Delineating the polarized and unpolarized parton structure of the nucleon

QCD Evolution Workshop,
Santa Fe, May 13, 2014

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Jefferson Lab

Overview

- Overview of unpolarized PDFs
- Updating the unpolarized distributions: **JR14**
- The role of the input scale and *procedural* bias

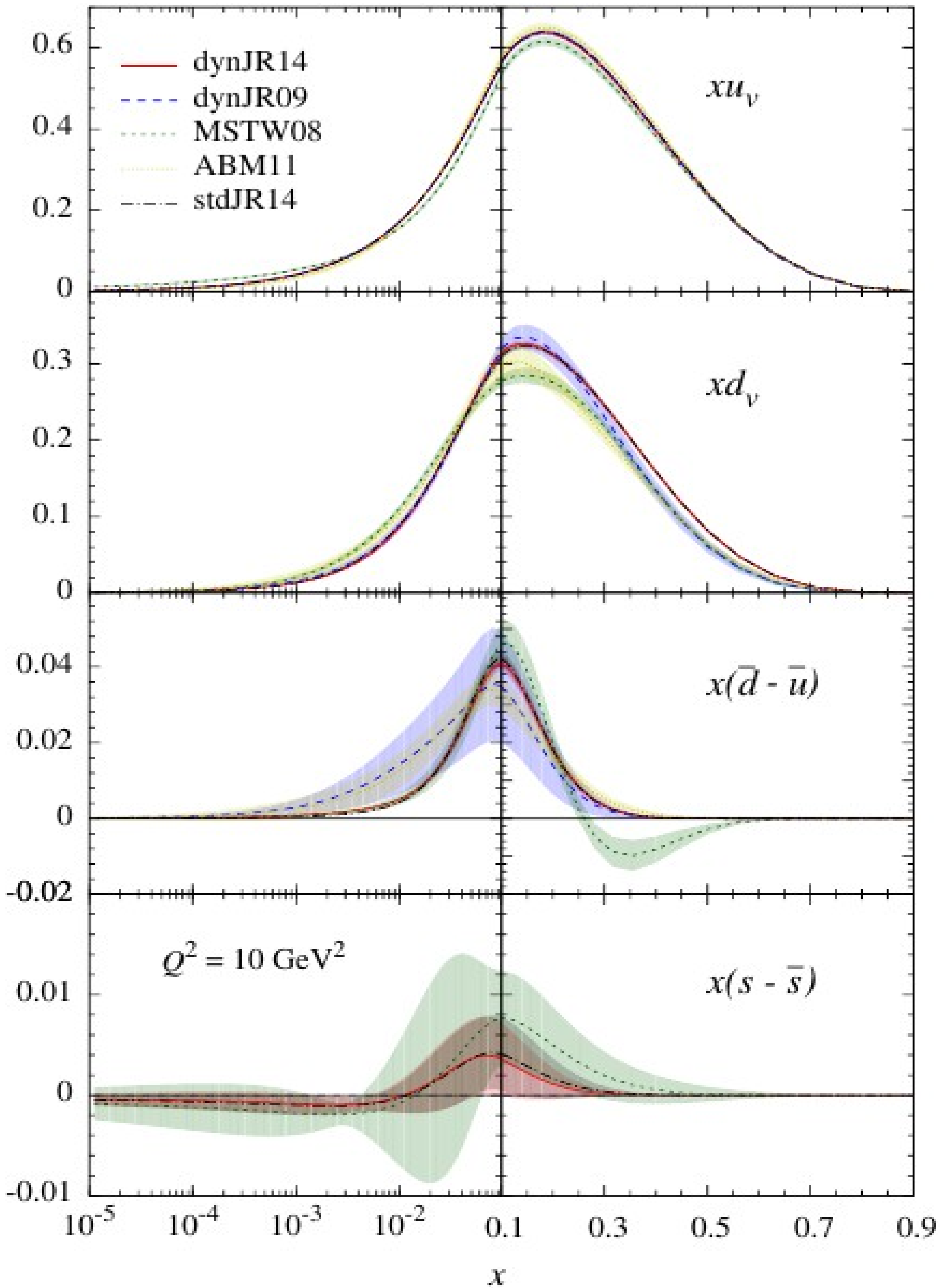
- The *Jefferson Lab Angular Momentum* collaboration
- Improving the description of polarized DIS: **JAM13**
- Large-x constraints and impact of (future) data from JLab
- Moving forwards: Including RHIC data

Our determinations of unpolarized PDFs and the strong coupling: JR

PJD, E. Reya, *Phys. Rev.* **D89** (2014) 074049

PJD, *Phys. Lett.* **B714** (2012) 301

Introduction: non-singlet sector



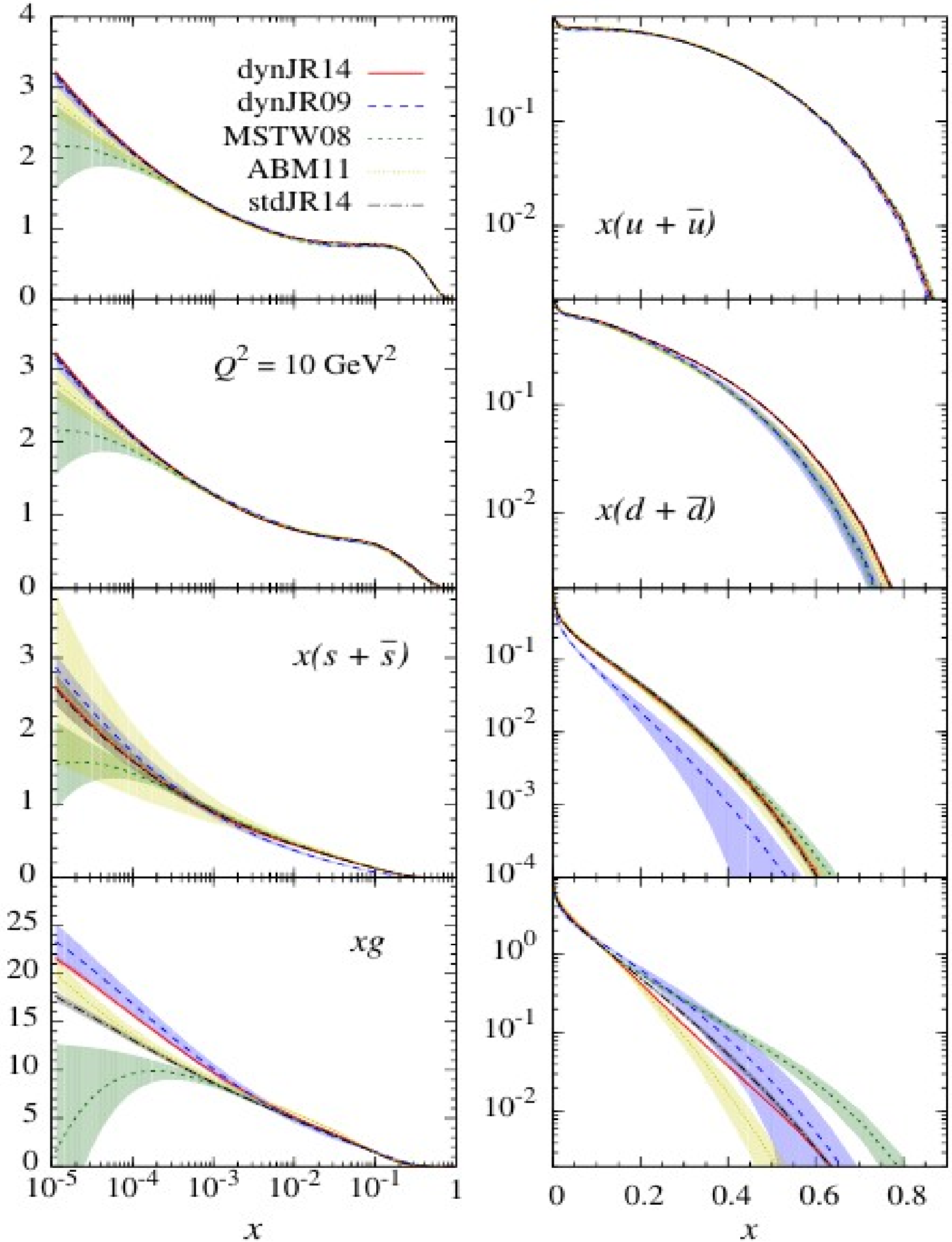
u-valence rather well determined

larger differences for d-valence, but also relatively stable

much smaller but can be determined using Drell-Yan σ^{pd}/σ^{pp} ratios

far less relevant except for ν, $\bar{\nu}$ differences in dimuon production

Introduction: singlet sector



sea distributions at small x determined by the gluon via RGE evolution

d/u ratio at large x sensitive to nuclear corrections and parametrizations

[CJ 2011]

strange-quark well determined from dimuon data (also HERMES, LHC)

largest and most relevant differences in the gluons and α_s values

Constraints on the gluon

Gluon only enters directly (at LO) in:

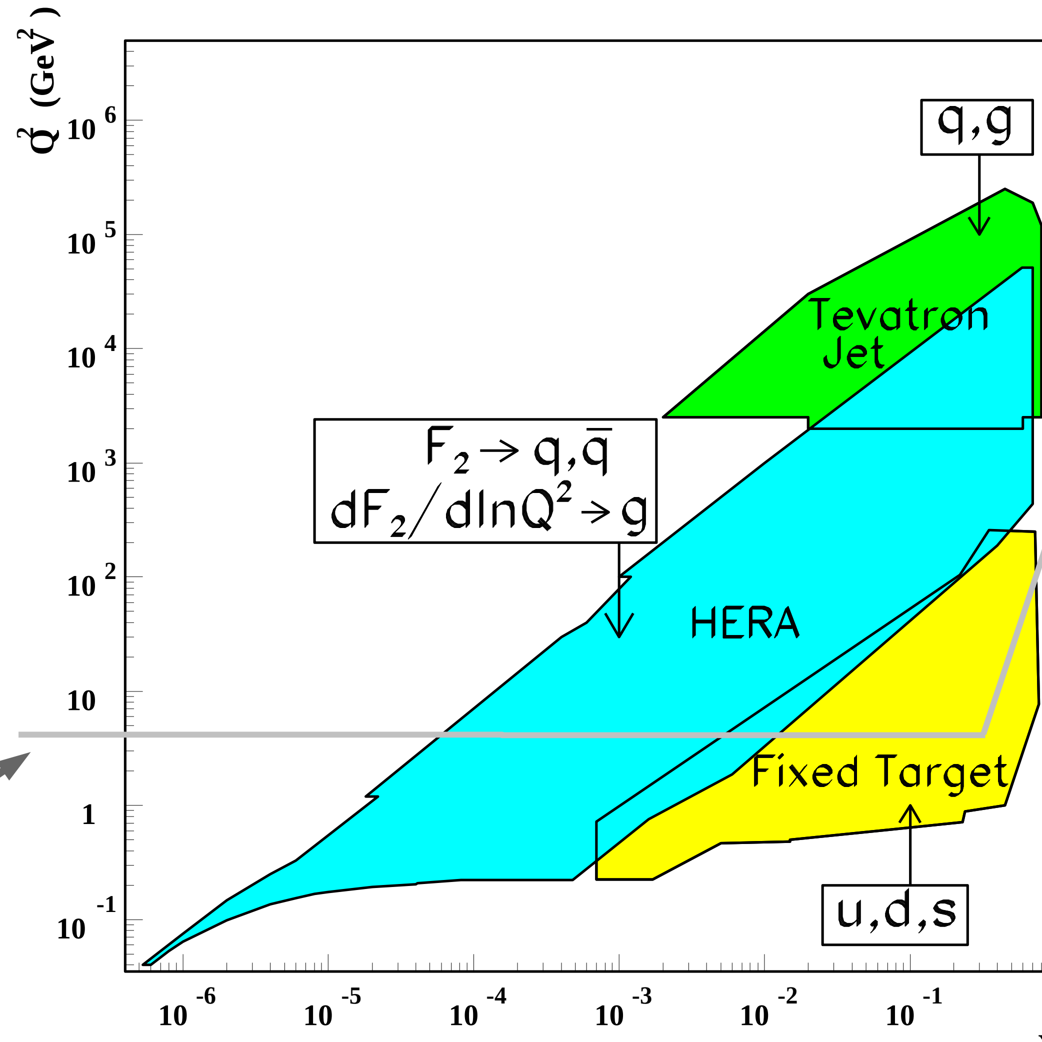
- F_L (both small and large x)
- HQ electroproduction (small x)
- Jet production (medium to large x)

But constrained via scaling violations in the small-x region

Momentum sum rule correlates small and large x

DIS data often excluded from fits:

$$Q^2 \gtrsim 4 \text{ GeV}^2, \; W^2 \gtrsim 10 \text{ GeV}^2$$



Moderate cuts lead to larger α_s , thus softer small-x gluons

[Particle Data Group]

Jet data also moderately increase α_s ; should not be used beyond NLO

(NNLO corrections are large)

Updating JR09: data selection

- Switched to HERA combined neutral-current DIS σ_r, σ_r^c

  and included charged-current

- F_2 replaced for cross-section for SLAC, BCDMS and NMC [ABM 2010]

