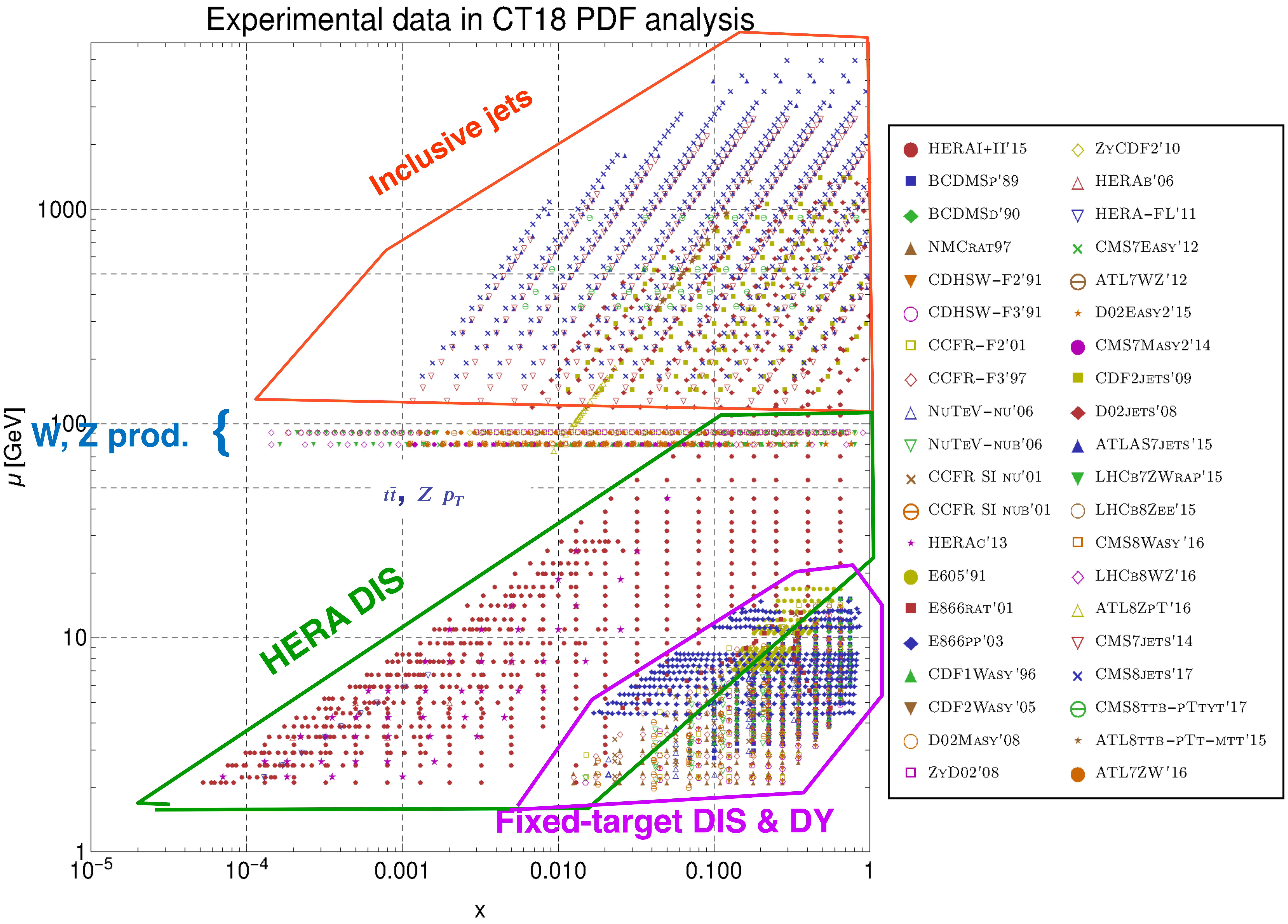




I studied the impact of deuteron DIS data on CJ and CT NLO fits

1. With no deuteron correction (**no d.c.)**
2. With fixed deuteron correction **(fixed d.c.)**
3. With free deuteron correction **(free d.c.)**
4. Without certain experiments **(no νA DIS, SLAC DIS, W rapidity asymmetry)**

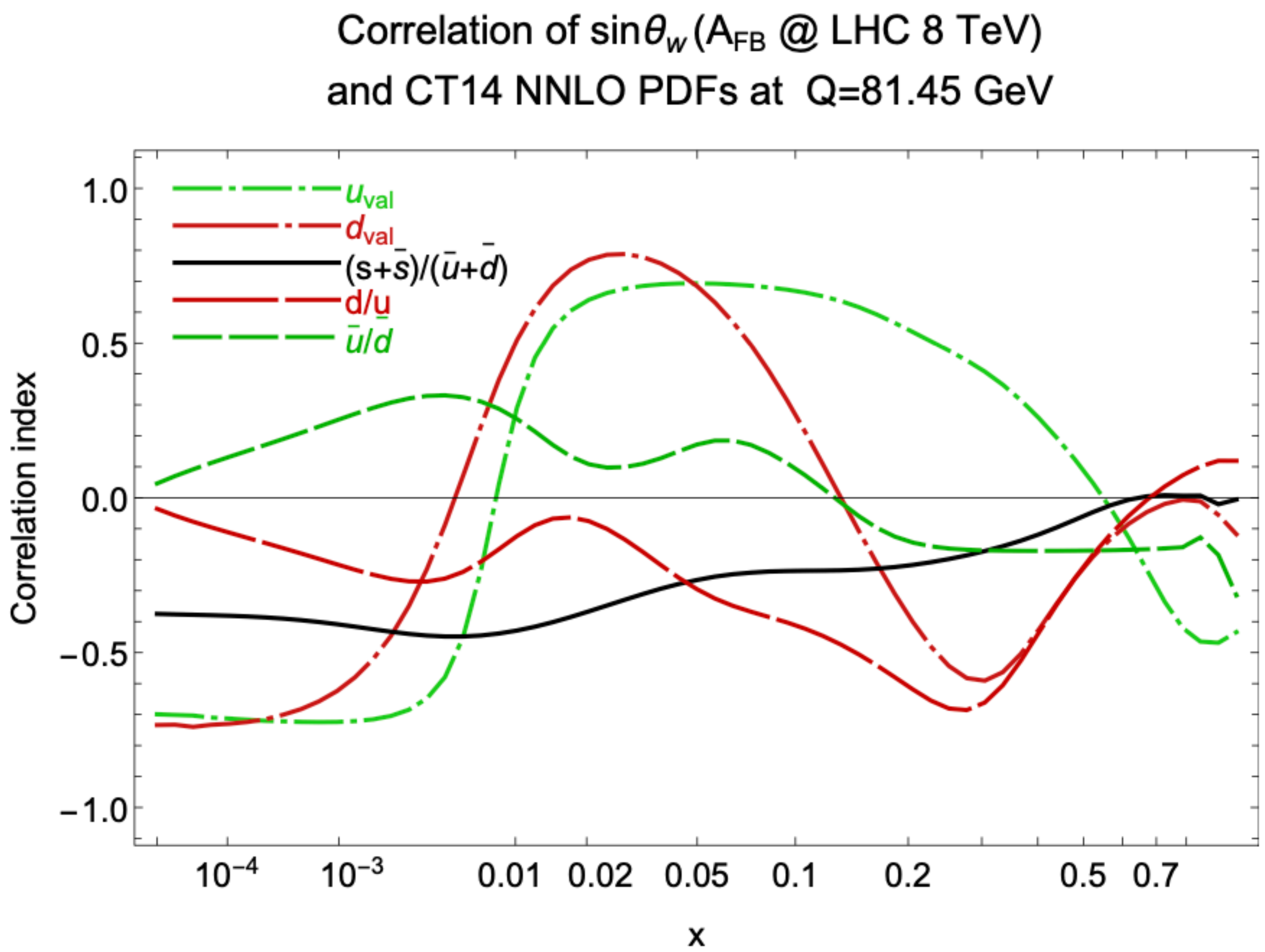
I compared CJ and CT PDF fits on the same footing using the L_2 sensitivity method (arXiv: 2102.01107 [hep-ph]).

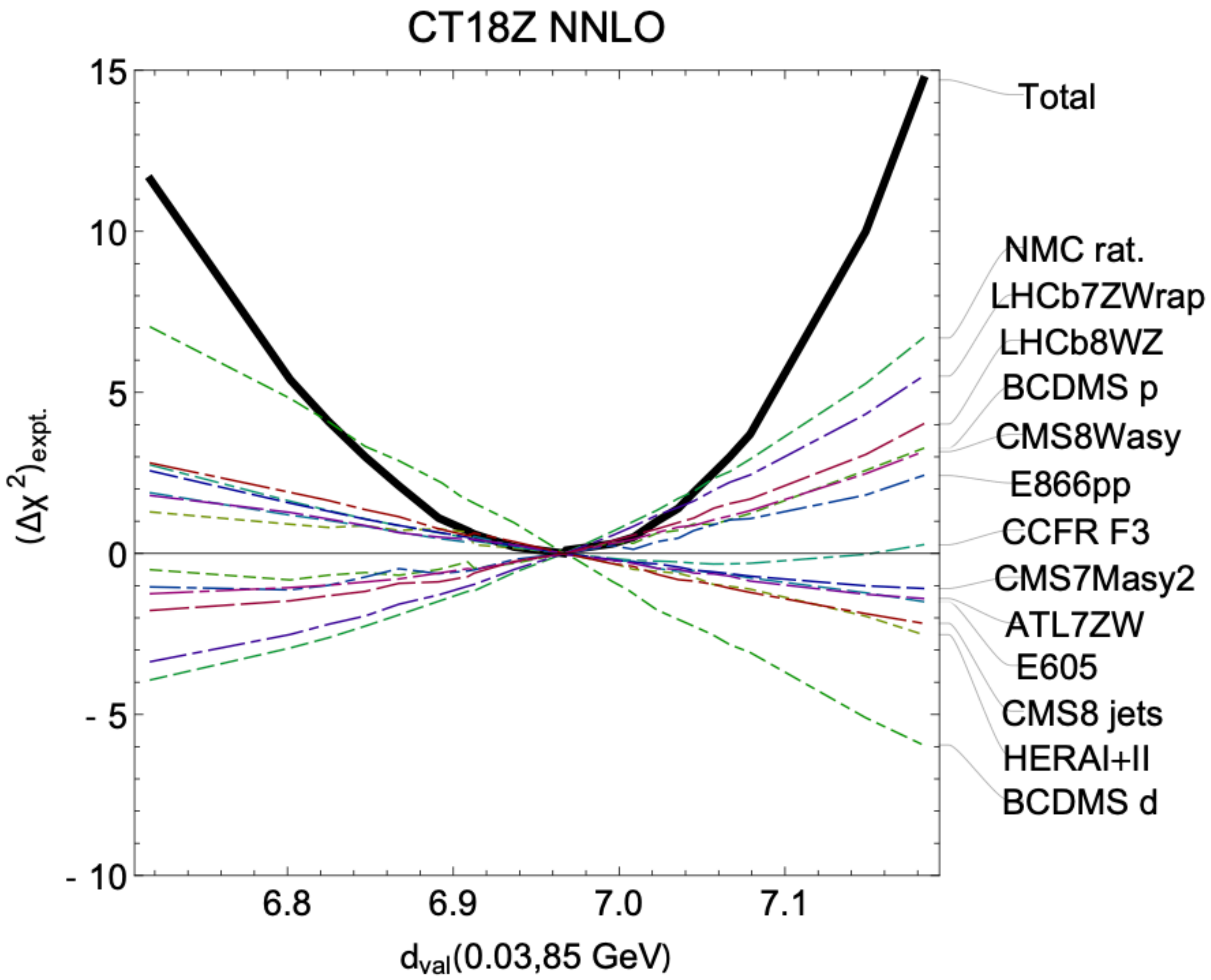


The CT18NNLO analysis (arXiv: 1912.10053), indicates that d, u, g and other flavors at $x > 0.3$, receive strong constraints from fixed target deuteron DIS data.

These constraints affect PDFs at $x \approx 0.01 - 0.05$ via the sum rules.

Correlations of the weak mixing angle at the LHC with the CT PDFs

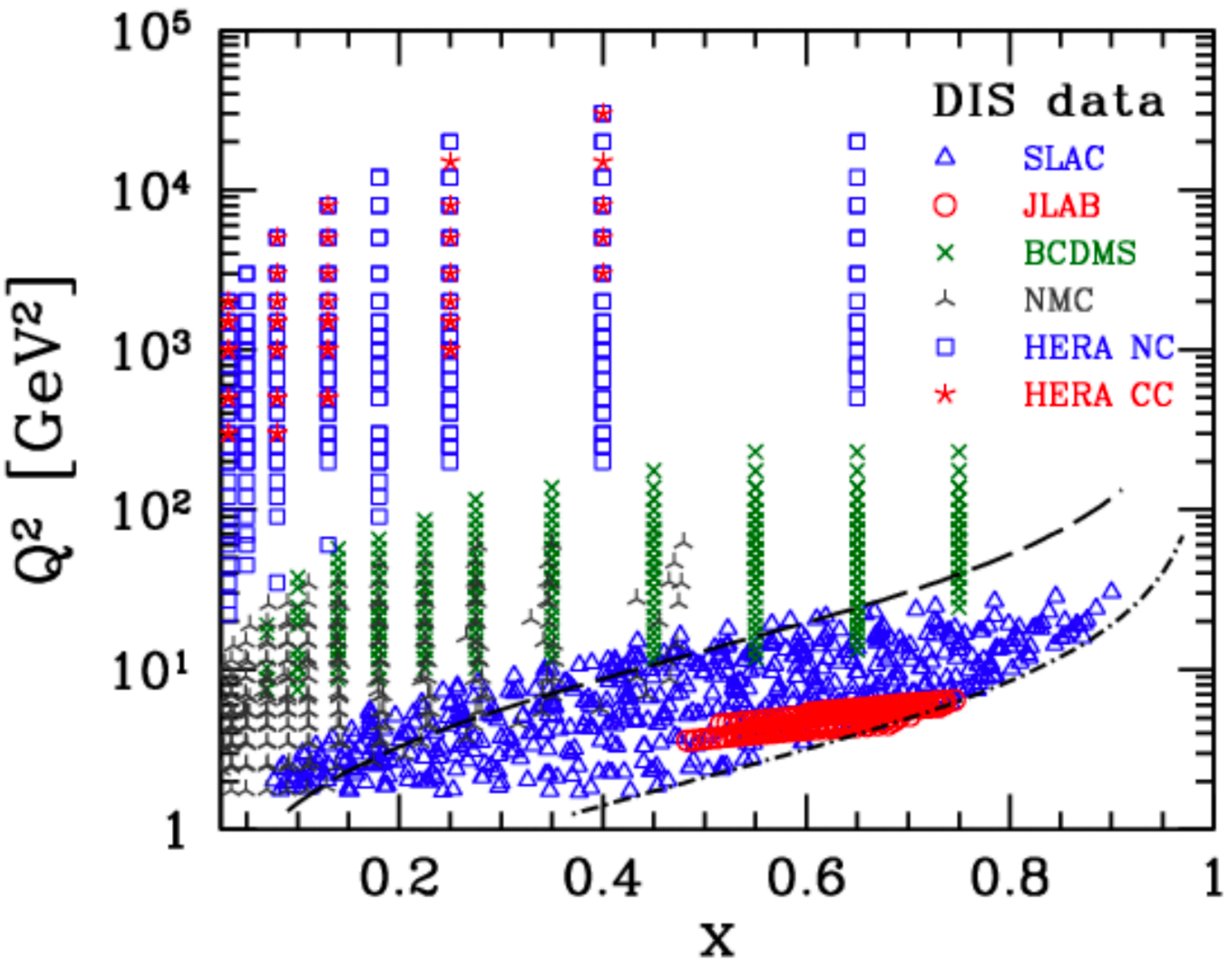




Left: The weak mixing angle determined from A_FB at the LHC is strongly correlated with to u_{val} and d_{val} at $x \sim 0.01 - 0.05$

Right: The Lagrangian multiplier method identifies that the BCDMS d and NMC rat data sets strongly effect the d_{val} at $x = 0.03$.

Deuteron DIS Experiments in the CJ and CT analyses



DIS Deuterium

- BCDMS F_2^d
- NMC F_2^d/F_2^p
- BoNuS F_2^n/F_2^d
- SLAC deuteron
- JLab deuteron
- HERMES deuteron

CT: BCDMS F_2^d, NMC F_2^d/F_2^p

CJ: all of the above

Intermediate and large-x regions of deuteron DIS data are affected by nuclear dynamics.

CJ implements a detailed model of nuclear effects at NLO

CT implements NNLO contributions and a larger data set

Deuteron Corrections: Theory

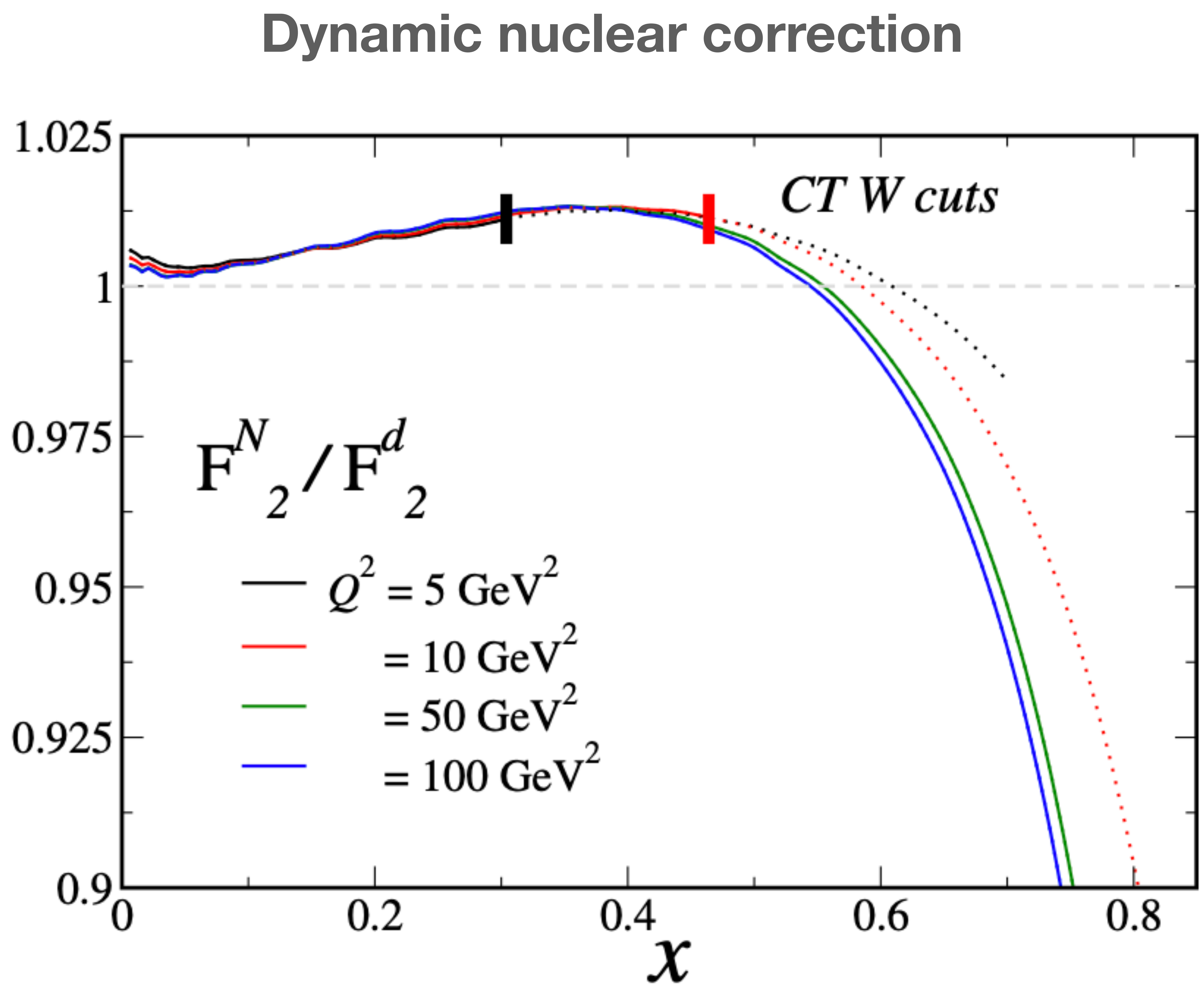
The isoscalar approximation to the deuteron PDF $f_a^d(x, Q^2)$ is modeled based on the proton PDF $f_a^p(x, Q^2)$.

In addition, complete treatment of the deuteron correction must include:

- virtuality of struck bound nucleon (off-shellness)
- relativistic Fermi motion
- nuclear wave function

In the CJ PDFs

Deuteron Corrections: Implementation



CJ

The deuteron correction is treated as nuclear wave-function effect, computed as the convolution of the bound nucleon's parton distributions and a nucleonic "smearing function"

$$f^d(x, Q^2) = \int \frac{dz}{z} \int dp_N^2\, \mathcal{S}^{N/d}(z, p_N^2)\, \tilde{f}^N(x/z, p_N^2, Q^2)$$

$$\tilde{f}^{q/N}(y, p_N^2, Q^2) = f^N(y, Q^2) + \frac{p_N^2 - M_N^2}{M_N^2}\,\delta f(y, Q^2) + O(\omega^2)$$

$f^N(y, Q^2)$: PDF of the free, on-shell nucleon

$O(\omega)$ term: off-shell effect

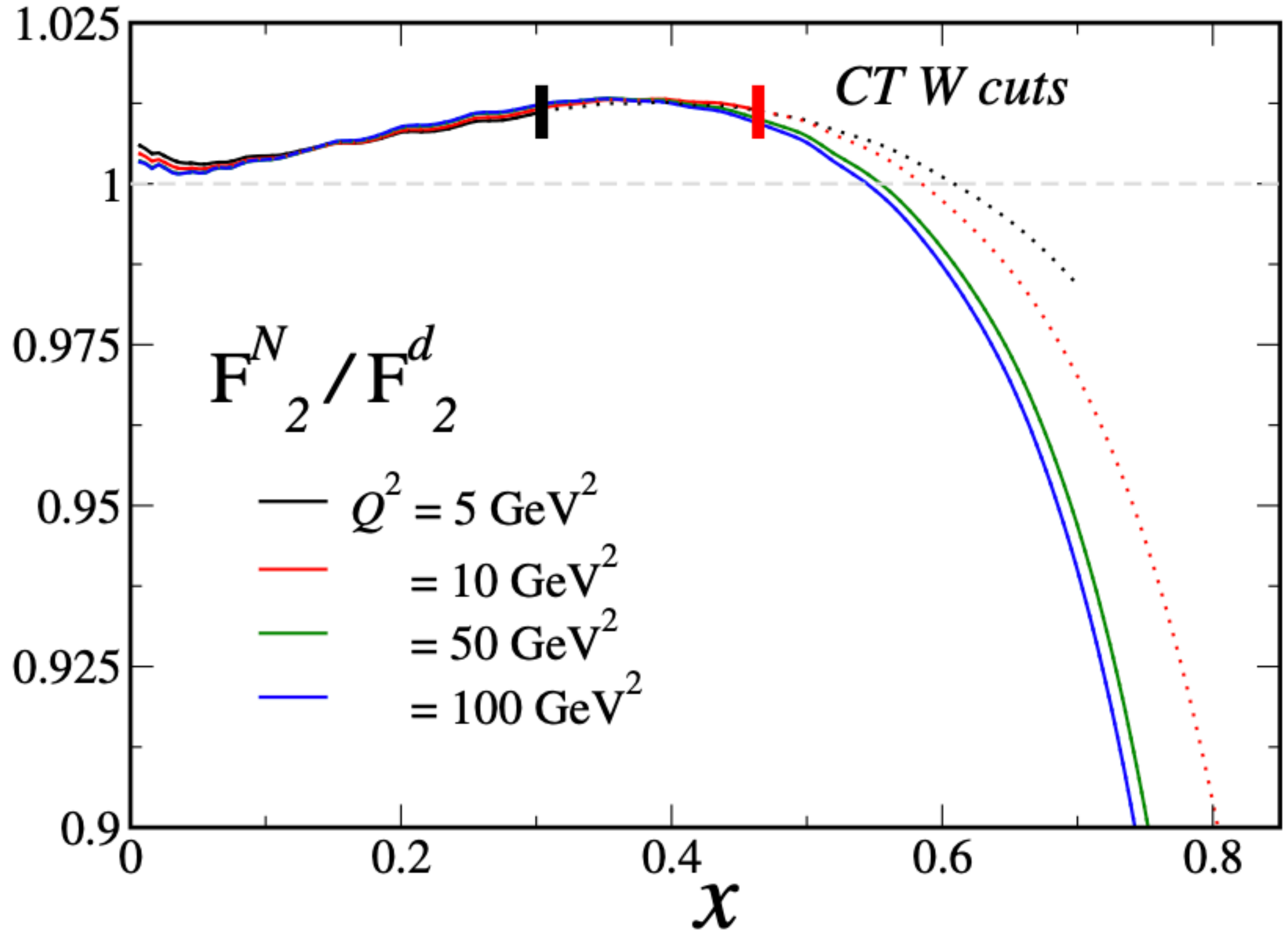
$$\delta f(x) = C(x - x_0)(x - x_1)(1 + x_0 - x)$$

Off-shell function

- Energy independent
- Satisfy quark-number sum rule.