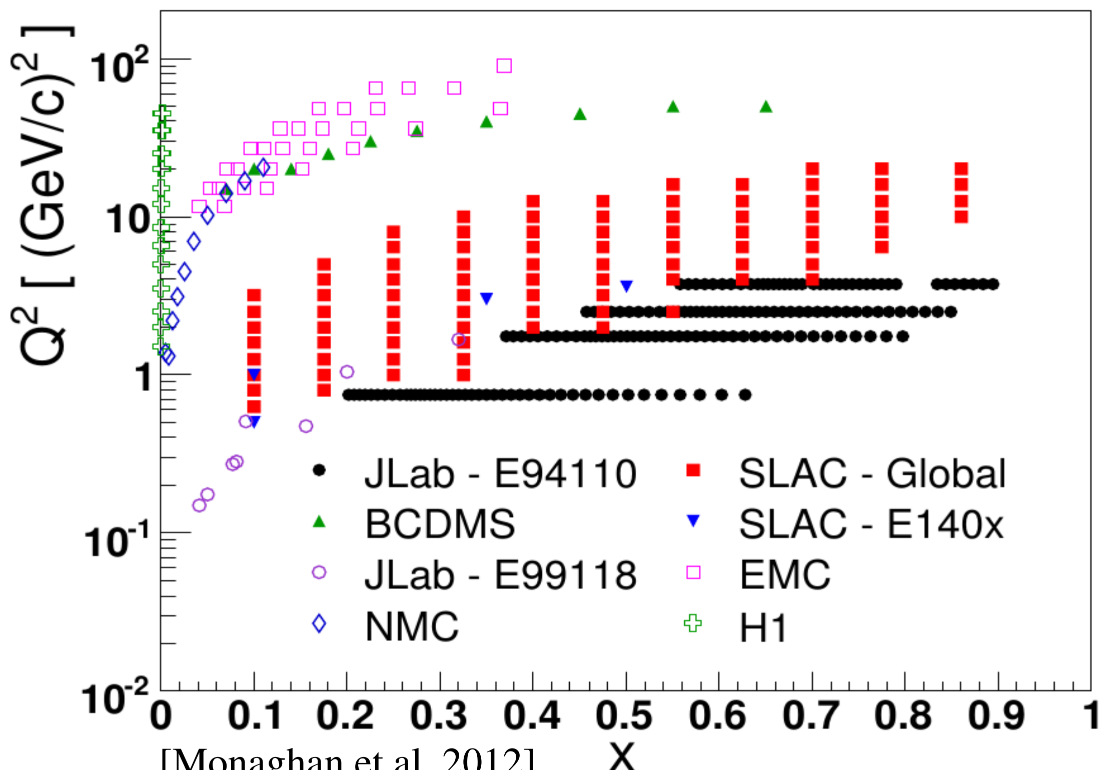
- From 30 points on *p/n* ratios to an equal-footing treatment of fixed-target data

- Dimuon data included in nominal fits

- JLab proton and deuteron data included (need lower *W* cuts)

$$Q^2 \geq 2\text{GeV}^2, W^2 \geq 3.5\text{GeV}^2$$

- Inclusion of Rosenbluth separated (F_2, F_L) data from H1, and from BCDMS, SLAC and JLab



[Monaghan et al. 2012]

Updating JR09: calculations

- Experimental correlations properly treated (also multiplicative errors)

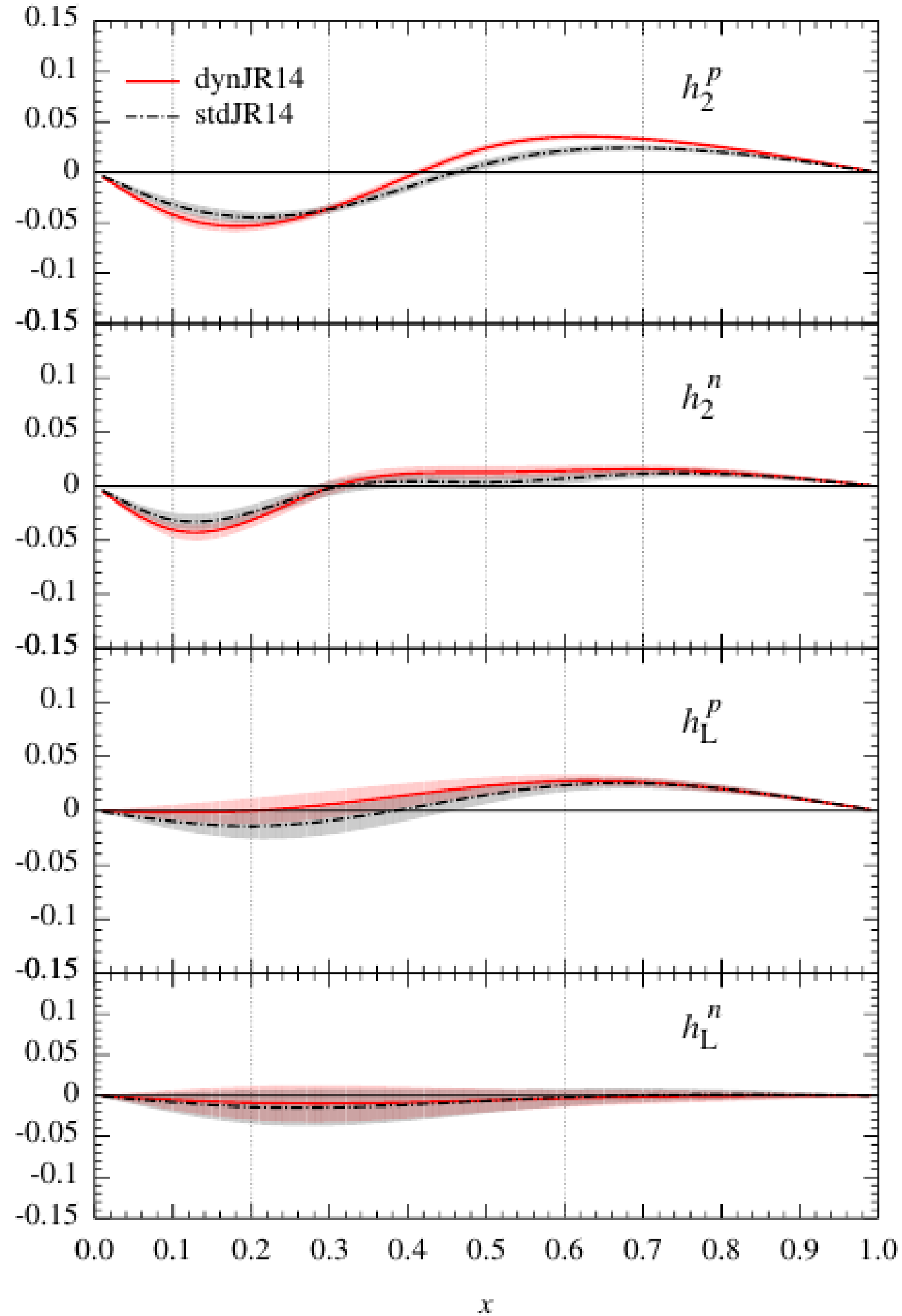
- Switched to $\overline{\mathrm{MS}}$ scheme for heavy quark masses [ABM 2010]

- Target mass corrections used also for F_L (in addition to F_2)

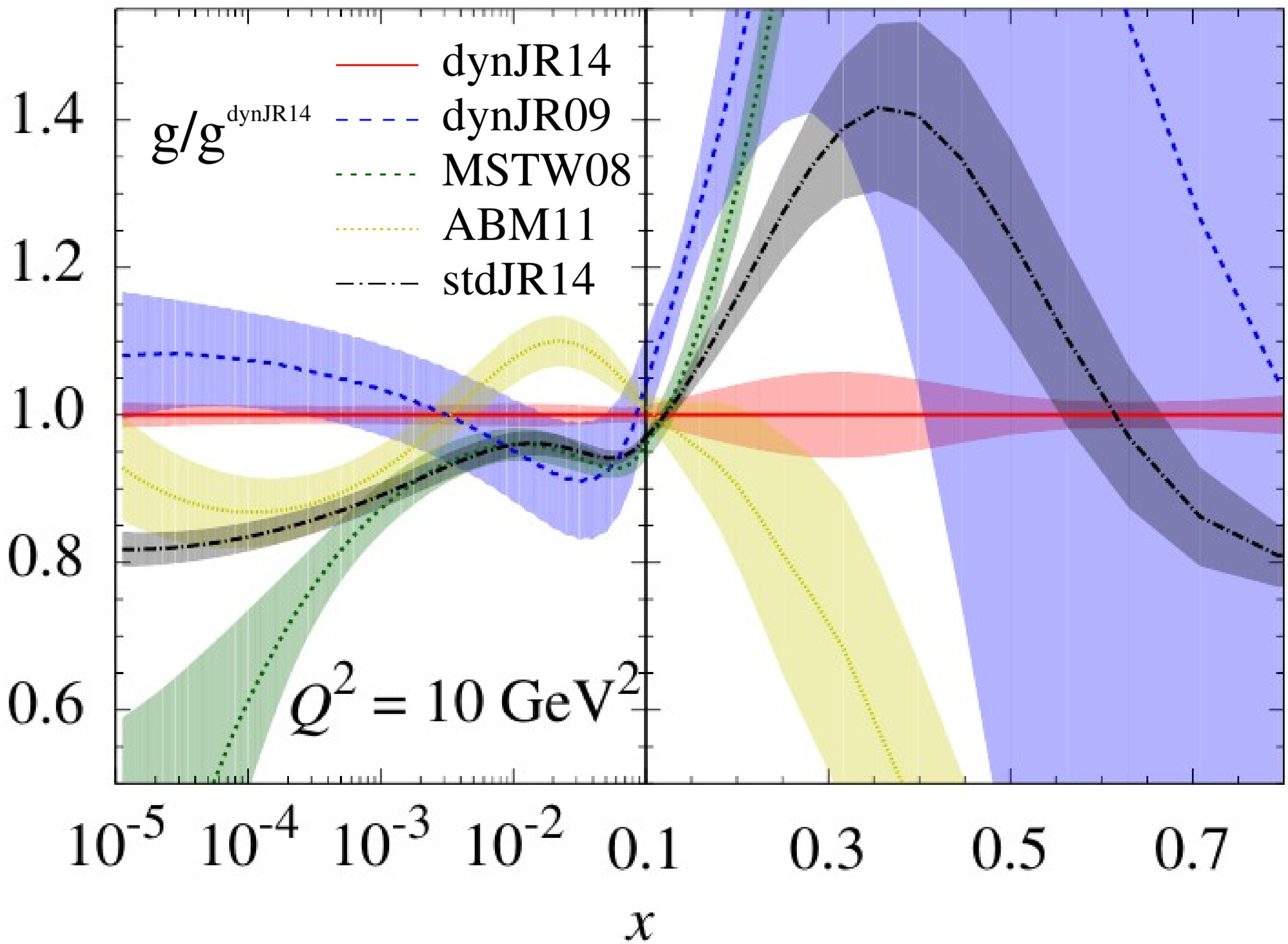
- Nuclear corrections for deuteron data [CJ 2012]

- Determination of higher-twist contributions to structure functions

$$F_{2,L}^{p,n}(x,Q^2) + \frac{h_{2,L}^{p,n}(x)}{Q^2}$$



Status of gluon distributions



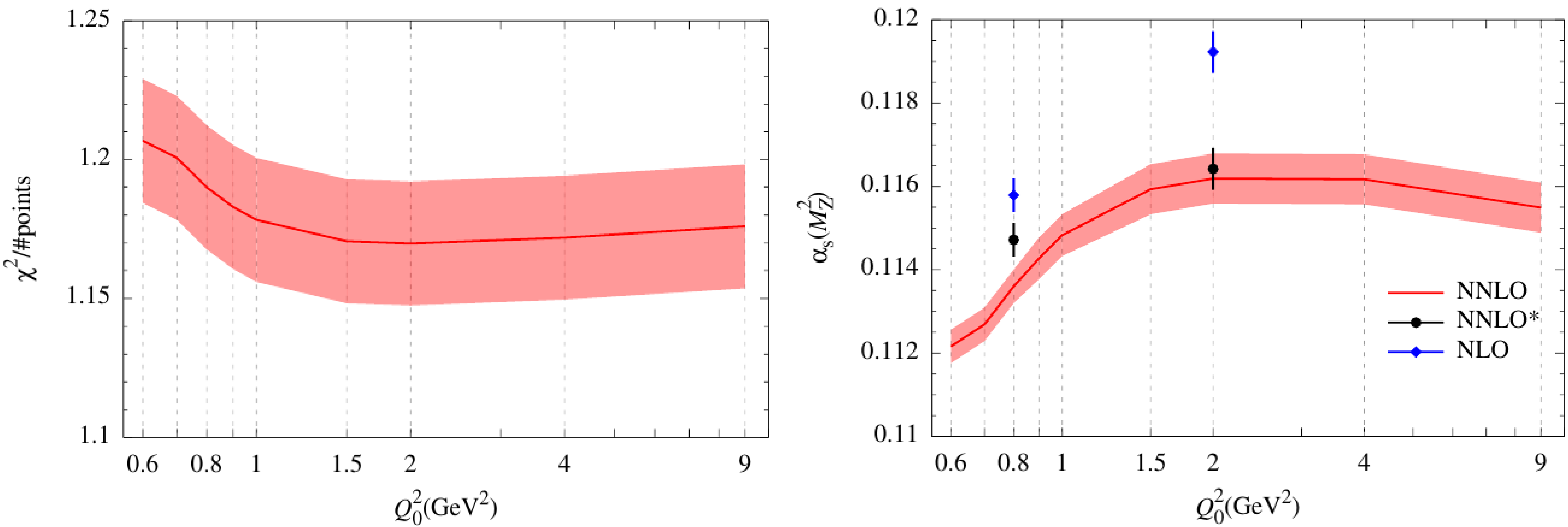
Reduced experimental uncertainties due to new constraints