Deuteron Corrections: Implementation

Dynamic nuclear correction



CT

The default CT is only weakly sensitive to the deuteron correction due to its W cut.

A variation of CT (fixed d.c.) adopts the fixed deuteron correction.

How to make CJ and CT fits as similar as possible?

We made the changes in the default CJ and CT frameworks to enable their comparisons

- CT NNLO -> NLO
- Uses tier 1 penalty only
- CT can apply a fixed deuteron correction

- CJ uses default NLO
- CJ can apply a free/ fixed deuteron correction

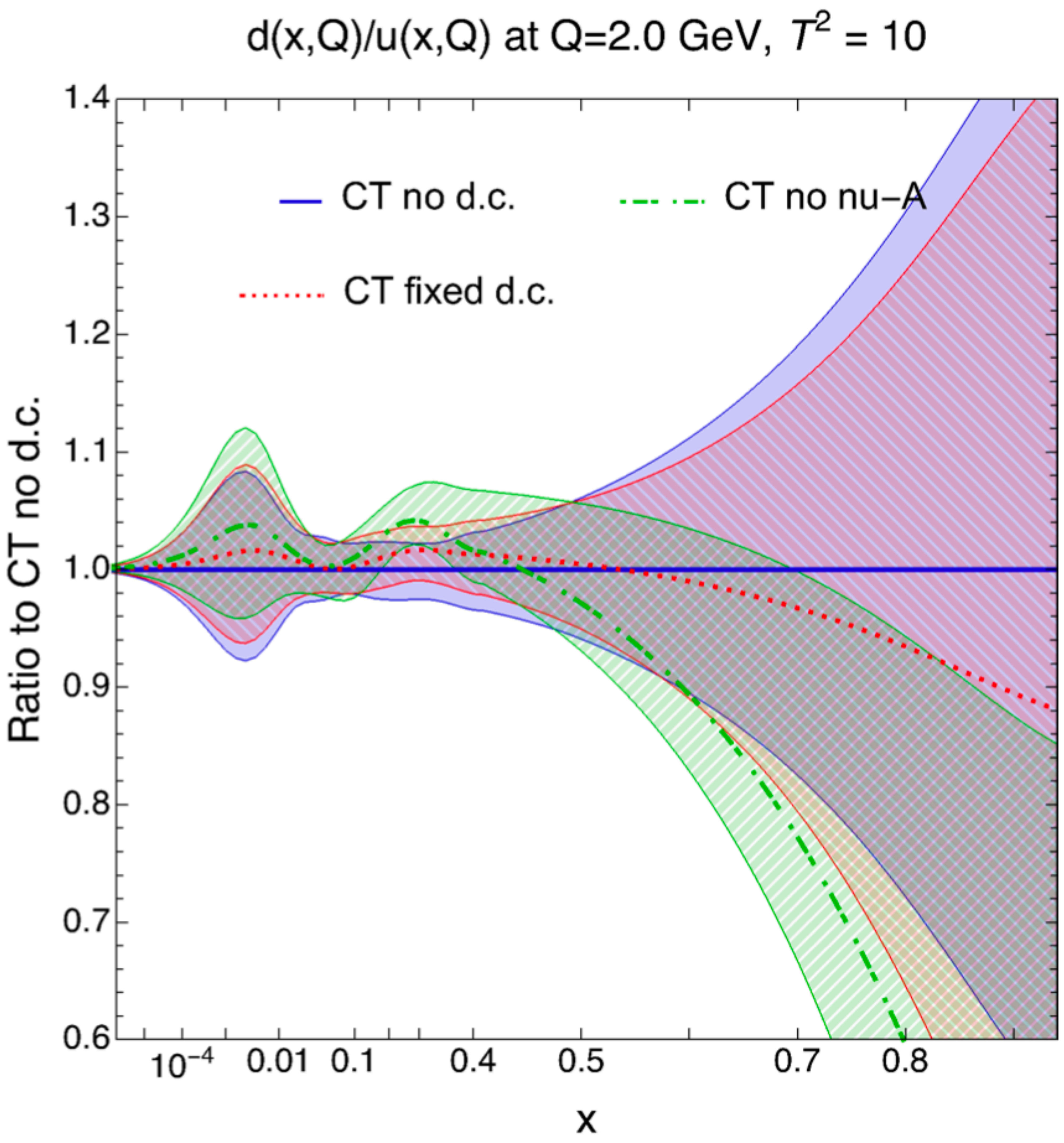
- Both generate Hessian PDF sets for $T^2 = 10$.
- Compare χ^2 pulls from large groups of experiments

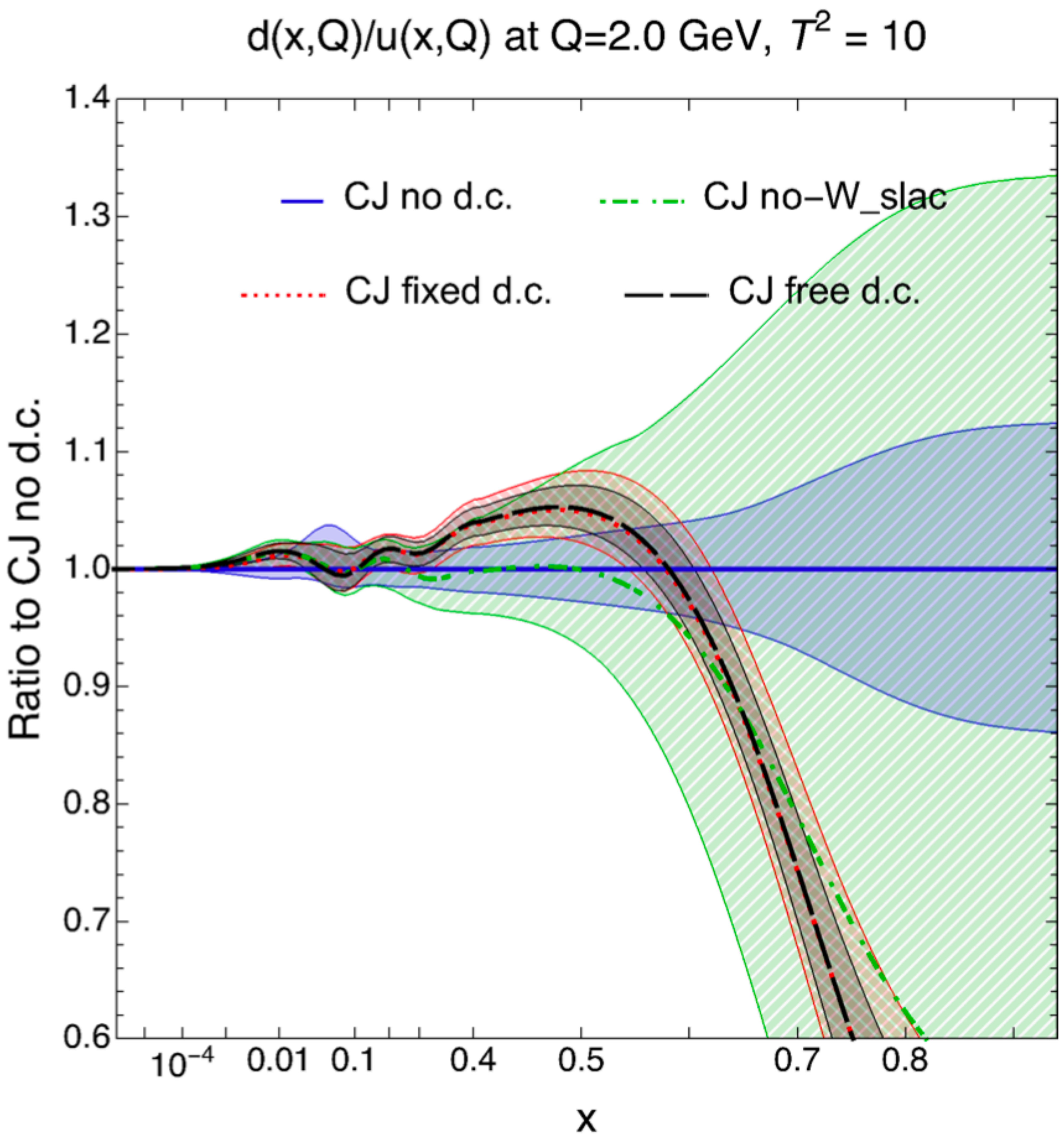
Selected experiment groups — **Various types of fits performed**