Systematic (*procedural*) uncertainties become dominant

The role of the input scale in PDF analysis

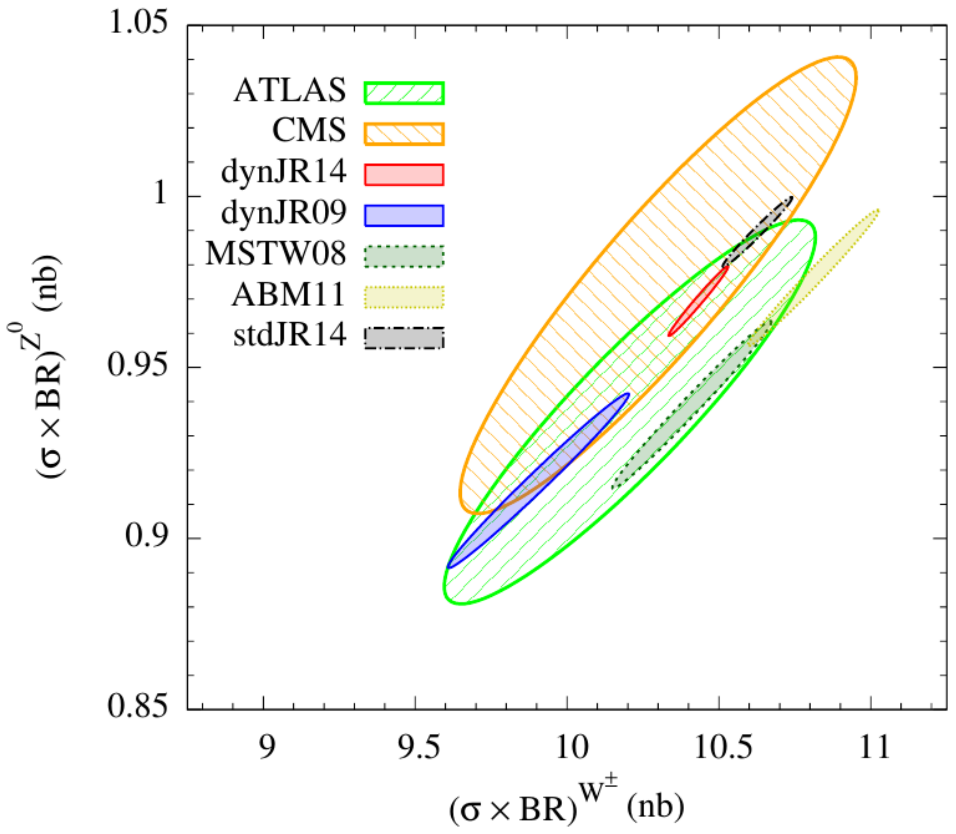
[PJD 2012]

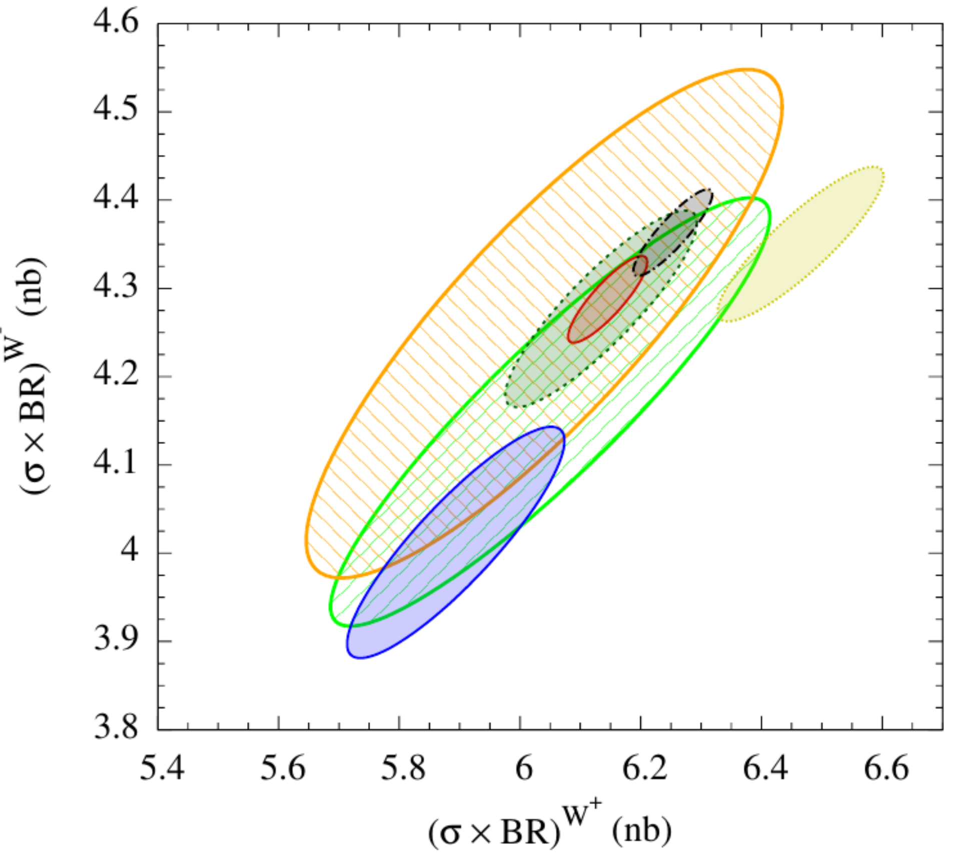
Any dependence is due to shortcomings of the estimation: *procedural bias*
(e.g. parametrization bias, backwards evolution to low scales, … rather general)



These variations can be used to estimate the procedural uncertainty
(devise a measure: e.g. in JR half the difference between dynamical and standard)

Benchmark cross-sections and other predictions





PDFs, details of the fits (correlations, eigenvectors, etc.), predictions for structure functions, LHC cross-sections, etc., available:

`http://users.hepforge.org/~pjimenezdelgado`

...and polarized PDFs: JAM

PJD, H. Avakian, W. Melnitchouk, arXiv:1403.3355

PJD, A. Accardi, W. Melnitchouk, *Phys. Rev.* **D89** (2014) 034025

The JAM collaboration

www.jlab.org/jam

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About JAM

The **JAM (Jefferson Lab Angular Momentum)** Collaboration is an enterprise involving theorists and experimentalists from the Jefferson Lab community to study the quark and gluon spin structure of the nucleon by performing global fits of spin-dependent parton distribution functions (PDFs).

Because of the unique capabilities of Jefferson Lab's CEBAF accelerator in measuring small cross sections at extreme kinematics, the JAM spin PDFs are particularly tailored for studies of the **large Bjorken-*x*** region, as well as the resonance-deep inelastic transition region at low and intermediate values of W and Q^2.

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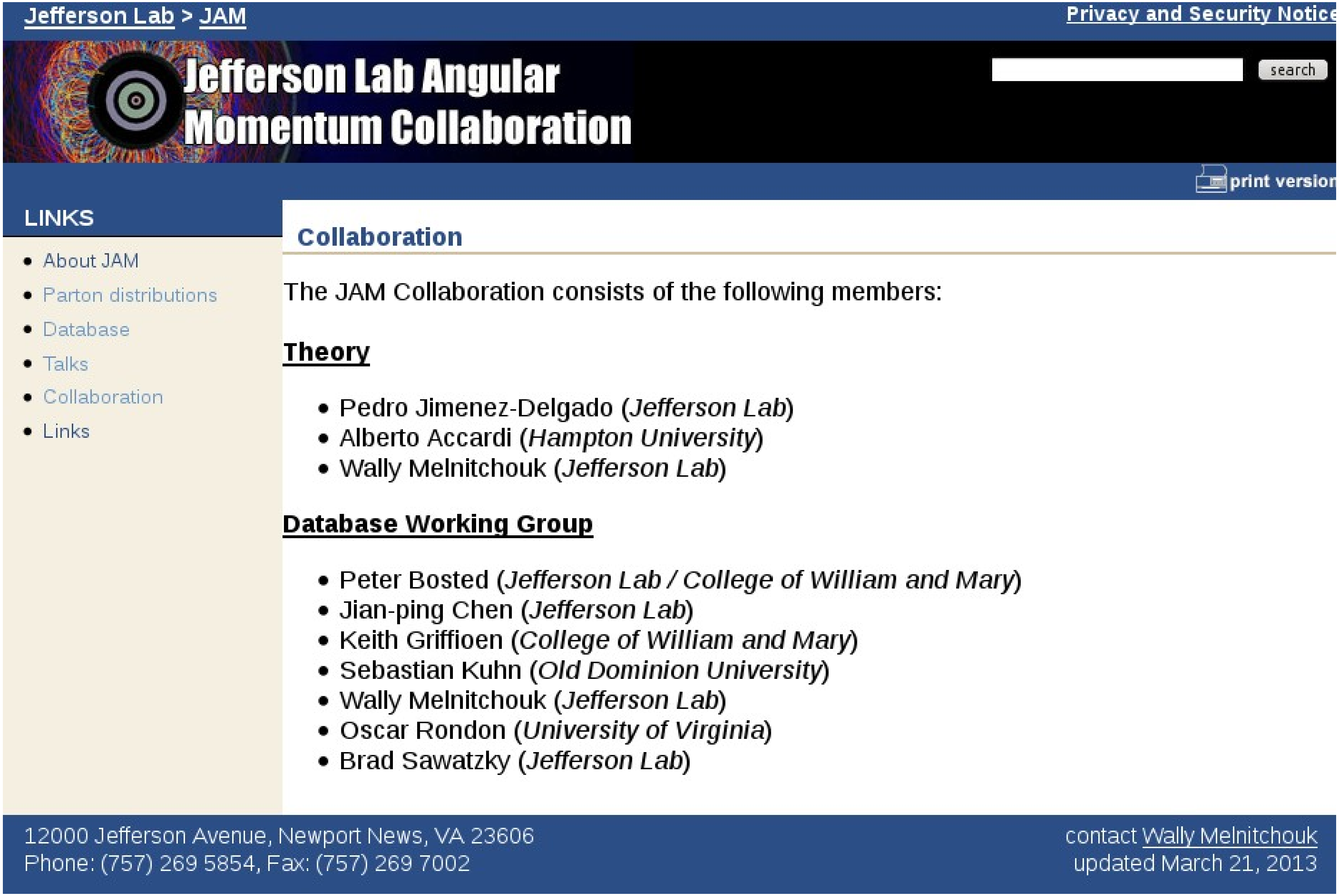
contact Wally Melnitchouk
updated March 21, 2013

Parallel effort to our unpolarized PDFs: CJ and JR

The JAM collaboration

www.jlab.org/jam



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Collaboration

The JAM Collaboration consists of the following members:

Theory

- Pedro Jimenez-Delgado (*Jefferson Lab*)
- Alberto Accardi (*Hampton University*)
- Wally Melnitchouk (*Jefferson Lab*)

Database Working Group

- Peter Bosted (*Jefferson Lab / College of William and Mary*)
- Jian-ping Chen (*Jefferson Lab*)
- Keith Griffioen (*College of William and Mary*)
- Sebastian Kuhn (*Old Dominion University*)
- Wally Melnitchouk (*Jefferson Lab*)
- Oscar Rondon (*University of Virginia*)
- Brad Sawatzky (*Jefferson Lab*)