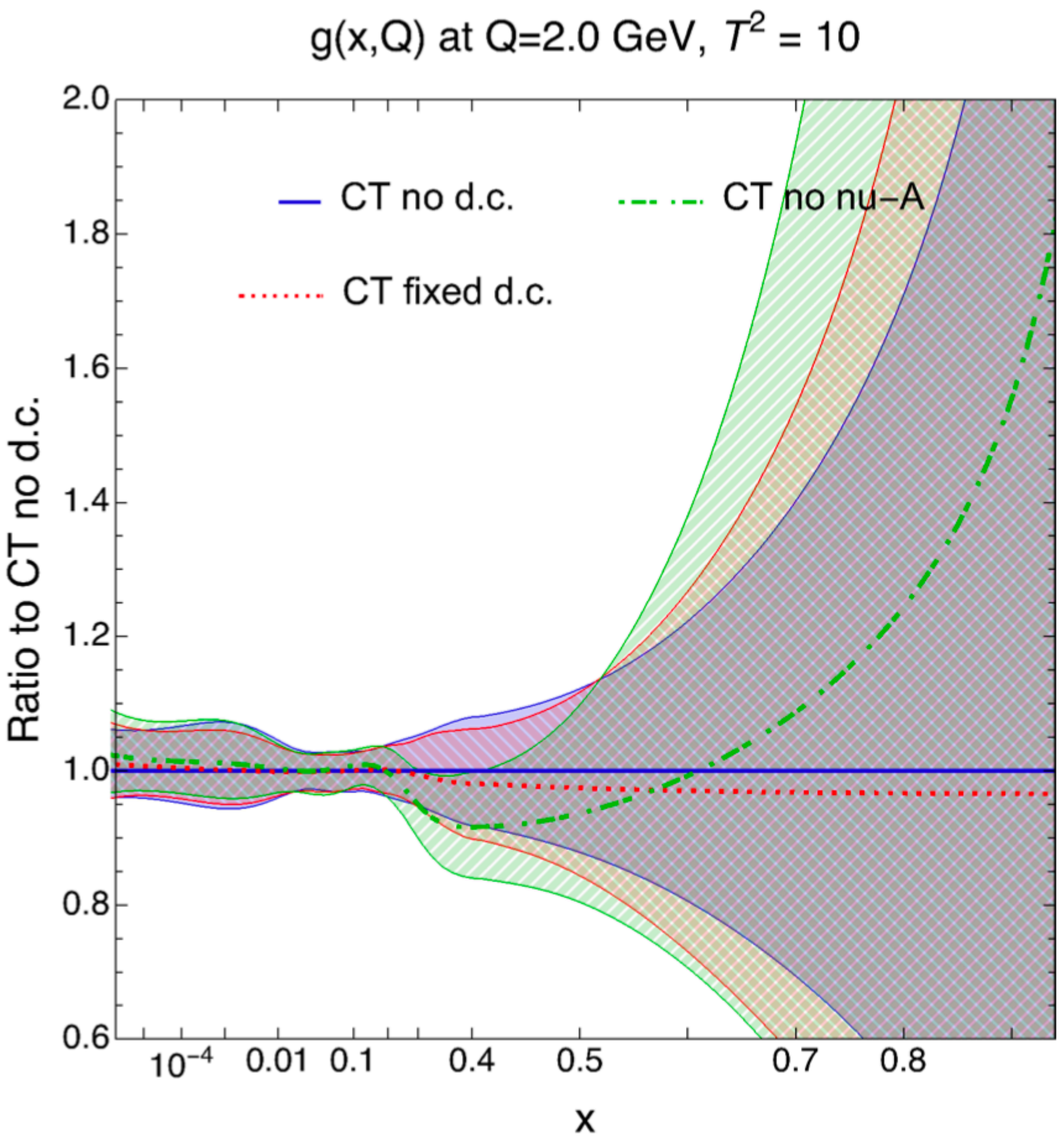
Group #	Experiment	CJ no d.c.	CJ fixed d.c.	CJ no-W_slac	CT no d.c.	CT fixed d.c.	CT no nu-A
1	γ+jet	62/56	61/56	60/56	–	–	–
2	Jets Tevatron	37/182	36/182	36/182	225/182	225/182	229/182
3	DIS proton	3007/2548	2973/2548	2330/1848	1818/1523	1812/1523	1806/1523
4	DIS deuteron	1363/1389	1214/1389	704/671	401/373	387/373	381/373
	SLAC deuteron (only)	**507/582**	**376/582**	–	–	–	–
5	WZ Tevatron	193/117	133/117	99/90	113/101	129/101	137/101
	CDF W asym. (only)	**14/13**	**17/13**	–	–	–	–
	DØ W asym. (only)	**82/14**	**12/14**	–	–	–	–
6	WZ LHC	–	–	–	267/185	347/185	315/185
7	Drell-Yan	302/250	284/250	272/250	454/318	348/318	344/318
8	**ν-A incl. DIS**	–	–	–	**269/336**	**279/336**	–
9	$t\bar{t}$ production	–	–	–	44/31	45/31	46/31
10	ν-A dimuon SIDIS	–	–	–	103/149	104/149	103/149
11	Jets LHC	–	–	–	594/483	595/483	598/483
	TOTAL	**4963/4542**	**4699/4542**	**3501/3097**	**4289/3670**	**4271/3670**	**3959/3334**

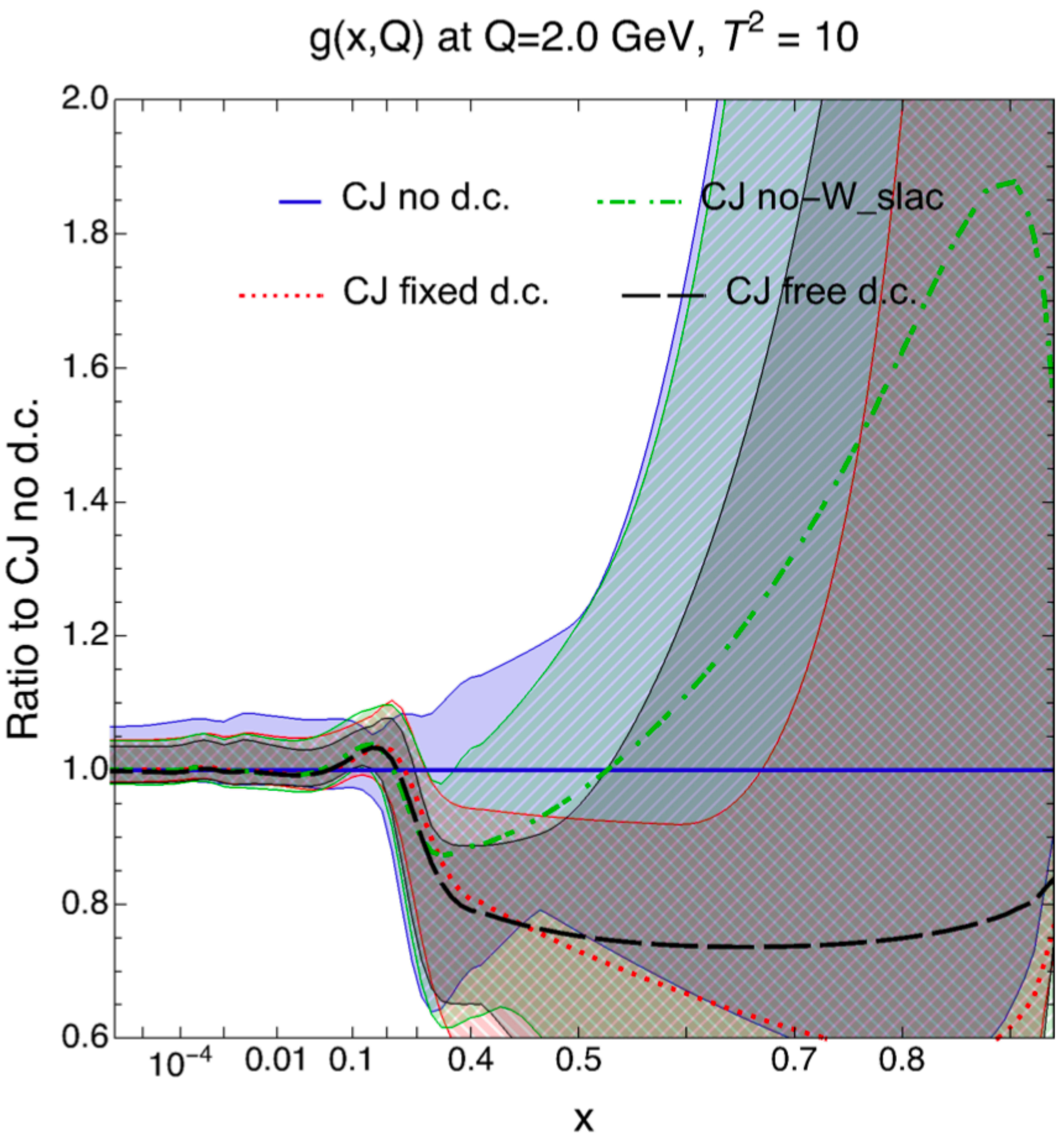
χ^2 **for CJ w/w.o. deuteron correction**

χ^2 **for CT w/w.o. k-factor deuteron correction**


d(x,Q)/u(x,Q) at Q=2.0 GeV, T^2 = 10
CT no d.c.
CT no nu−A
CT fixed d.c.
Ratio to CT no d.c.
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
10^{-4}
0.01
0.1
0.4
0.5
0.7
0.8
x


d(x,Q)/u(x,Q) at Q=2.0 GeV, T^2 = 10
CJ no d.c.
CJ no−W_slac
CJ fixed d.c.
CJ free d.c.
Ratio to CJ no d.c.
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
10^{-4}
0.01
0.1
0.4
0.5
0.7
0.8
x


g(x,Q) at Q=2.0 GeV, T^2 = 10
Ratio to CT no d.c.
CT no d.c.
CT no nu−A
CT fixed d.c.
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
10^{-4}
0.01
0.1
0.4
0.5
0.7
0.8
x


g(x,Q) at Q=2.0 GeV, T^2 = 10
Ratio to CJ no d.c.
CJ no d.c.
CJ no−W_slac
CJ fixed d.c.
CJ free d.c.
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
10^{-4}
0.01
0.1
0.4
0.5
0.7
0.8
x

How can we isolate pulls of various experiments on the PDFs in the complicated global fits?

We apply the Hessian sensitivity method(TJ Hobbs et al, arXiv:1904.00022)

L_2 Sensitivity $Sens_{E,f,L_2}(x, Q)$

It is a linear approximation for $\Delta(\chi^2_E)$ of a certain experiment E when some PDF $f_a(x, Q)$ at some (x, Q) increases by its +68% c.l. Hessian PDF uncertainty.

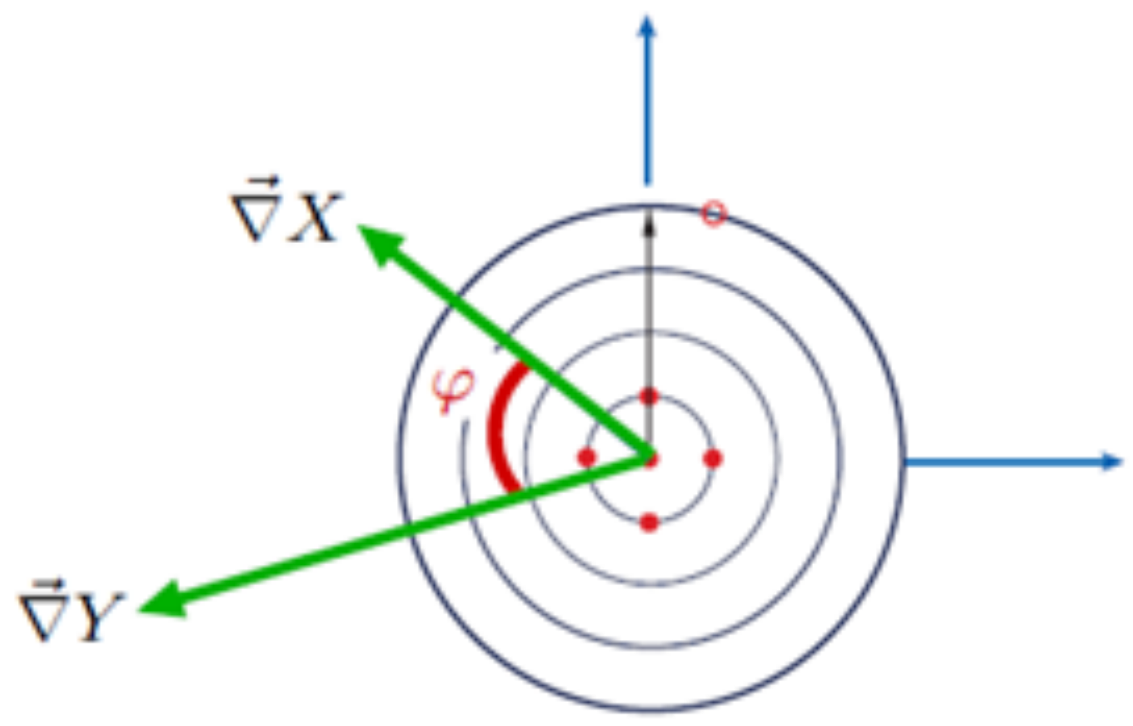
Definition: $Sens_{E,f,L_2}(x, Q) = |\overrightarrow{\nabla\chi^2_E}| cos(\langle \overrightarrow{\nabla\chi^2_E}, \overrightarrow{\nabla f} \rangle)$

Correlation: $Corr_{E,f}(x, Q) = cos(\langle \overrightarrow{\nabla\chi^2_E}, \overrightarrow{\nabla f} \rangle)$

$\overrightarrow{\nabla\chi^2_E} = \{\chi^2_E(\overrightarrow{a}_{2*i+1}) - \chi^2_E(\overrightarrow{a}_{2*i}), i \in \{1..N\}\}$

$\overrightarrow{\nabla f} = \{f(x, Q)(\overrightarrow{a}_{2*i+1}) - f(x, Q)(\overrightarrow{a}_{2*i}), i \in \{1..N\}\}$