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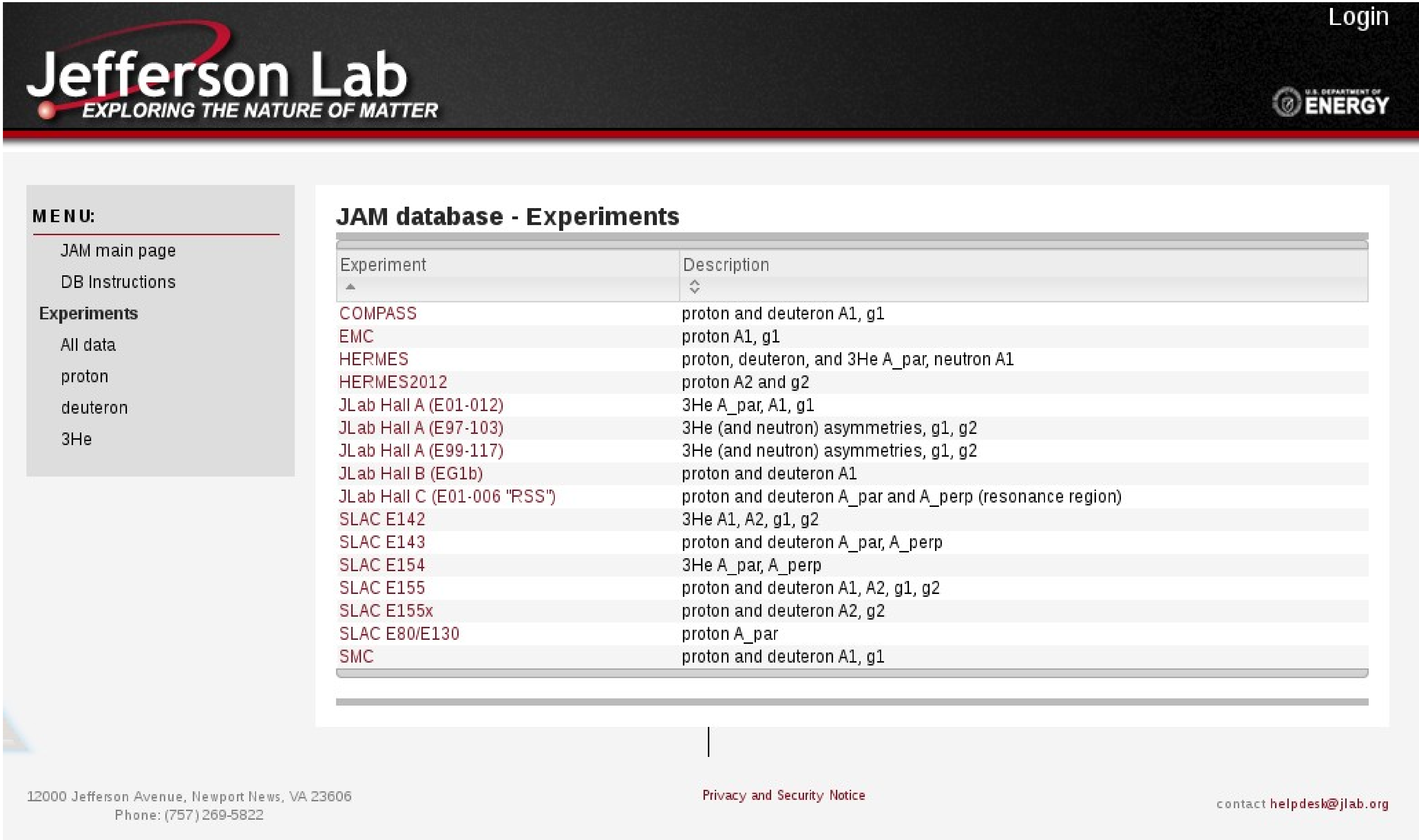
contact Wally Melnitchouk
updated March 21, 2013

to start with, open to further contributions

The JAM database

Public database with all data on polarized scattering experiments



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  - All data
  - proton
  - deuteron
  - 3He

JAM database - Experiments

Experiment	Description
COMPASS	proton and deuteron A1, g1
EMC	proton A1, g1
HERMES	proton, deuteron, and 3He A_par, neutron A1
HERMES2012	proton A2 and g2
JLab Hall A (E01-012)	3He A_par, A1, g1
JLab Hall A (E97-103)	3He (and neutron) asymmetries, g1, g2
JLab Hall A (E99-117)	3He (and neutron) asymmetries, g1, g2
JLab Hall B (EG1b)	proton and deuteron A1
JLab Hall C (E01-006 "RSS")	proton and deuteron A_par and A_perp (resonance region)
SLAC E142	3He A1, A2, g1, g2
SLAC E143	proton and deuteron A_par, A_perp
SLAC E154	3He A_par, A_perp
SLAC E155	proton and deuteron A1, A2, g1, g2
SLAC E155x	proton and deuteron A2, g2
SLAC E80/E130	proton A_par
SMC	proton and deuteron A1, g1

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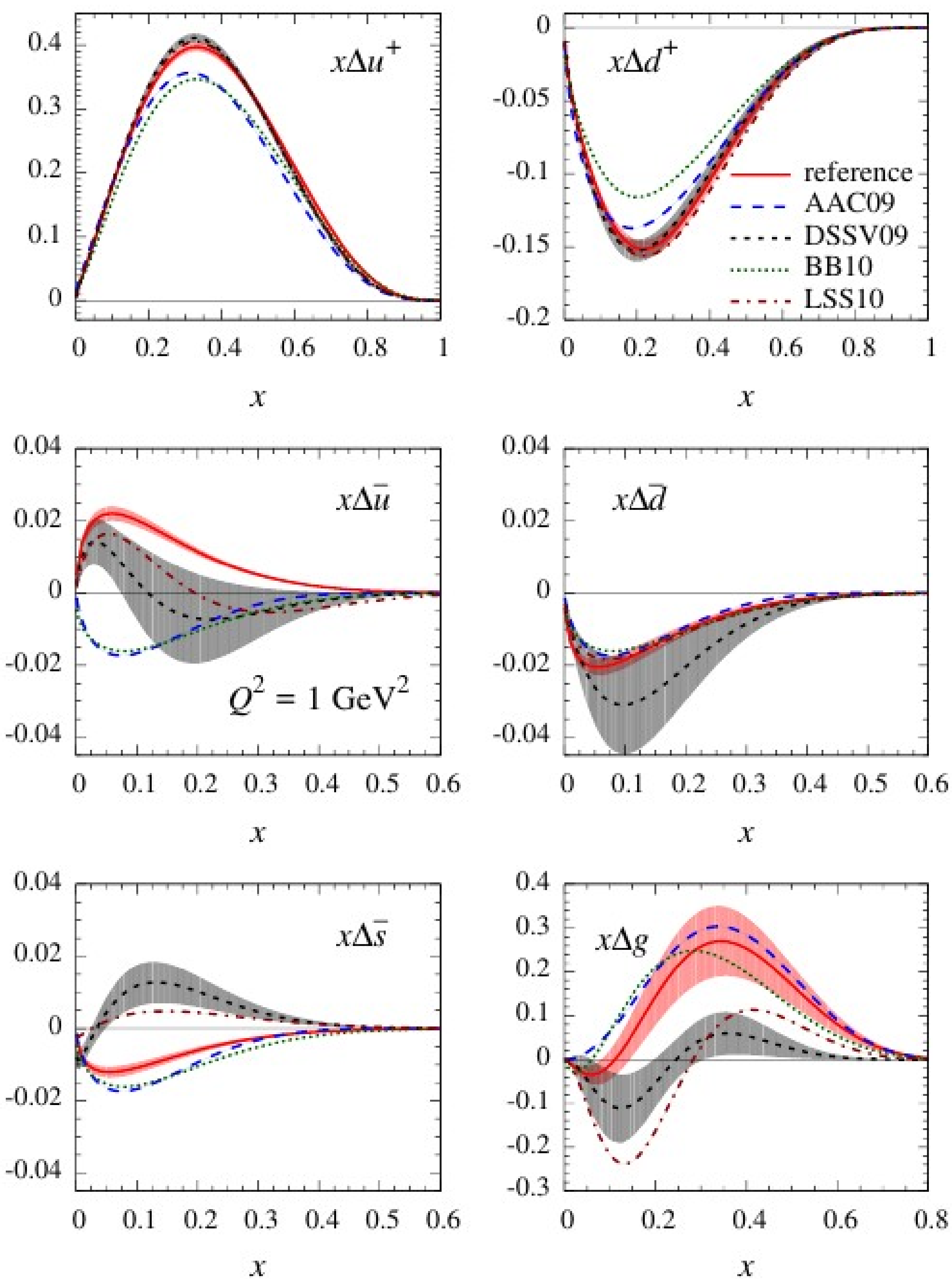
Current status of polarized PDFs



Worse known than the unpolarized

$\Delta u^+ = \Delta u + \Delta\bar{u}$ and

$\Delta d^+ = \Delta d + \Delta\bar{d}$ better known

Sea distributions $\Delta\bar{u},\ \Delta\bar{d}$

do not enter in DIS asymmetries

Δg less known, determined mainly from RHIC data (also COMPASS)

Data considered at this (first) stage

World data on polarized DIS (for $Q^2 \geq 1\ \mathrm{GeV}^2$, $W^2 \geq 3.5\ \mathrm{GeV}^2$)

experiment	reference	observable	target	N_{data}	$\chi^2(\mathrm{LT})/N_{\mathrm{dat}}$	$\chi^2(\mathrm{JAM})/N_{\mathrm{dat}}$
EMC	[1]	A_1	p	10	0.42	0.39
SMC	[29]	A_1	p	12	0.36	0.36
	[29]	A_1	d	12	1.59	1.66
	[30]	A_1	p	8	1.37	1.35
	[30]	A_1	d	8	0.54	0.56
COMPASS	[31]	A_1	p	15	0.95	0.97
	[32]	A_1	d	15	0.57	0.51
SLAC E80/E130	[33]	$A_\parallel$	p	23	0.52	0.54
SLAC E142	[34]	A_1	^{3}He	8	0.58	0.70
	[34]	A_2	^{3}He	8	0.70	0.70
SLAC E143	[35]	$A_\parallel$	p	85	0.85	0.81
	[35]	$A_\perp$	p	48	0.95	0.91
	[35]	$A_\parallel$	d	85	1.05	0.85
	[35]	$A_\perp$	d	48	0.92	0.91
SLAC E154	[36]	$A_\parallel$	^{3}He	18	0.43	0.42
	[36]	$A_\perp$	^{3}He	18	1.00	1.00
SLAC E155	[37]	$A_\parallel$	p	73	1.00	0.92
	[37, 38]	$A_\perp$	p	66	1.00	0.96
	[39]	$A_\parallel$	d	73	0.98	0.97
	[38, 39]	$A_\perp$	d	66	1.51	1.49
SLAC E155x	[40]	$\tilde{A}_\perp$	p	117	2.17	1.64
	[40]	$\tilde{A}_\perp$	d	117	0.90	0.84
HERMES	[41]	$A_\parallel$	p	37	0.38	0.39
	[41]	$A_\parallel$	d	37	0.86	0.85
	[42]	A_1	"n"	9	0.29	0.30
	[43]	A_2	p	20	1.07	1.16
JLab E99-117	[44]	$A_\parallel$	^{3}He	3	0.62	0.06
	[44]	$A_\perp$	^{3}He	3	1.08	0.87
COMPASS	[48]	$\Delta g/g$	p	1	5.27	2.71
total				1043	1.07	0.98
JLab E97-103*	[45]	$A_\parallel$	^{3}He	2	—	—
	[45]	$A_\perp$	^{3}He	2	—	—
JLab EG1b*	[47]	A_1	p	766	—	—
(prelim.)	[47]	A_1	d	767	—	—

Mainly on *measured* asymmetries:

$$A_\parallel = D(A_1 + \eta A_2)$$

$$A_\perp = d(A_2 - \xi A_1)$$

D, d depend on

$$R = \frac{F_L}{(1+\gamma^2)F_2 - F_L}$$

$$\gamma^2 = 4\frac{M^2}{Q^2}x^2$$

We *consistently* develop our own unpolarized analysis in parallel (JR NLO)

Dedicated analyses of the impact of *individual* data sets from JLab

Parametrization

Only *two* independent combinations of quark distributions contribute:

$$x\Delta u^+(x,Q_0^2) = N_u\, x^{a_u}(1-x)^{b_u}(1+A_u\sqrt{x}+B_u\, x) \qquad \Delta q^+ \equiv \Delta q + \Delta\bar{q}$$

$$x\Delta d^+(x,Q_0^2) = N_d\, x^{a_d}(1-x)^{b_d}(1+A_d\sqrt{x}+B_d\, x) \qquad Q_0^2 = 1\ \mathrm{GeV}^2$$

Constrains from hyperon decays relate N_u and N_d, and fix N_s :

$$\int_0^1 (\Delta u^+ - \Delta d^+)dx = 1.269 \pm 0.003 \qquad \int_0^1 (\Delta u^+ + \Delta d^+ - 2\Delta s^+)dx = 0.586 \pm 0.031$$

The *x*-dependence of the sea has been fixed by counting rule and imposing:

$$\lim_{x\to 0} \Delta\bar{q}(x,Q_0^2) = \frac{1}{2}\lim_{x\to 0} \Delta q^+(x,Q_0^2) \qquad \frac{1}{2}\left(\left|\frac{\Delta\bar{q}^{(2)}}{\Delta\bar{s}^{(2)}}\right| + \left|\frac{\Delta\bar{s}^{(2)}}{\Delta\bar{q}^{(2)}}\right|\right) = 1 \pm 0.25$$

For the gluon we leave N_g and B_g as free parameters

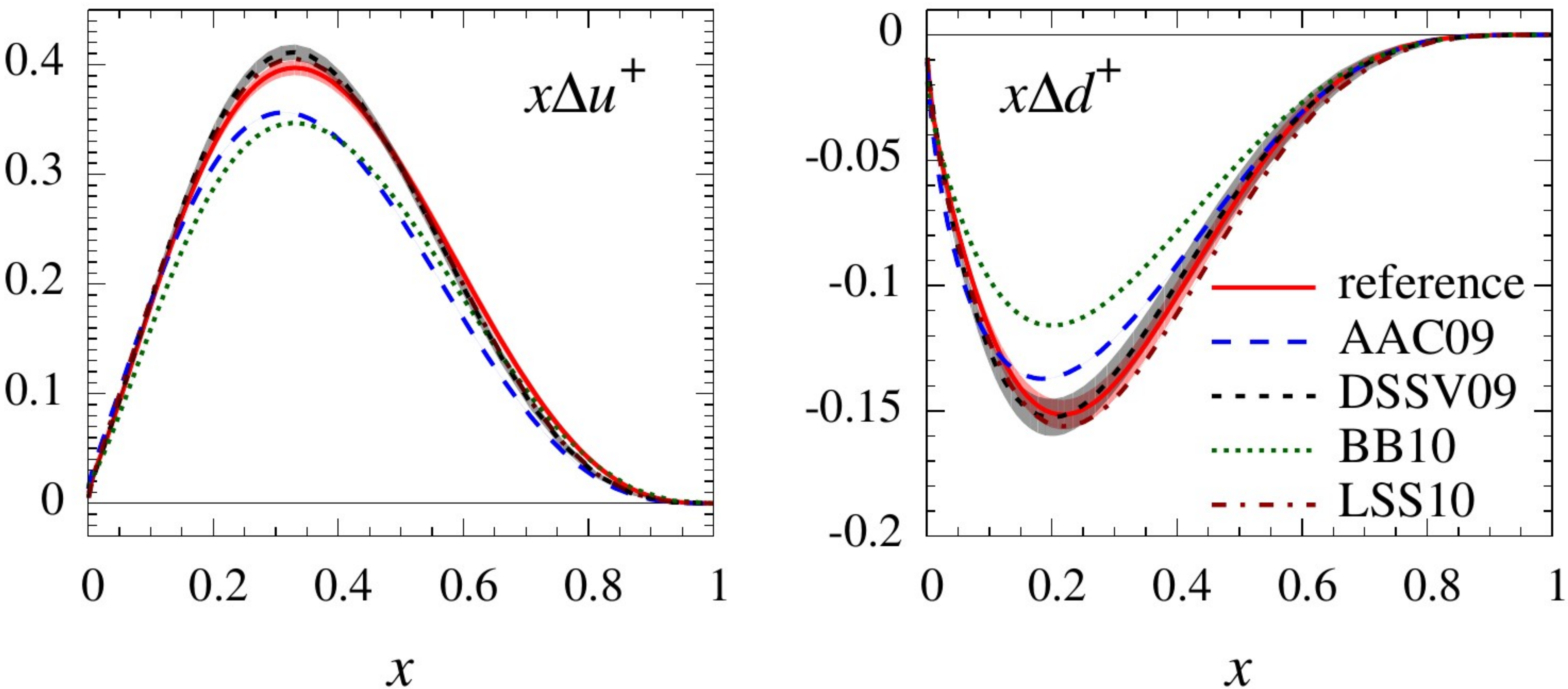
Goal is to asses the impact of improvements in DIS description (corrections)

Nominally 13 (LT) + 14 (HT) = 27 parameters to be determined

Simple fit without further corrections: reference

Nuclear targets treated with the "effective polarization" approximation:

$$g_1^d = (1 - \tfrac{3}{2} w_d)(g_1^p + g_1^n) \qquad g_1^{\mathrm{He3}} = P_n\, g_1^n + P_p\, g_1^p$$



More similar to DSSV, LSS than to others

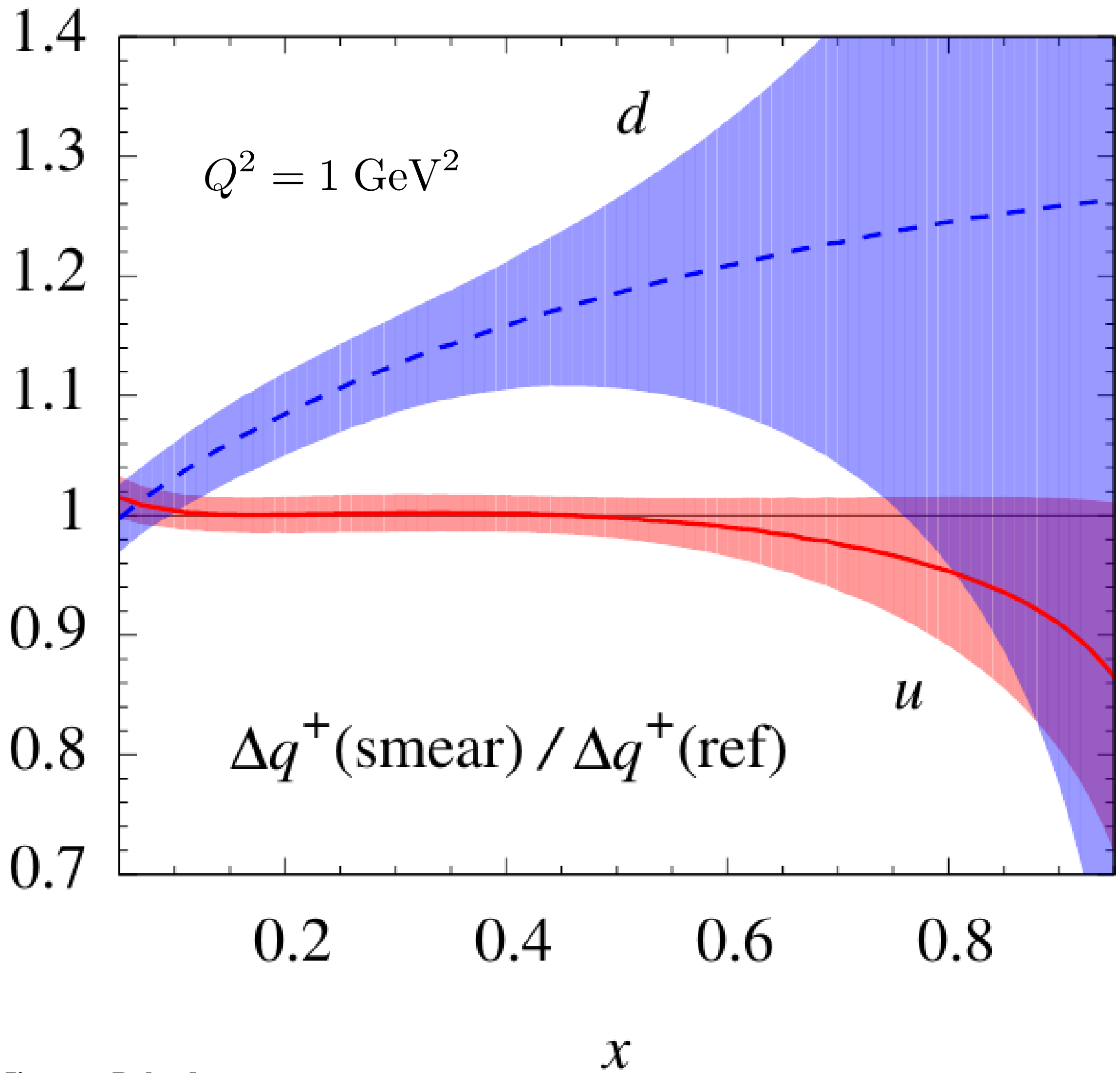
Baseline for assessing the impact of additional corrections

Improved description of nuclear targets

Improved by using "smearing functions" derived from nuclear wave functions:

$$g_i^A(x) = \sum_{j=1,2} \int \frac{dy}{y}\, f_{jN}(y,\gamma)\, g_j^N\left(\frac{x}{y}\right) \qquad \gamma^2 = 1 + 4\frac{M^2}{Q^2}x^2$$

[Kulagin, Petti 06]



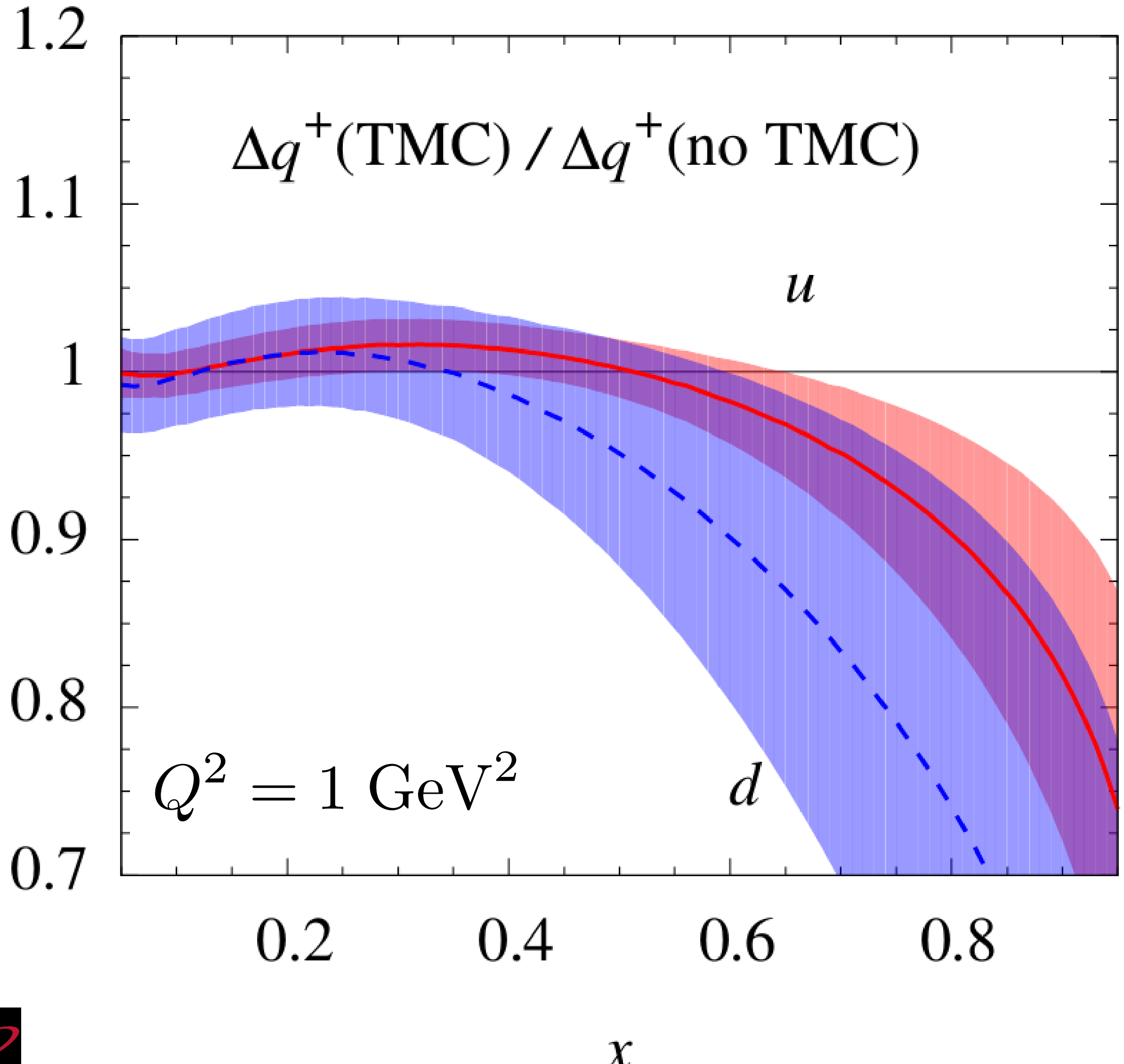
Most relevant for Δd in the medium- and large-x region

Target-mass corrections

We use power corrections from finite target mass calculated in the OPE approach:

$$g_1^{\mathrm{TMC}}(n) = g_1(n) + \frac{M^2}{Q^2}\frac{n^2(n+1)}{(n+2)^2}g_1(n+2) + \frac{M^4}{Q^4}\ldots + \mathcal{O}(\frac{M^8}{Q^8})$$

[Bluemlein, Tkabladze 99]



Relevant for both Δu and Δd in the large-x region

Both TMC and nuclear corrections *should* be included in global fits

Higher twist contributions

We consider also corrections from higher twist contributions:

$$g_1 = g_1^{\tau=2} + g_1^{\tau=3} + g_1^{\tau=4}$$

[Wandzura, Wilczek 77]

$$g_2 = g_2^{\tau=2} + g_2^{\tau=3}$$

$$g_2^{\tau=2}(n, Q^2) = g_2^{WW} = -\frac{n-1}{n} g_1^{\tau=2}(n, Q^2)$$

The Bluemlein-Tkabladze relation: $$g_1^{\tau=3}(x, Q^2) = 4x^2 \frac{M^2}{Q^2} \left(g_2^{\tau=3}(x, Q^2) - 2 \int_x^1 \frac{dy}{y} g_2^{\tau=3}(y, Q^2) \right)$$

[Bluemlein, Tkabladze 99]

With a phenomenological parametrization :

$$g_2^{\tau=3} = A[\ln x + (1-x) + \tfrac{1}{2}(1-x)^2] + (1-x)^3[B + C(1-x) + D(1-x)^2 + E(1-x)^3]$$

[Braun *et al.* 09]