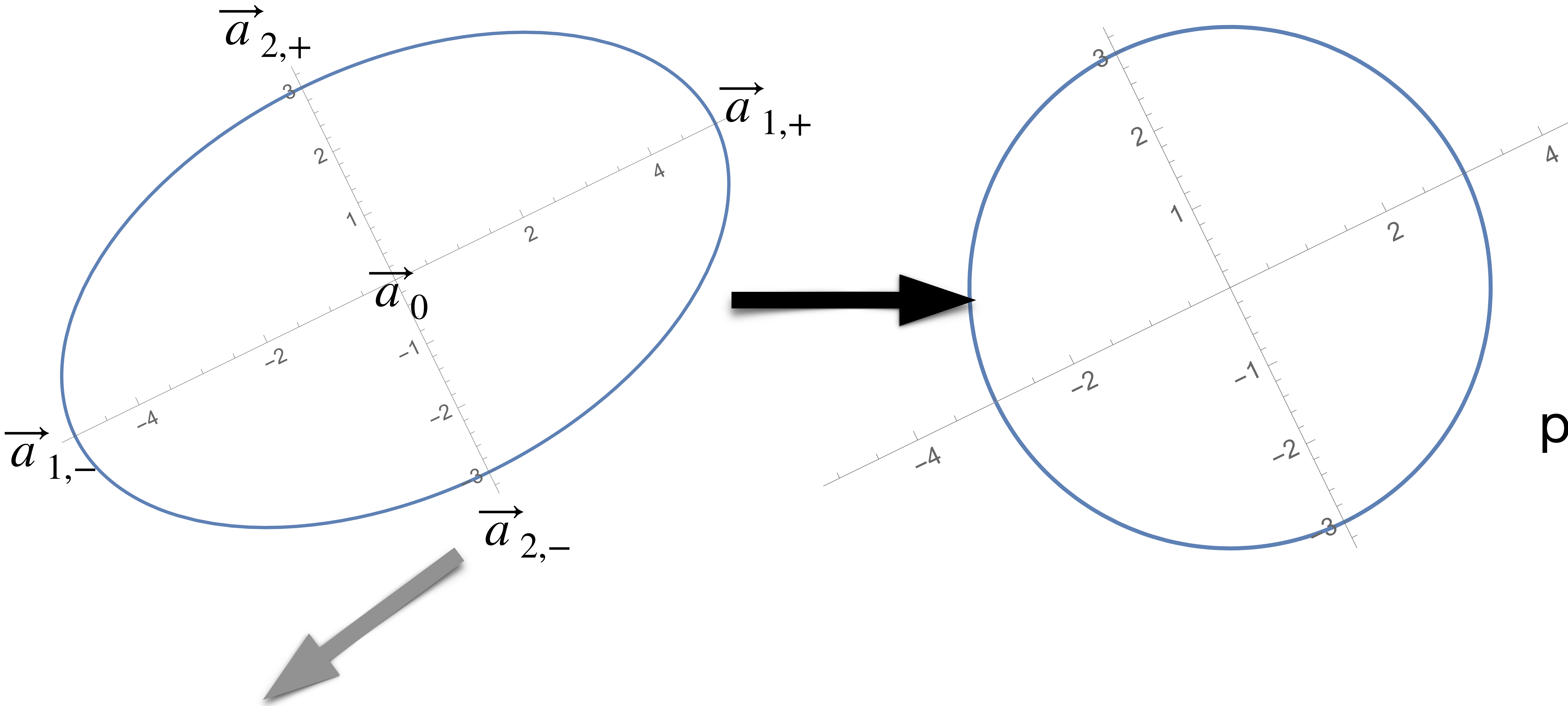
(N is the number of pdf parameters)



$Sens_{E,f,L_2}(x, Q)$ is *fast* to calculate, and with *good accuracy*.

Understand the correlation / L_2 sensitivity

Hyperellipsoid in pdf parameter space corresponding to 68% C.L. defined by $\Delta\chi^2_{\text{tot}} = 10$

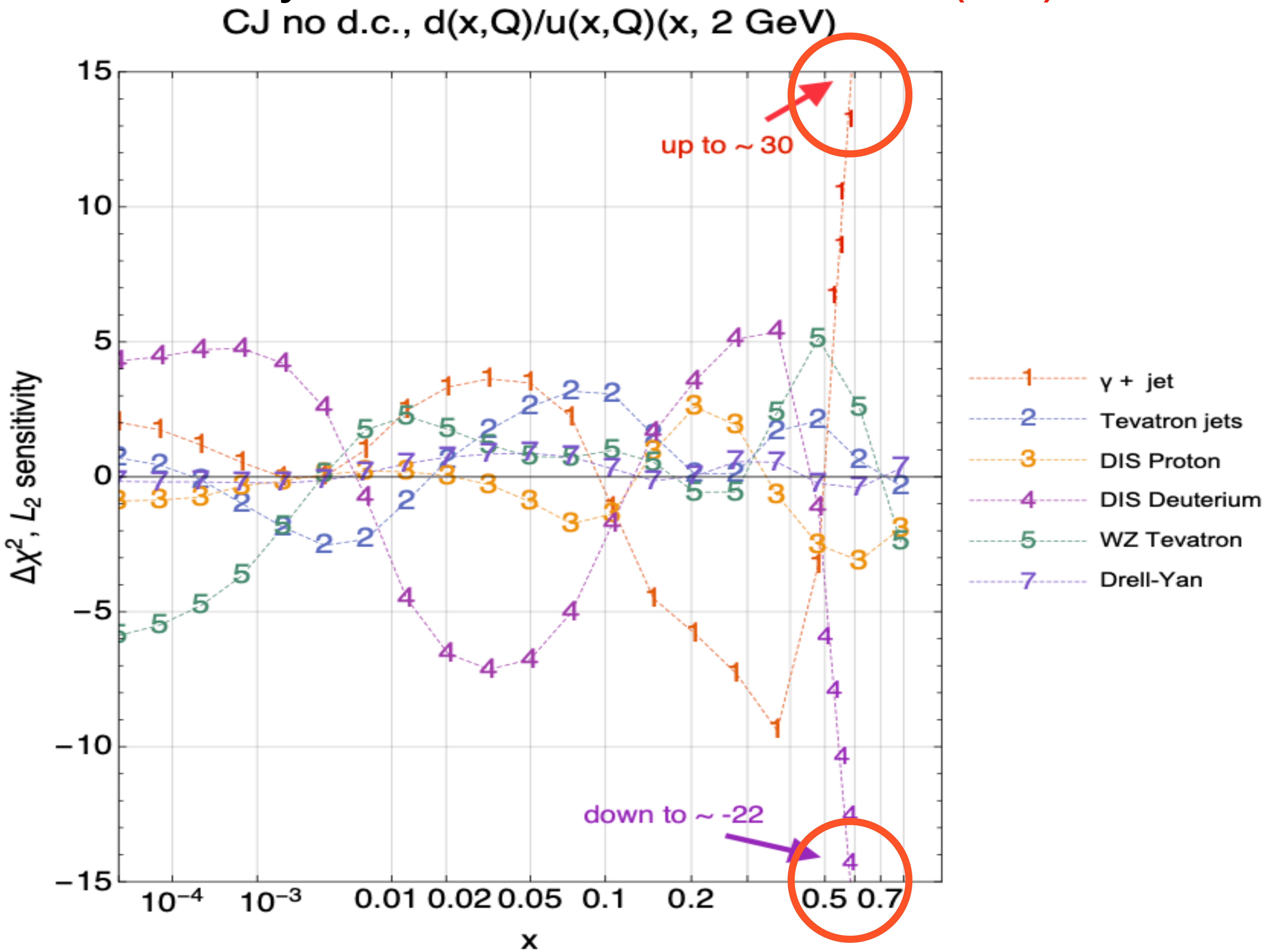


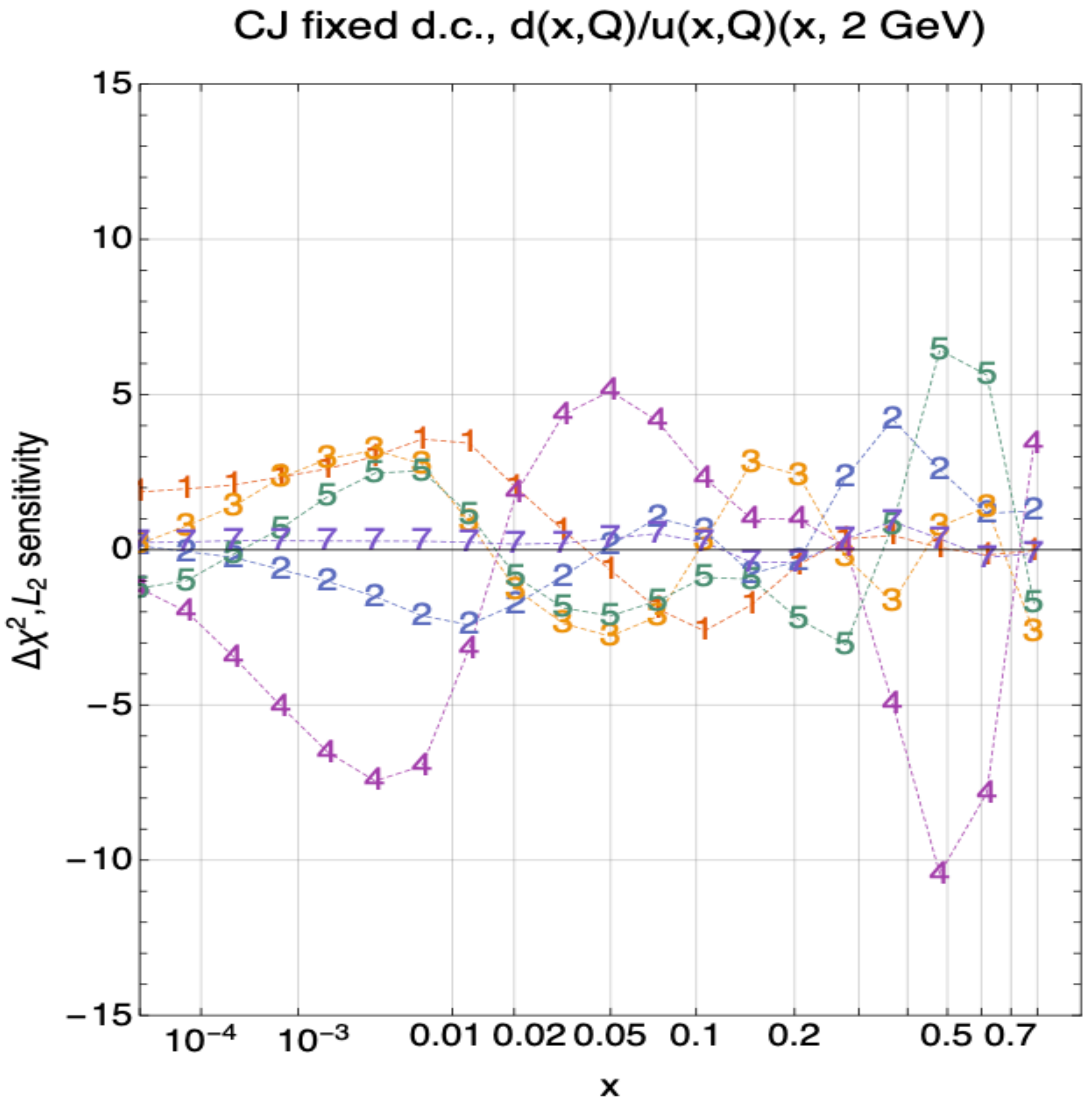
Eigenvector directions of the Hessian matrix

Correlation measures the cosine of the angle between the gradients of quantities X, Y in the adjusted PDF parameter space.

$Sens_{E,f,L_2}(x, Q)$ is the projection of the X's gradient onto Y's gradient in the adjusted PDF parameter space.