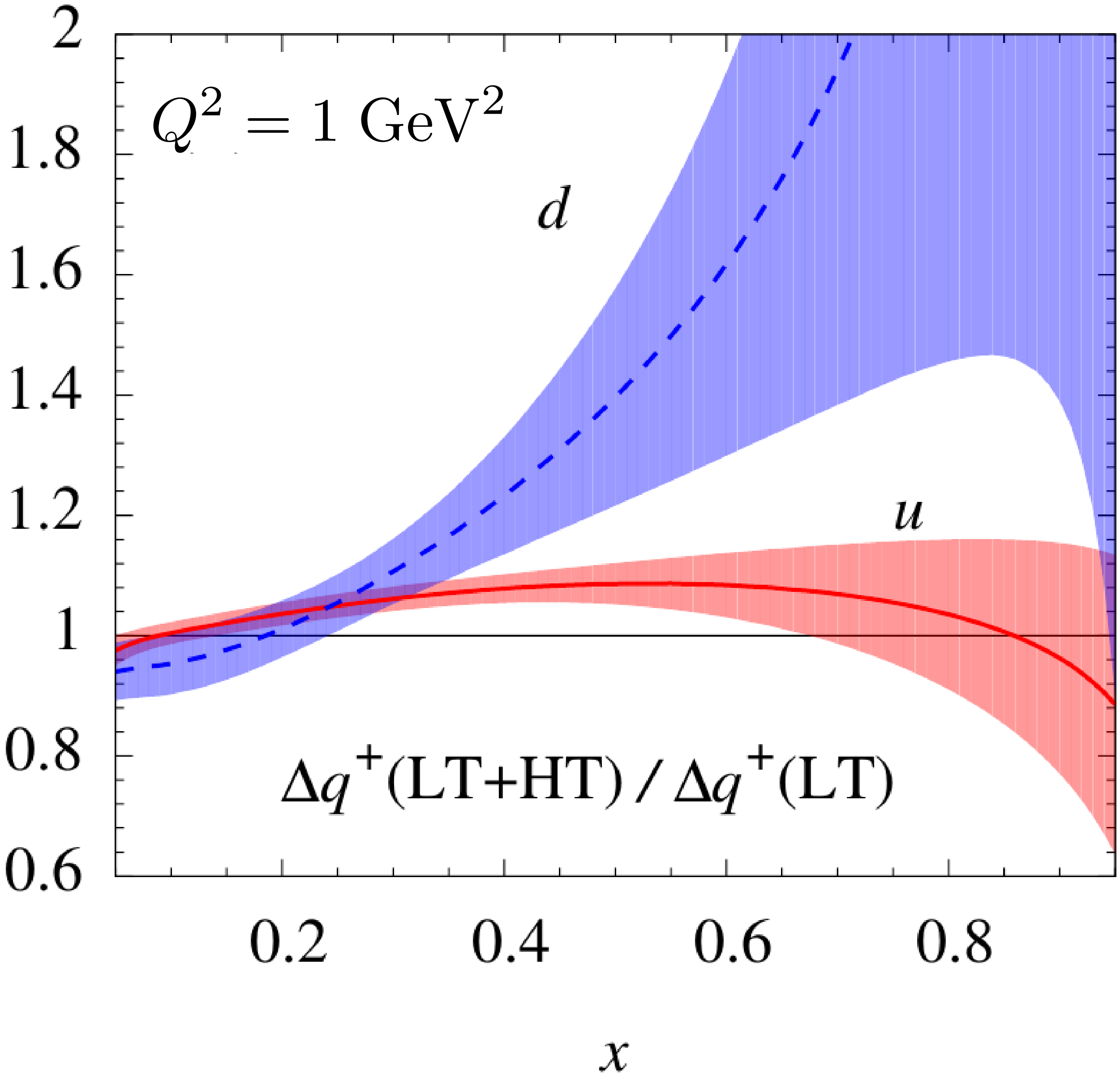
And a splines approximation for: $$g_1^{\tau=4} = \frac{h(x)}{Q^2}$$

$$\int_0^1 dx\, g_2^{\tau=3} = 0$$

Possible scale dependence in h and $g_2^{\tau=3}$ have been neglected

Higher twist contributions

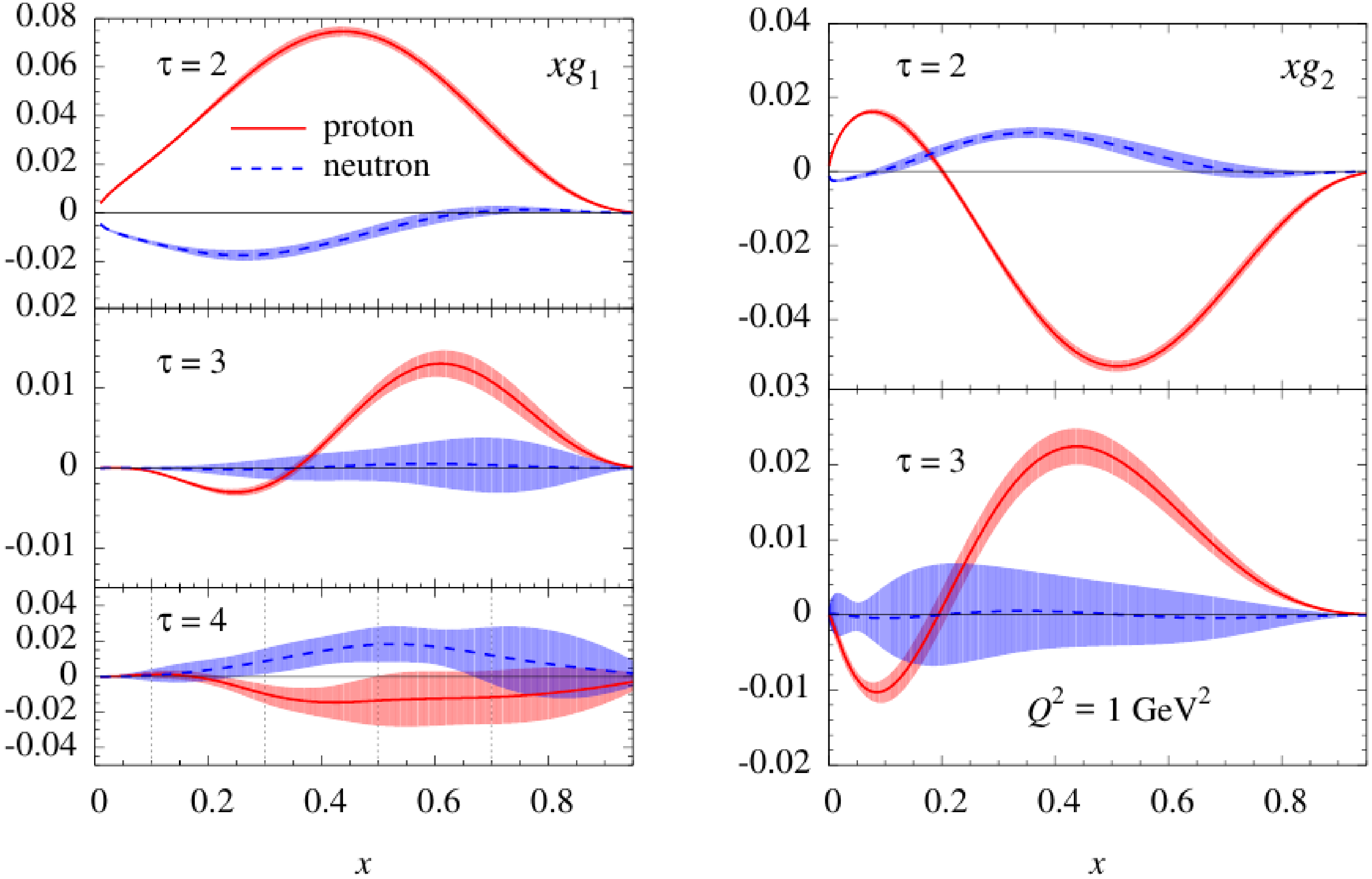
Considerable improvement of χ^2 for some sets (globally $1.07 \to 0.98\,,\ 3\sigma$)



Very large changes in Δd

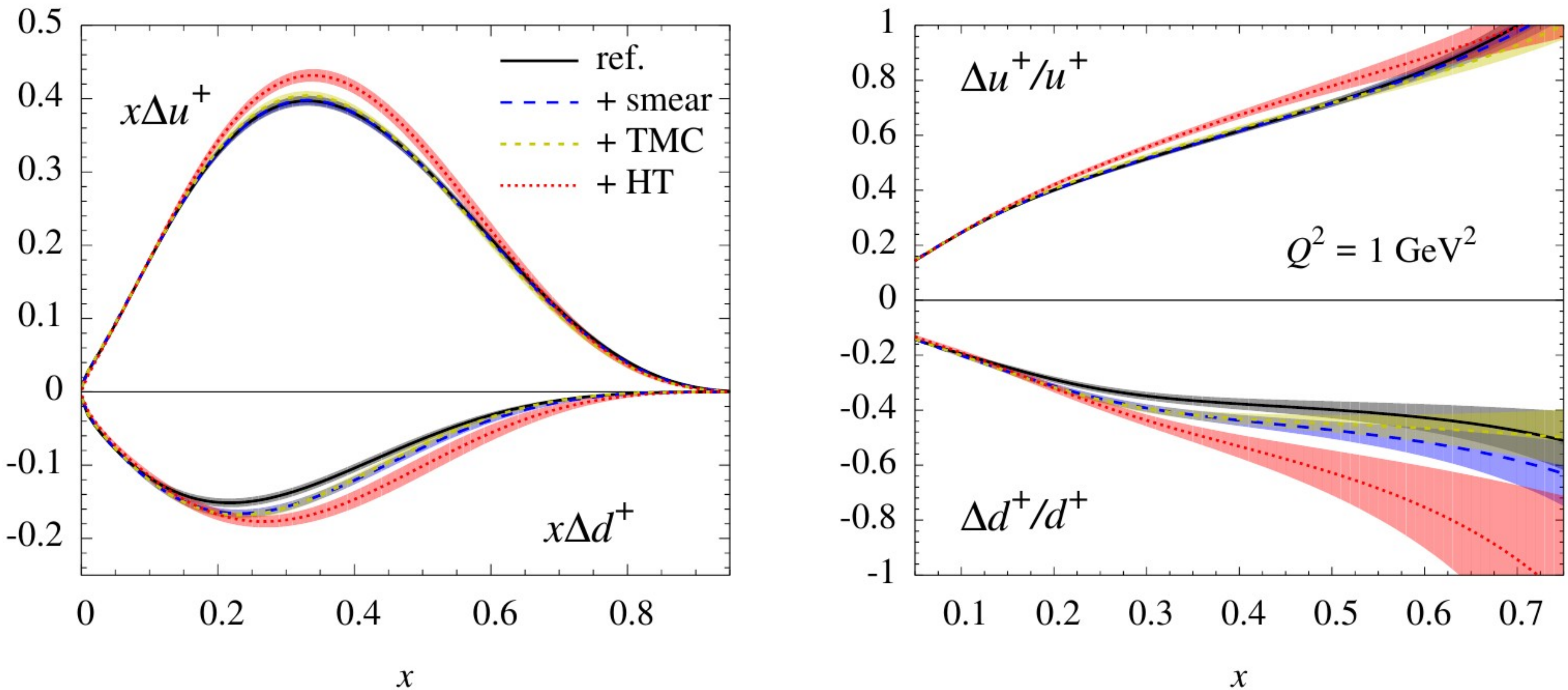
Higher twist contributions

It is possible to determine *simultaneously* higher-twist contributions for g_1 and g_2



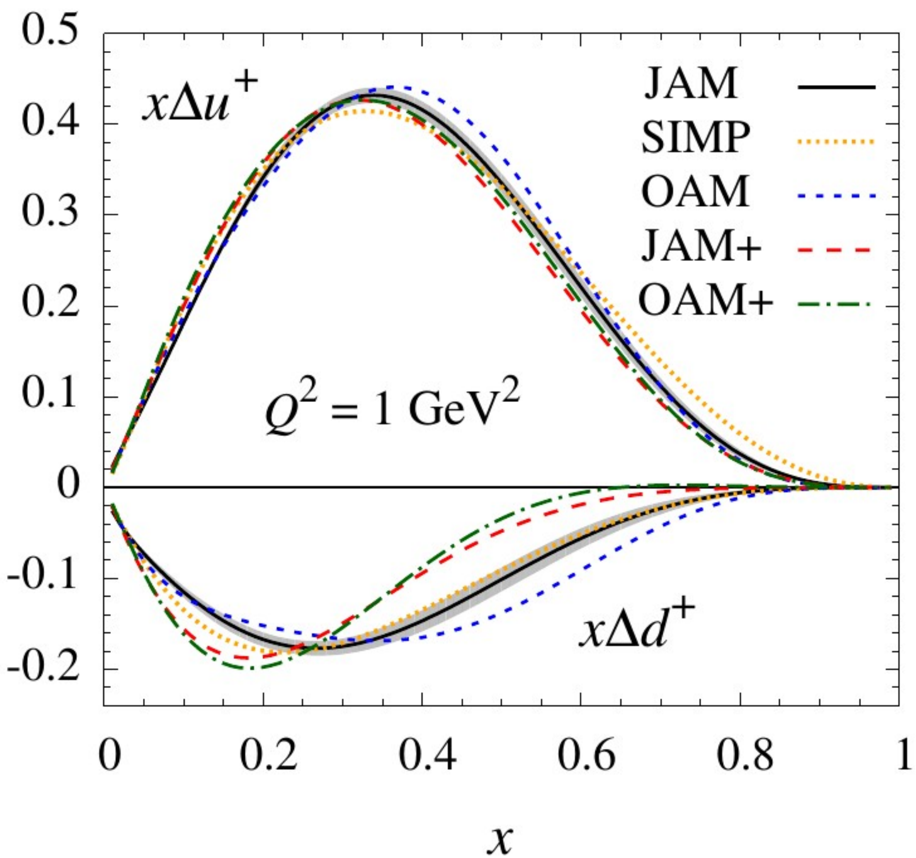
Qualitative agreement with previous (separated) determinations