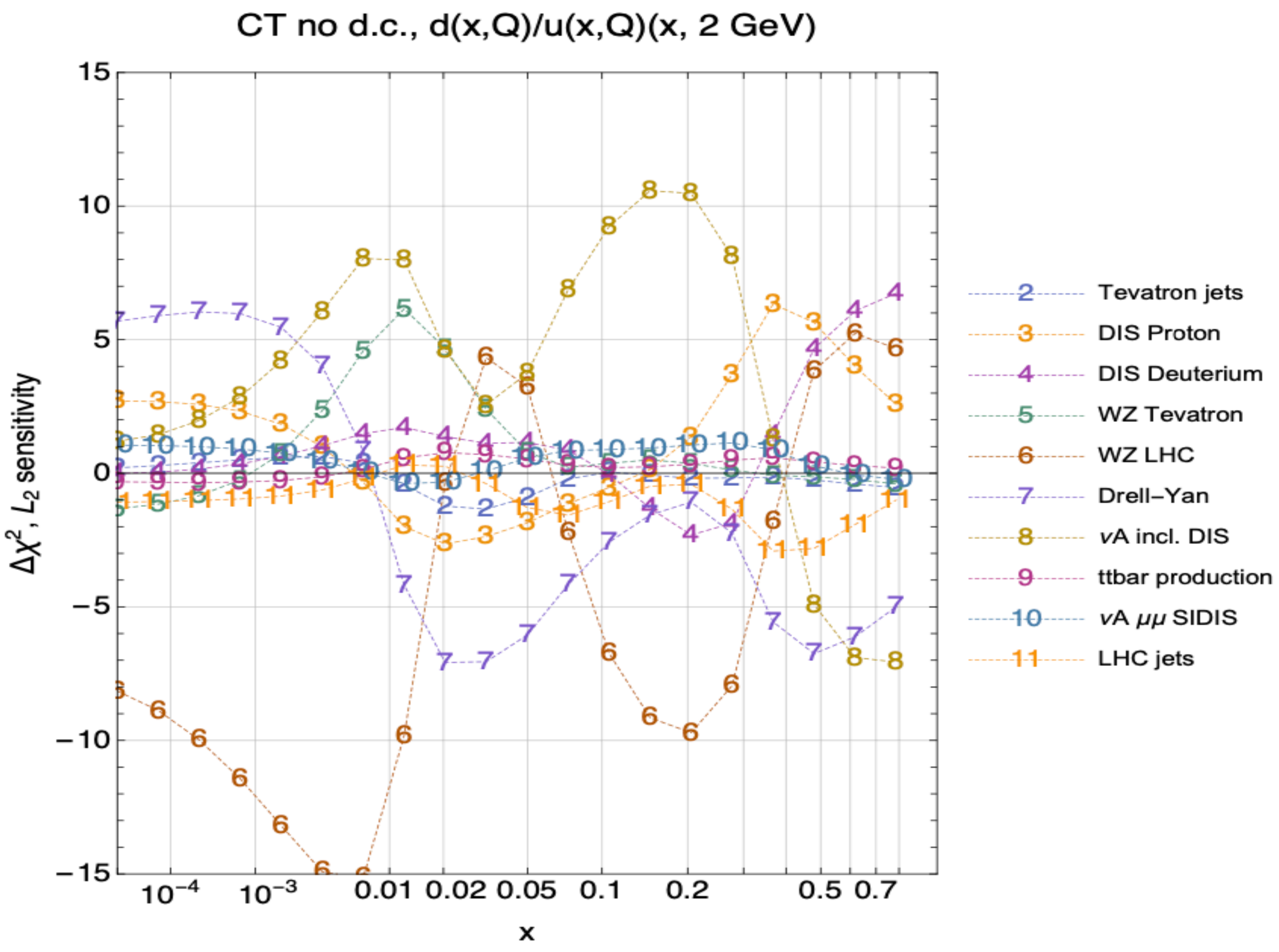
Sensitivity to d/u for CJ15 without (left) and with (right) fixed deuteron correction

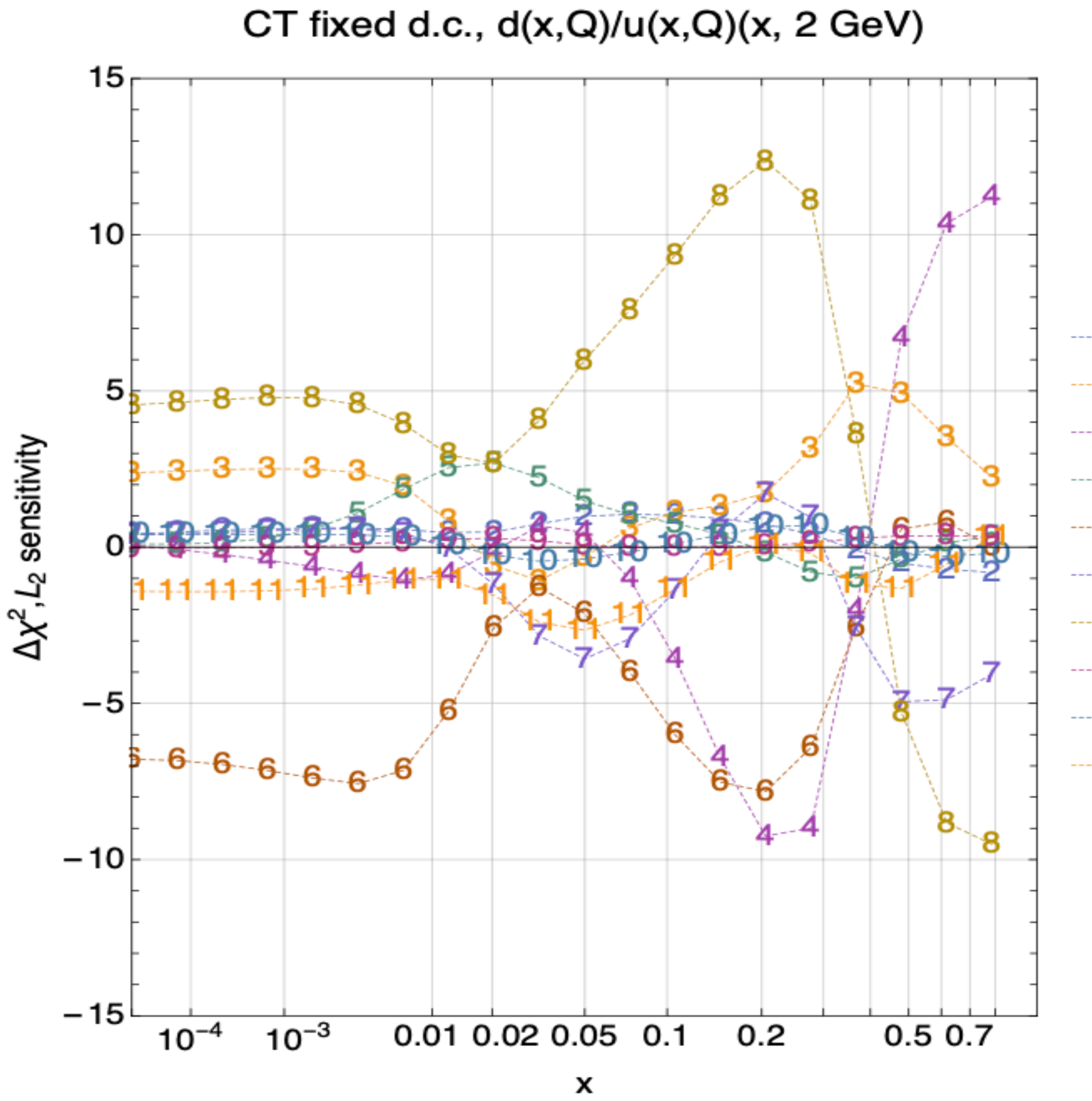




Nuclear correction reduces competing L_2 pulls at high x, leads to the reduction of the error band.

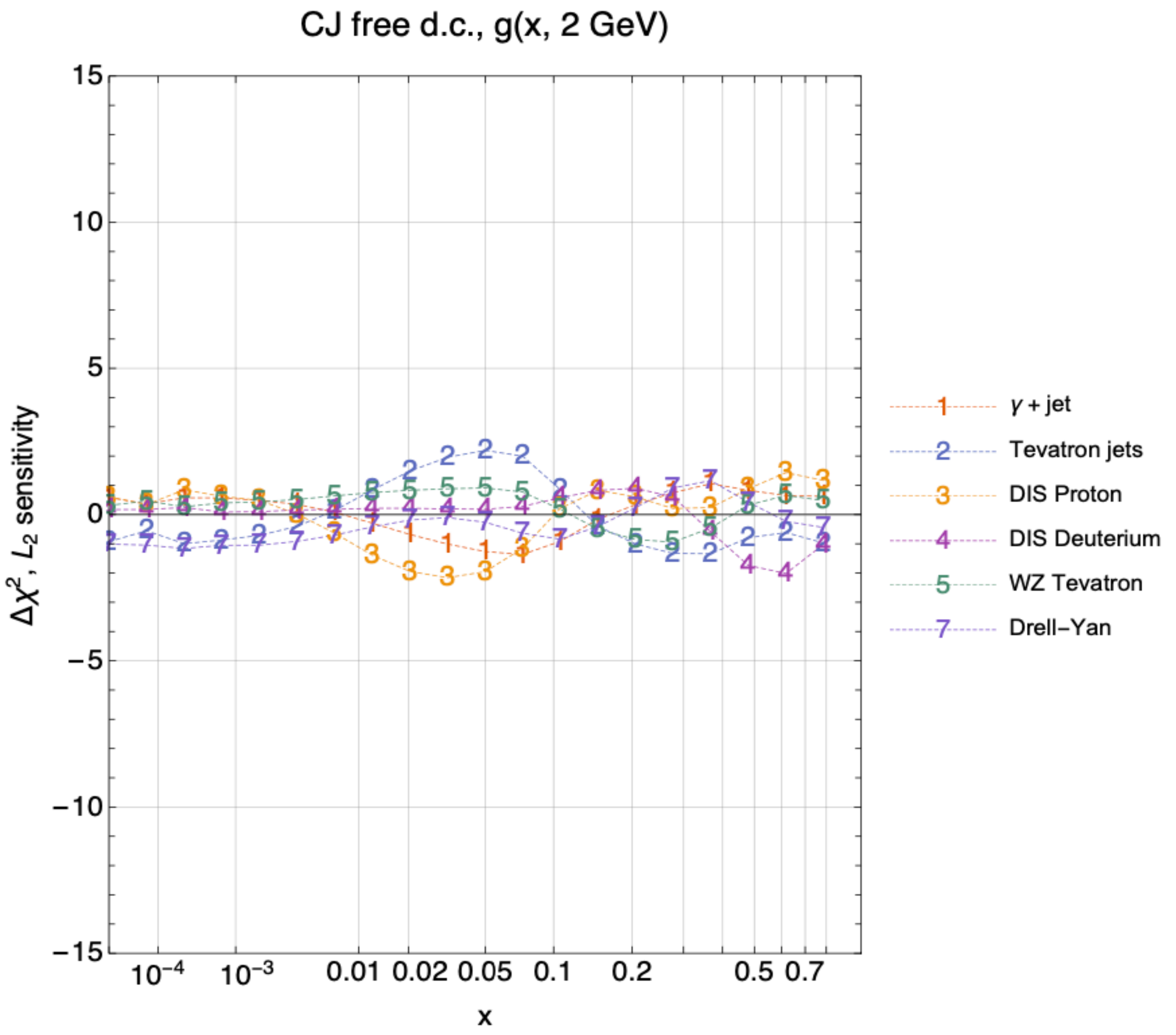
Sensitivity to d/u for CT18 without (left) and with (right) fixed nuclear correction