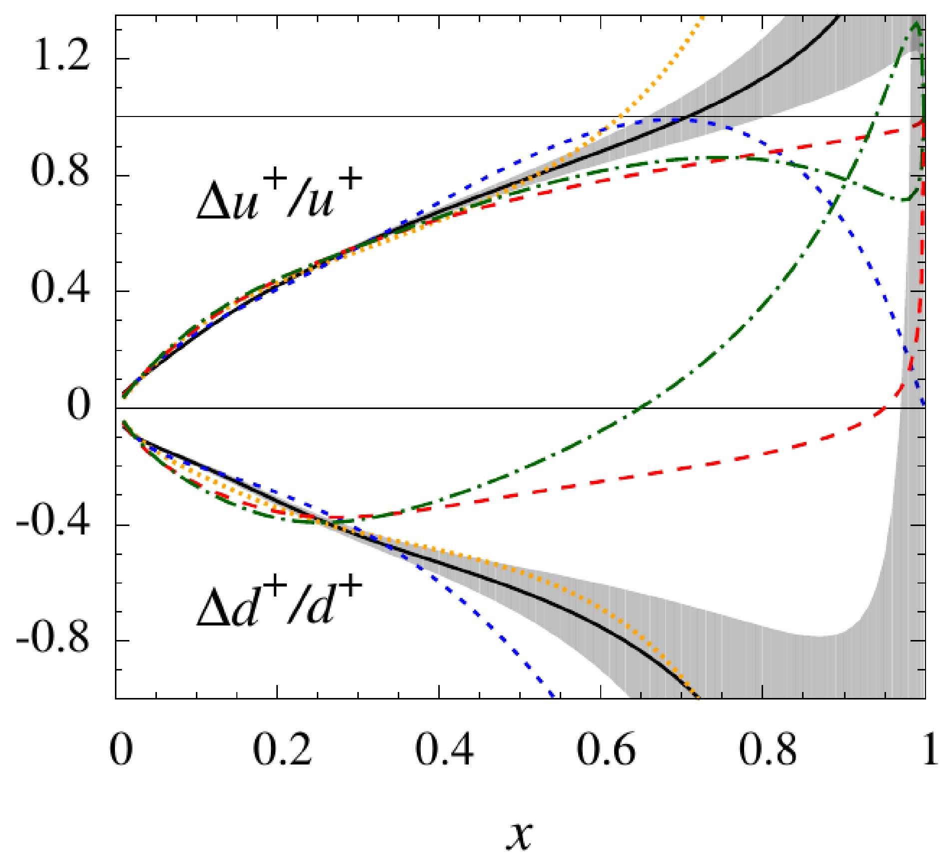
Including all these corrections



This corrections are *manifestly important* for PDF extractions

Constraints at large x

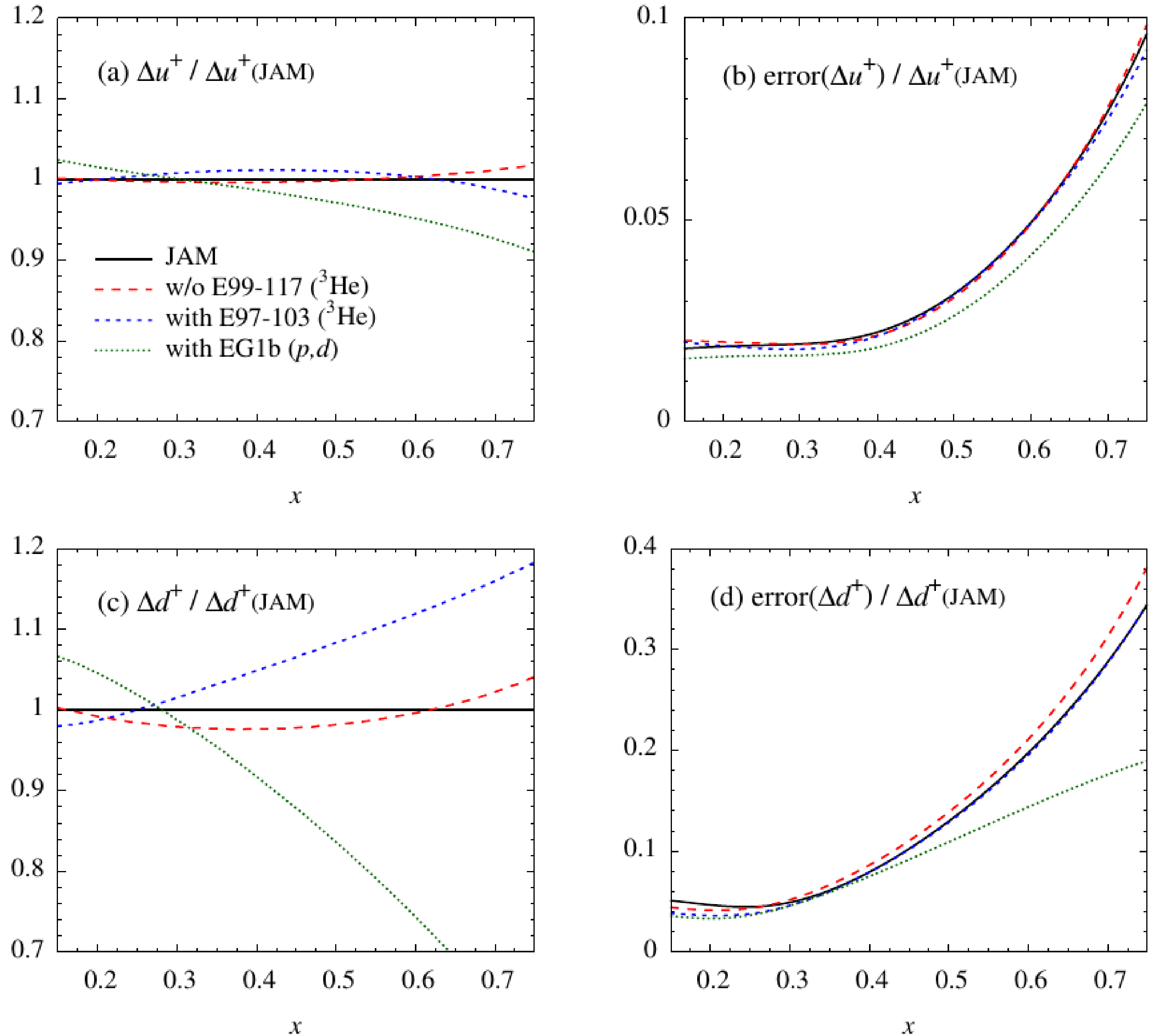




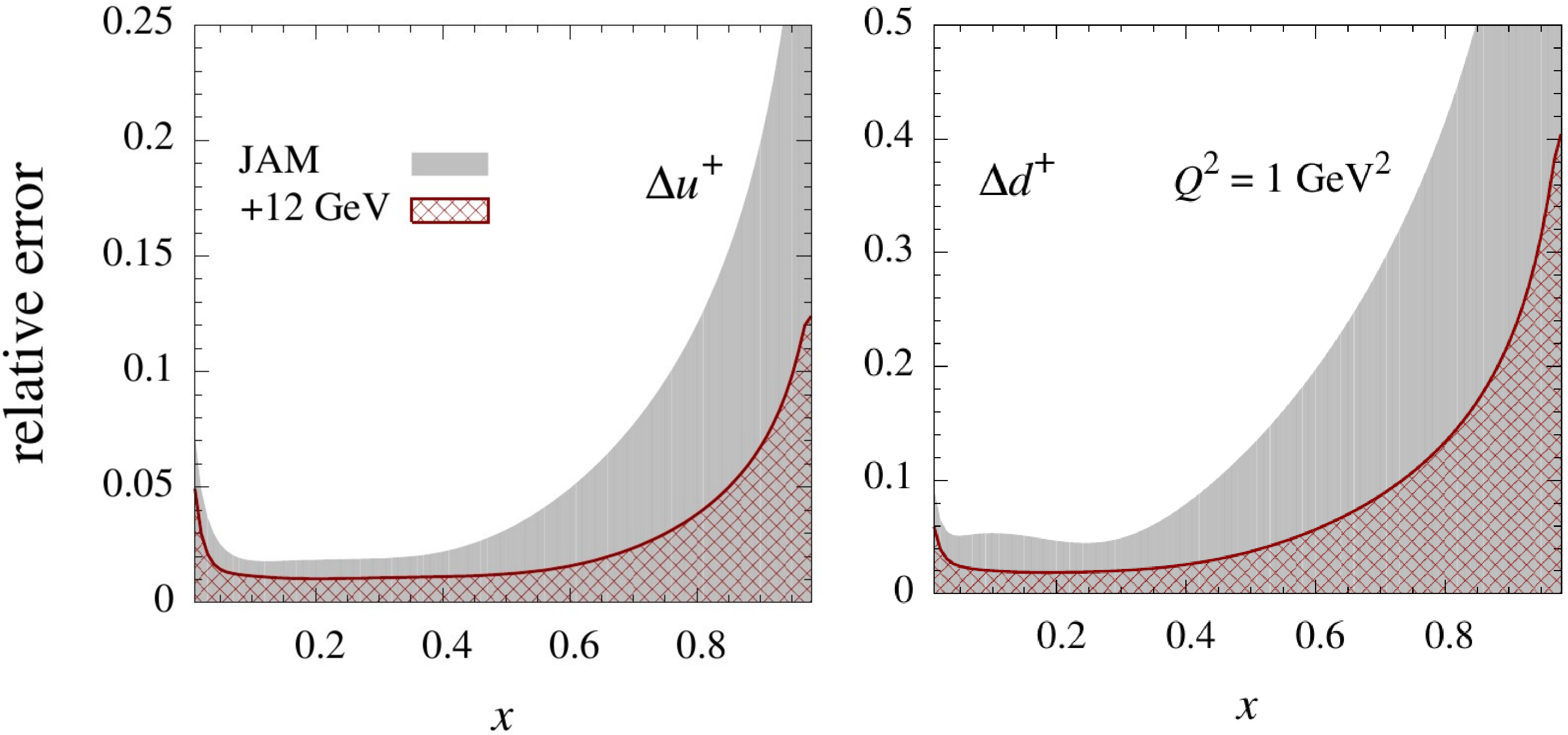
Current data can be accommodated by a range of large-x behaviors

Systematic uncertainties should be considered, and more data needed ...

Impact of JLab data



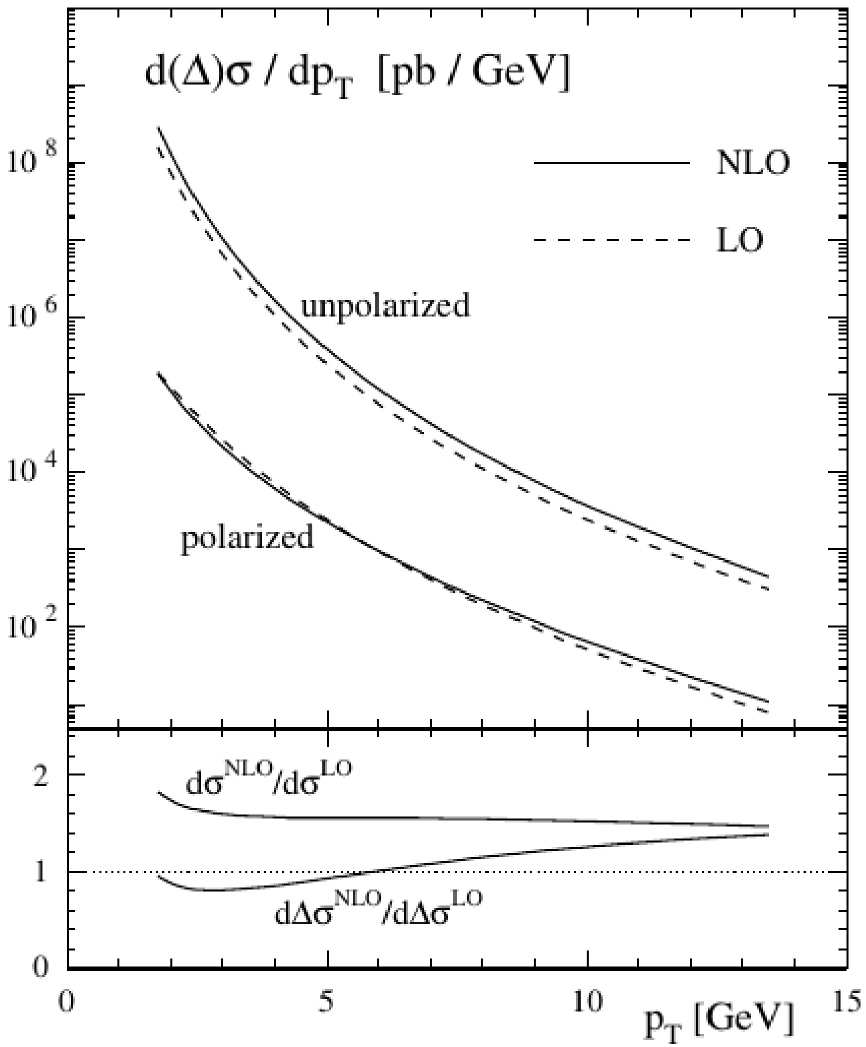
Impact of JLab 12 data



70% reduction of experimental uncertainty for $0.6 \leq x \leq 0.8$

Moving forwards: including RHIC data

High p_T pion production at RHIC: $pp \to \pi^0 X$



[B. Jäger *et al.*, PRD67 (2003) 054005]

$$A_{LL}^{\pi} = \frac{d\Delta\sigma}{d\sigma} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}}$$

We use scaled LO (K-factors):

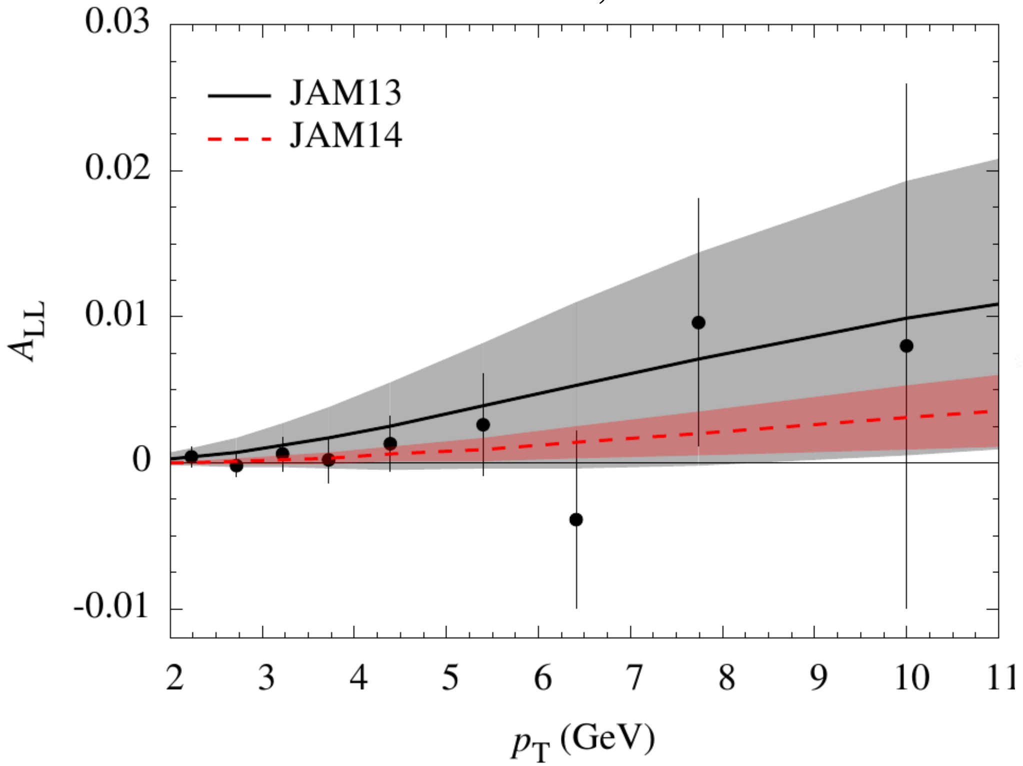
$$d\Delta\sigma^{NLO} = 1 \times d\Delta\sigma^{LO}$$

$$d\sigma^{NLO} = 1.5 \times d\sigma^{LO}$$

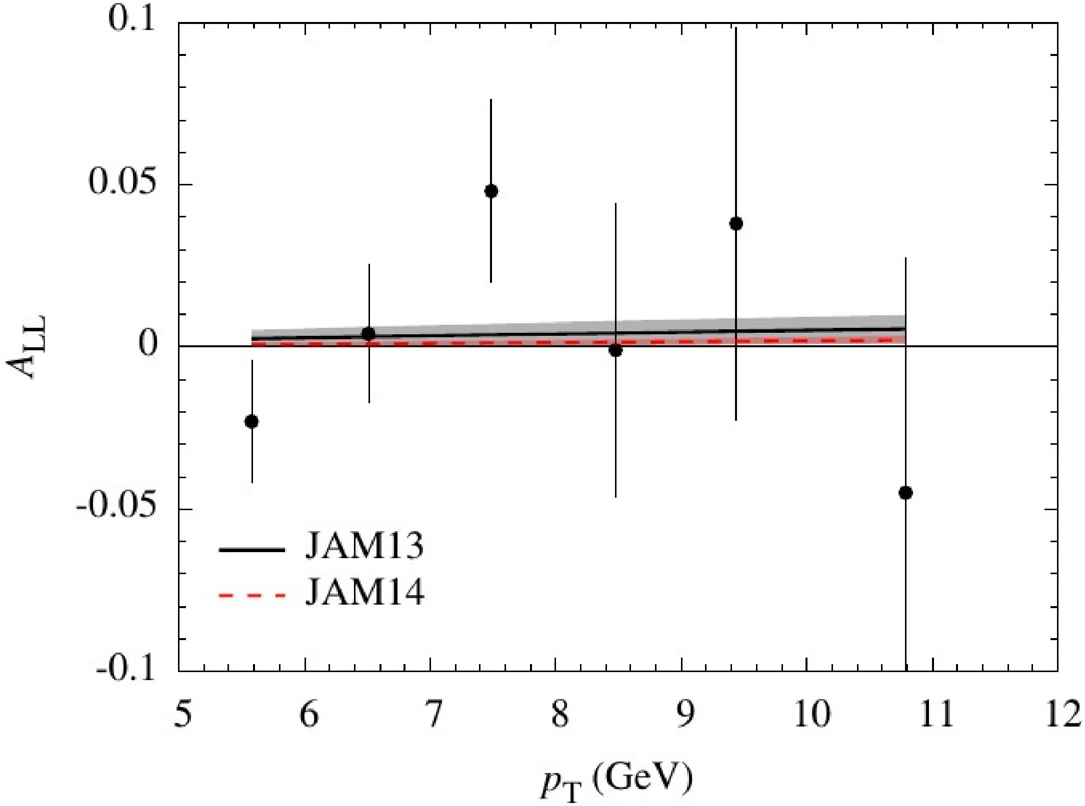
One should use the full calculation, however experimental errors are large

Moving forwards: including RHIC data

Data from PHENIX, arXiv:1402.6296



Data from STAR, PRD89(2014)012001

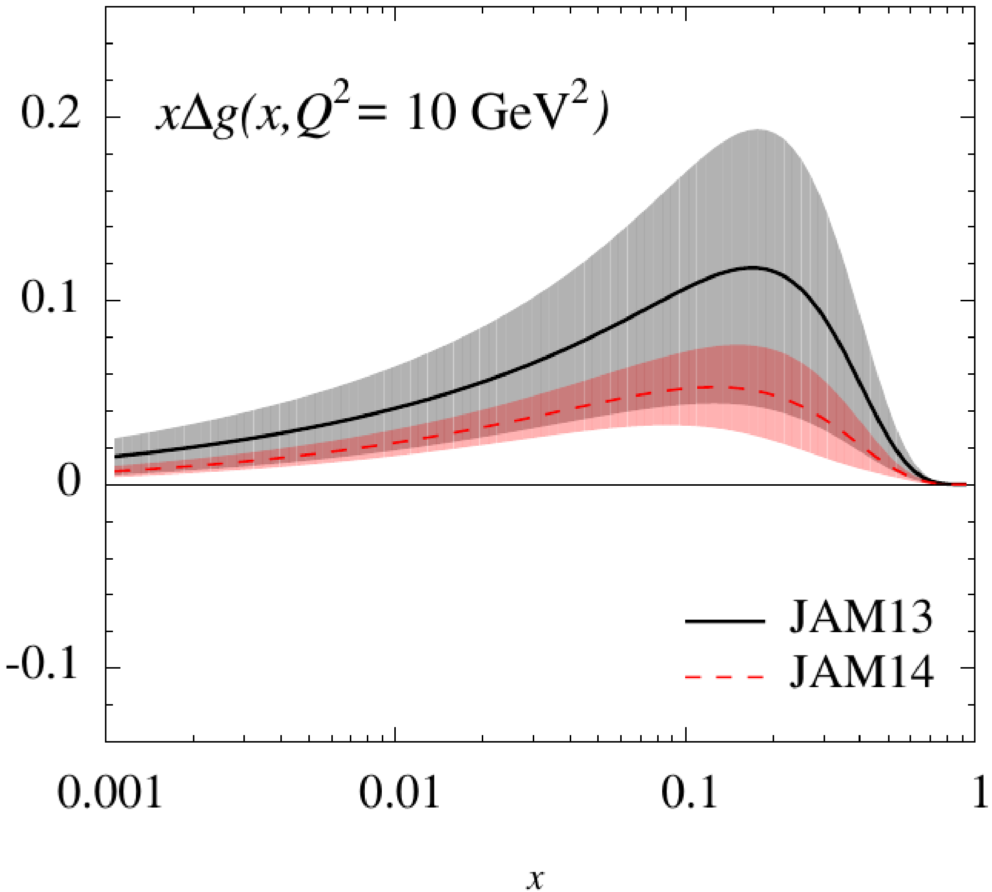


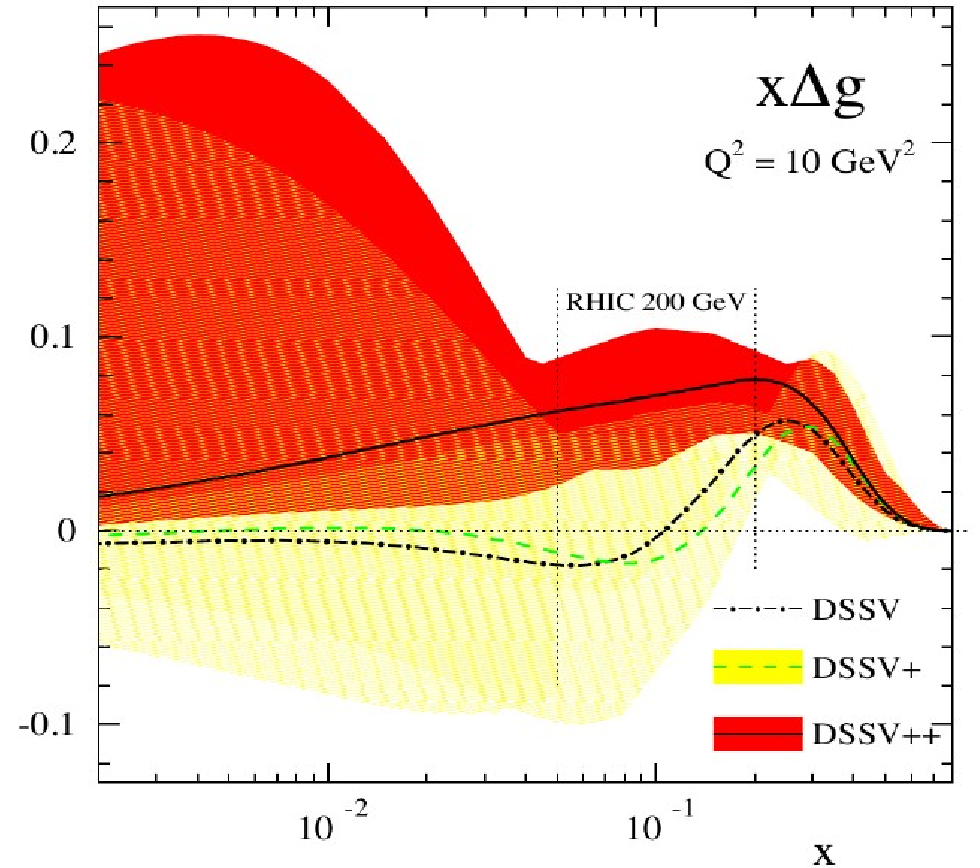
Already “well described” by JAM because of relatively large errors

Data do not affect quark distributions or DIS asymmetries, but do constrain Δg at small x

Preliminary!!

Effect on the polarized gluon distribution





$$\int_{0.05}^{0.2} \Delta g(x,Q^2 = 10\,\mathrm{GeV}^2)\,dx = 0.10^{+0.06}_{-0.07} \quad \text{[DSSV]}$$

Quite comparable with DSSV++ , except for small-x error band

$$\int_{0.05}^{0.2} dx\ \Delta g(x, Q^2 = 10^2) = 0.15 \pm 0.09 \to 0.07 \pm 0.03$$

JAM13 JAM14

Preliminary!!

Summary and outlook

Last update JR14 of our unpolarized distributions has recently been presented

Results not very different from JR09 although with several improvements

A *procedural bias* which is usually disregarded in PDF analysis can be estimated from input-scale variations and is *not* always *small*

Next natural step: inclusion of LHC data

First JAM results on the determination of polarized parton distributions:
- More accurate nuclear corrections relevant
- Target mass corrections should be used
- Complete inclusion of higher-twist possible and *manifestly important*

Dedicated studies of large-x region and impact of JLab data

Other developments in progress or planned: RHIC, SIDIS, EIC, combined fit …