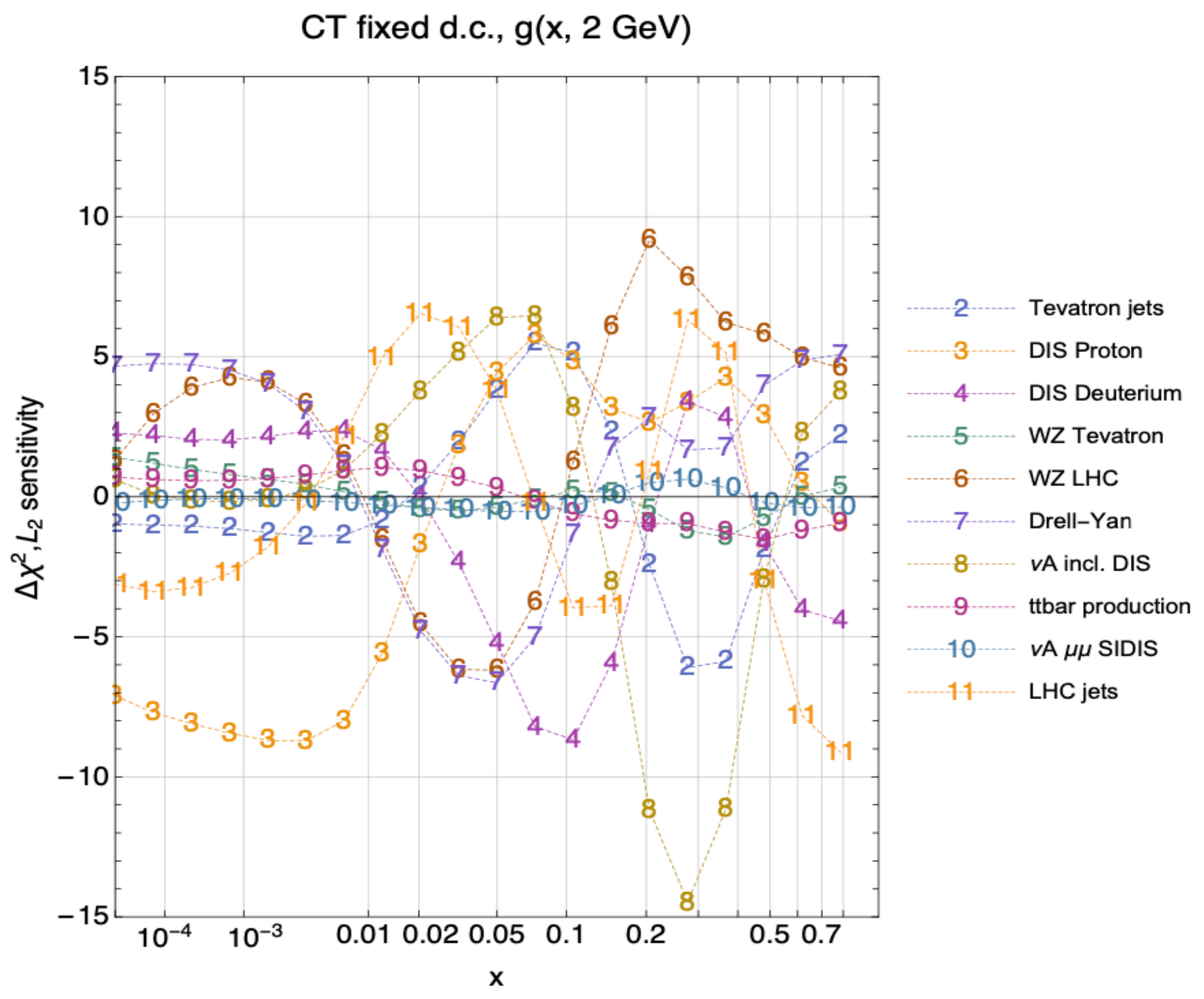




Nuclear correction in CT case doesn't reduce tension that much but has some impact on χ^2_E and pulls of some experiments, such as DIS deuterium.

Sensitivity to g for CJ with fixed (left) and CT fixed (right) deuteron correction





Summary

- The PDF sensitivity is a statistical indicator that quantifies constraints from experiments on PDFs in CTEQ global PDF fits.

- The sensitivity method is applied to understand the origin of pulls on d/u, g and other flavors in the CJ and CT fits. Pulls are affected by the nuclear correction in fixed-target DIS.

- The treatment of nuclear effects at large x in PDF fits affects the PDF uncertainties in LHC electroweak precision measurements.

- The deuteron corrections, while comparable to uncertainties in the modern NNLO fits, will play a more important role in the future.

Thank you for you attention!

Backup

CT and CJ experiments

			CT	CJ	
1	γ+jet	DØ γ+jet		301-304	[62]
2	Jets Tevatron	CDF Run-2 inclusive jet production	504	204	[63]
		DØ Run-2 inclusive jet production	514	203	[64]
3	DIS Proton	HERA Run I+II	160	80,82,83,93-96	[23]
		BCDMS F_2^p	101	3	[25]
		H1 σ_r^b	145		[65]
		Combined HERA charm production	147		[66]
		H1 F_L	169		[67]
		HERMES proton		17	[68]
		SLAC proton		5	[69]
		JLab proton		7	[70]
		NMC F_2		51	[71]
4	DIS Deuterium	BCDMS F_2^d	102	4	[24]
		NMC F_2^d/F_2^p	104	53	[22]
		BoNuS F_2^n/F_2^d		55	[72]
		SLAC deuteron		6	[69]
		JLab deuteron		8	[70]
		HERMES deuteron		18	[68]
5	WZ Tevatron	CDF Run-1 lepton A_{ch} , $p_{Tl} > 25$ GeV	225		[73]
		CDF Run-2 electron A_{ch} , $p_{Tl} > 25$ GeV	227	128	[74]
		DØ Run-2 muon A_{ch} , $p_{Tl} > 20$ GeV	234		[75]
		DØ Run-2 Z rapidity	260		[76]
		CDF Run-2 Z rapidity	261	140	[77]
		DØ Run-2 9.7 fb^{-1} electron A_{ch} , $p_{Tl} > 25$ GeV	281	130	[78]
		DØ Z		141	[79]
		CDF W asymmetry		131	[80]
		DØ W asymmetry		132	[81]
		DØ lepton asymmetry 13		134	[82]

			CT	CJ	
6	WZ LHC	LHCb 7 TeV 1.0 fb^{-1} W/Z forward rapidity cross sec.	245		[83]
		LHCb 8 TeV 2.0 fb^{-1} $Z \to e^- e^+$ forward rapidity cross sec.	246		[84]
		CMS 8 TeV 18.8 fb^{-1} muon charge asymmetry A_{ch}	249		[85]
		LHCb 8 TeV 2.0 fb^{-1} W/Z cross sec.	250		[86]
		ATLAS 8 TeV 20.3 fb^{-1}, Z p_T cross sec.	253		[87]
		CMS 7 TeV 4.7 fb^{-1} muon A_{ch} , $p_{Tl} > 35$ GeV	266		[88]
		CMS 7 TeV 840 pb^{-1} electron A_{ch} , $p_{Tl} > 35$ GeV	267		[89]
		ATLAS 7 TeV 35 pb^{-1} W/Z cross sec., A_{ch}	268		[90]
7	Drell-Yan	E605	201		[91]
		E866, σ^{pd}/σ^{pp}	203		[92]
		E866, σ^{pp}	204	108	[93]
		E866, σ^{pd}		110	[93]
8	ν-A incl. DIS	CDHSW F_2	108		[94]
		CDHSW xF_3	109		[94]
		CCFR F_2	110		[95]
		CCFR xF_3	111		[26]
9	ttbar production	CMS 8 TeV 19.7 fb^{-1} , $t\bar{t}$ norm. top p_T and y cross sec.	573		[96]
		ATLAS 8 TeV 20.3 fb^{-1}, $t\bar{t}$ p_T^t, $m_{t\bar{t}}$ abs. spectrum	580		[97]
10	ν-A dimuon SIDIS	NuTeV $\nu\mu\mu$ SIDIS	124		[45]
		NuTeV $\nu\bar{\mu}\mu$ SIDIS	125		[45]
		CCFR $\nu\mu\mu$ SIDIS	126		[46]
		CCFR $\nu\bar{\mu}\mu$ SIDIS	127		[46]
11	Jets LHC	CMS 7 TeV 5 fb^{-1}, single incl. jet cross sec., R = 0.7	542		[98]
		ATLAS 7 TeV 4.5 fb^{-1}, single incl. jet cross sec., R = 0.6	544		[99]
		CMS 8 TeV 19.7 fb^{-1}, single incl. jet cross sec., R = 0.7	545		[100]

PDF Fits

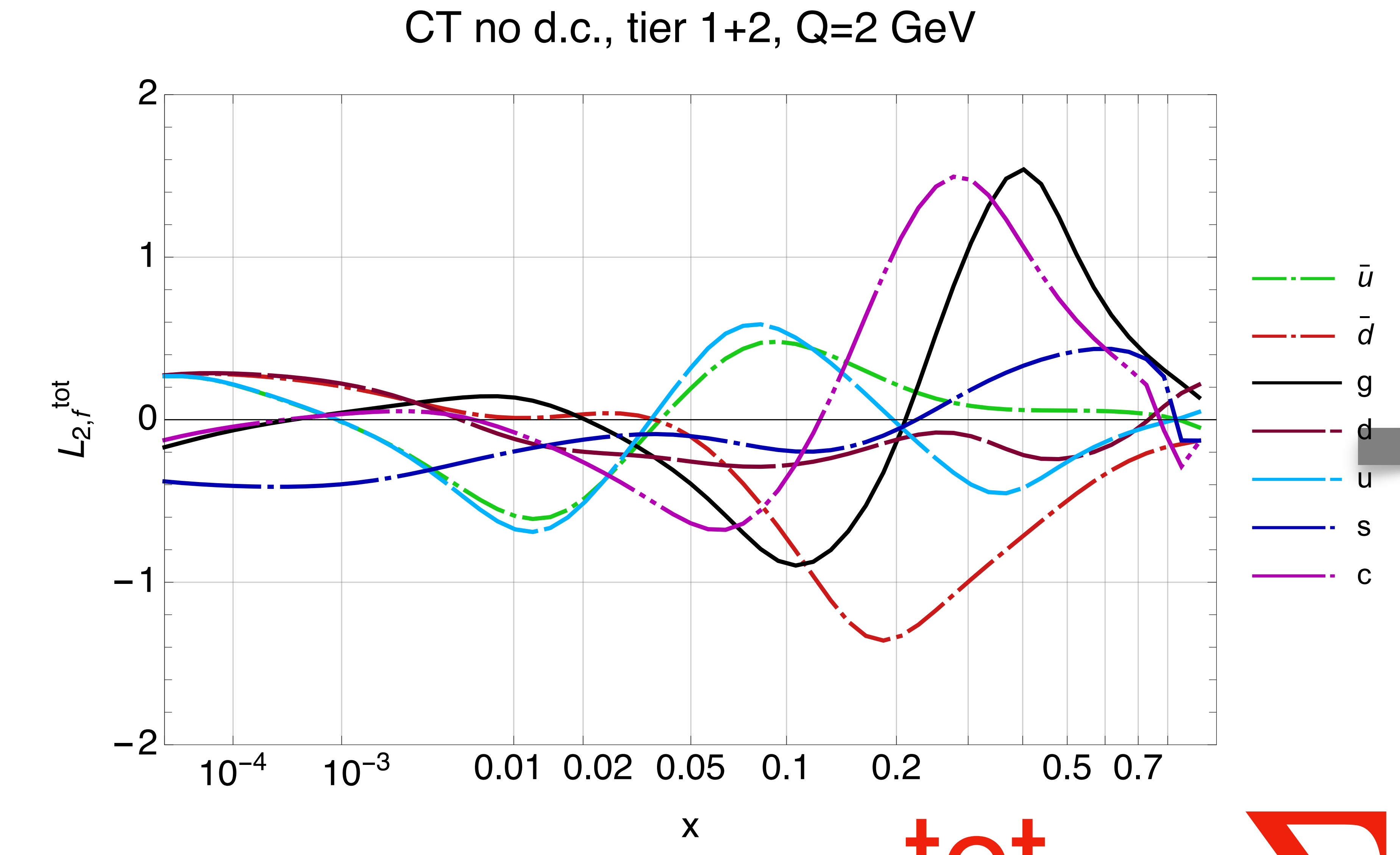
No first principle prediction for PDFs.

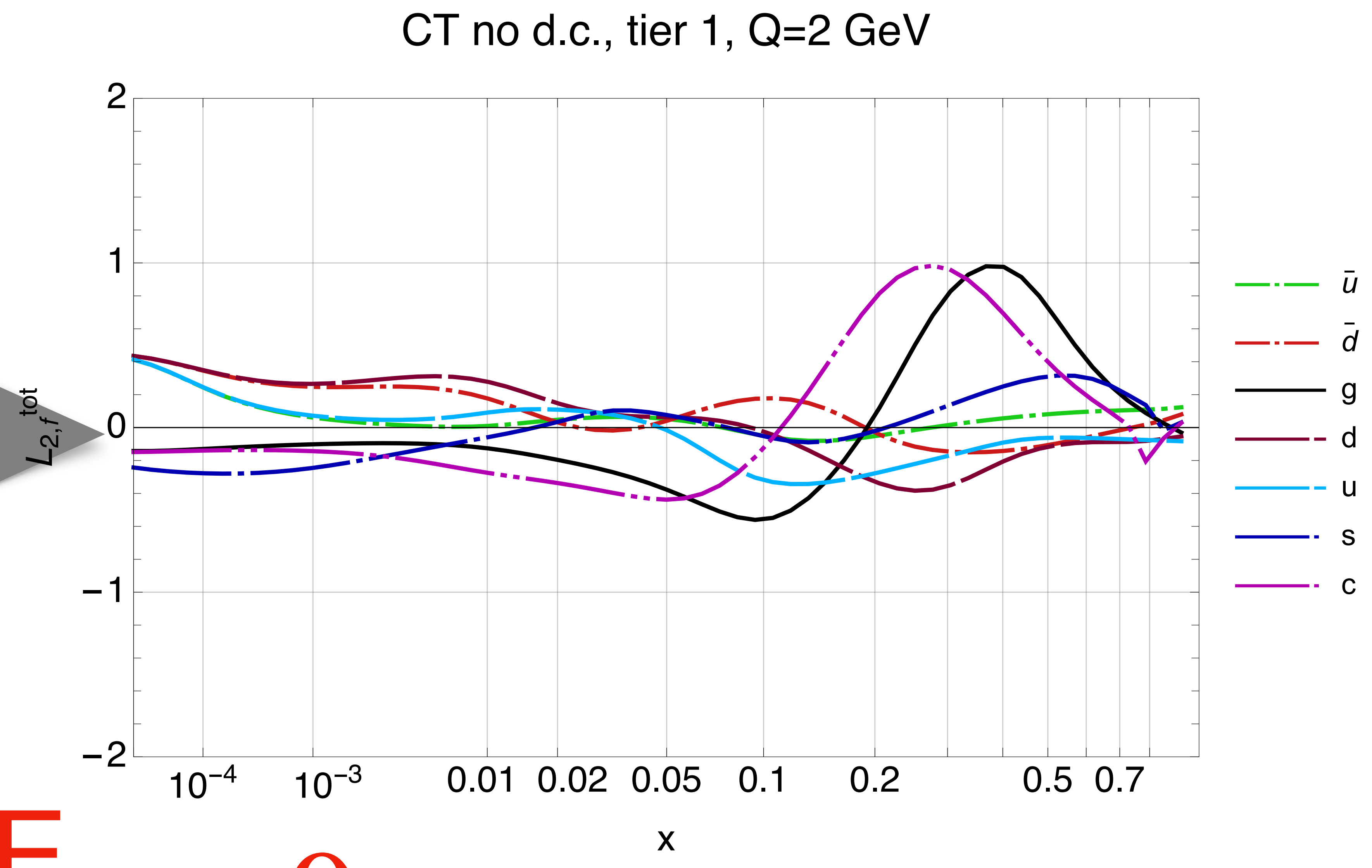
For CTEQ-TEA (Tie-Jiun Hou et al, arXiv:1908.11394) **and CTEQ-JLab** (JF Owens et al, arXiv:1212.1702) **PDF parameterizations take the form:**

$$f_i(x, Q = Q_0) = a_{0,i} x^{a_{1,i}} (1 - x)^{a_{2,i}} P(x, a_{\ldots,i})$$

Dynamic flavors at initial scale Q_0 ~ 1GeV: u, d, s, g and anti-quarks

PDF parameterizations contain large number of parameters:
24 in CJ15, 29 in CT18, and it's a complicated process.

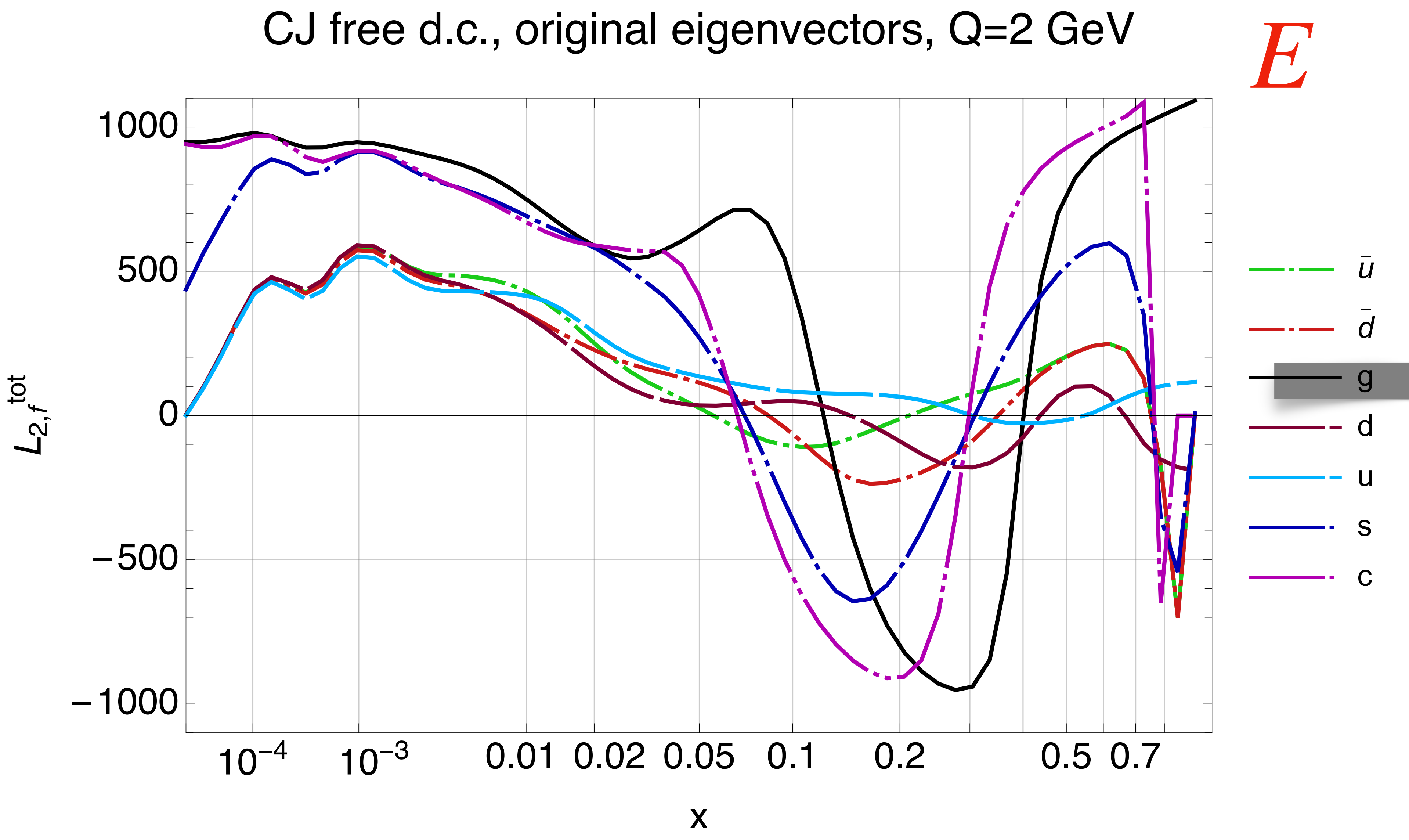


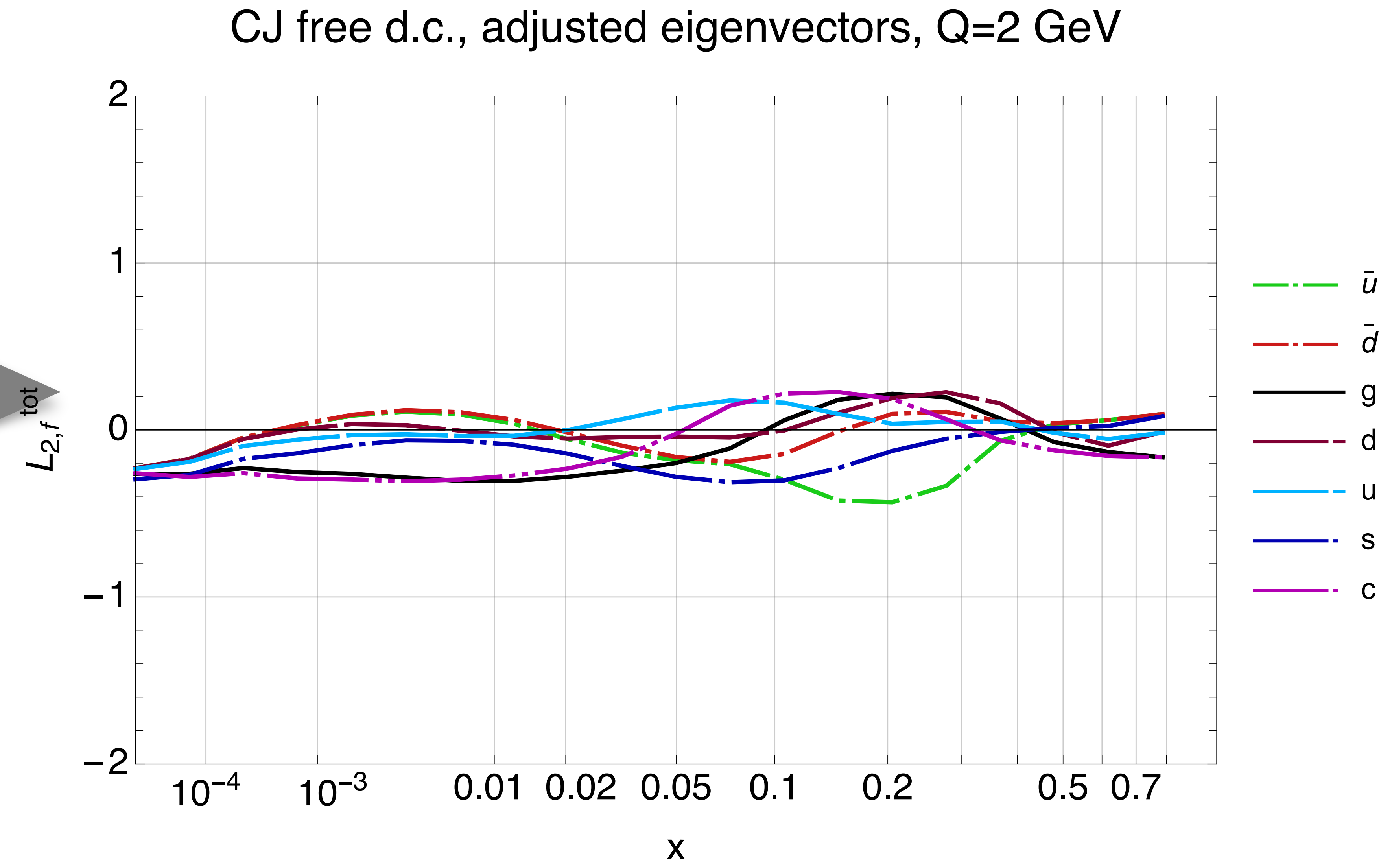


CT

- Tier-1 penalties only
- Switch to NLO
- Fixed $\Delta\chi^2 = 10$

$$L_{2,f}^{\text{tot}} = \sum_E L_{2,f}^{\text{E}} \approx 0$$





CJ

- Adjust non-gaussian eigen-directions
- Fixed $\Delta\chi^2 = 10$