Extractions of polarized and unpolarized parton distributions functions

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Theory Seminar, May 8, 2013
DESY Zeuthen/Humboldt Universität zu Berlin

Jefferson Lab

Extractions of polarized and unpolarized parton distributions functions

- The *Jefferson Lab Angular Momentum* collaboration: ***JAM***
- Improving the description of polarized DIS
- Impact of Jefferson Lab data

- The dynamical approach to PDFs
- Updating the unpolarized distributions: ***JR***
- The role of the input scale in PDF analysis

The JAM collaboration

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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

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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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to start with, open to further contributions

The JAM database

Public database with all data on polarized scattering experiments (DIS for now)

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- DB Instructions

Experiments

- 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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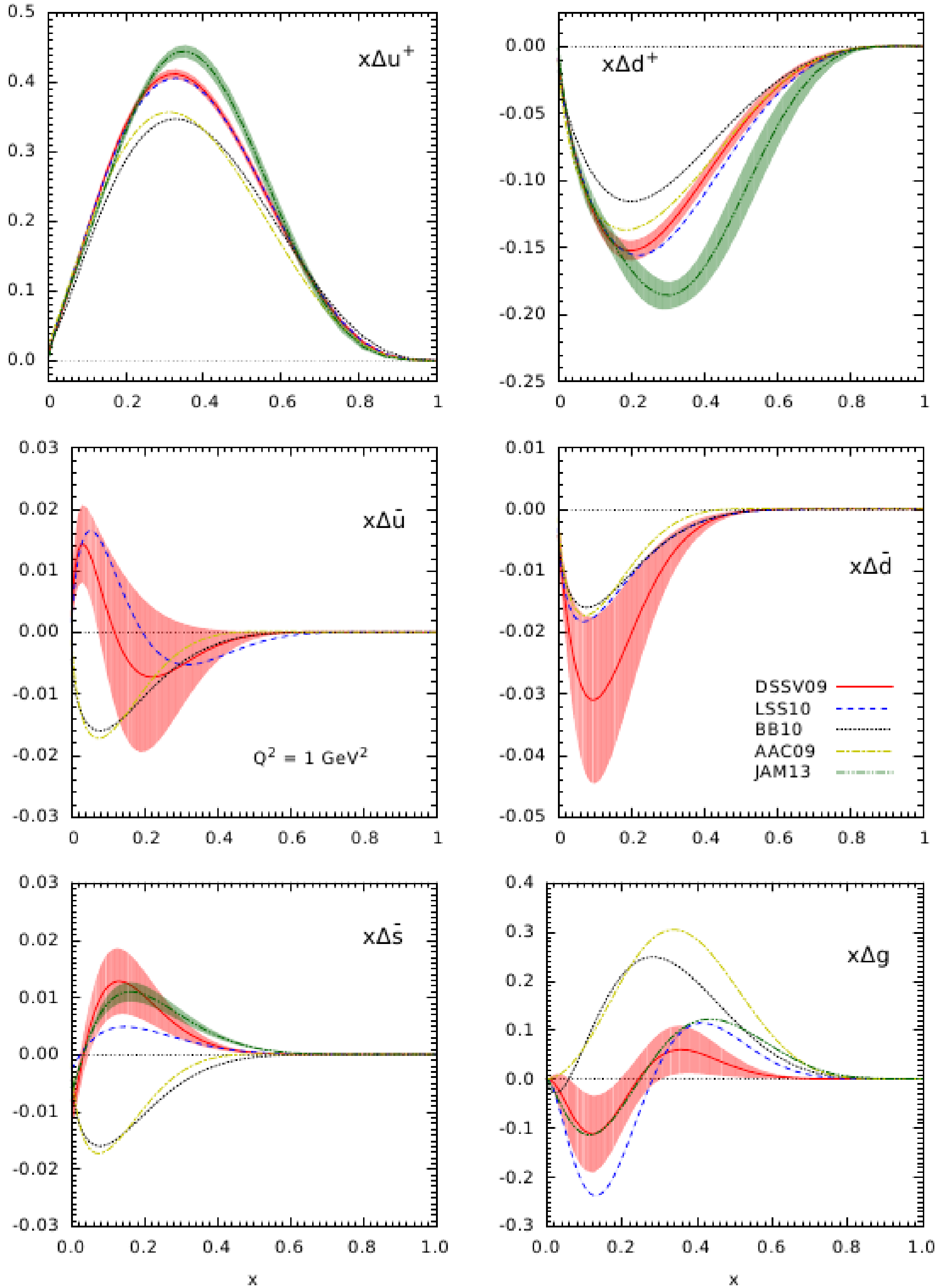
Data and theory comparison with other groups

	DIS	SIDIS	hadron collider	nuclear smearing	TMCs	HT g_1	HT g_2
DSSV 09	✓	✓	✓				
AAC 09	✓		✓				
BB 10	✓				✓	✓	∼
LSS 10	✓	✓			✓	✓	
NNPDF 13	✓				✓		
JAM 13	✓			✓	✓	✓	✓

Presently concentrated on improvements in the theoretical description of DIS

Long-term objective is to tick all the boxes (include SIDIS and RHIC data)

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 $\Delta \bar{u}, \ \Delta \bar{d}, \ \Delta \bar{s}$

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 $Q^2 \geq 1\ \mathrm{GeV}^2$, $W^2 \geq 3.5\ \mathrm{GeV}^2$)

PROTON	**SLAC E80/E130:** G. Baum et al., Phys. Rev. Lett. **51**, 1135 (1983)
	EMC: J. Ashman et al., Nucl. Phys. **B328**, 1 (1989)
	SMC: B. Adeva et al., Phys. Rev. D **58**, 112001 (1998)
	Phys. Rev. D **60**, 072004 (1999)
	Erratum-ibid. Phys. Rev. D **62**, 079902 (2000)
	COMPASS: M.G. Alekseev et al., Phys. Lett. B **690**, 466 (2010)
	SLAC E143: K. Abe et al., Phys. Rev. D **58**, 112003 (1998)
	SLAC E155: P.L. Anthony et al., Phys. Lett. B **493**, 19 (2000)
	Phys. Lett. B **458**, 529 (2000)
	SLAC E155x: P.L. Anthony et al., Phys. Lett. B **553**, 18 (2003)
	HERMES: A. Airapetian et al., Phys. Rev. D **75**, 012007 (2007)
	JLab Hall B (EG1b): Y. Prok et al., Phys. Lett. B **672**, 12 (2009)
	HERMES: A. Airepetian et al., Eur. Phys. J. C **72**, 1921 (2012)
DEUTERON	**SMC:** B. Adeva et al., Phys. Rev. D **58**, 112001 (1998)
	Phys. Rev. D **60**, 072004 (1999)
	Erratum-ibid. Phys. Rev. D **62**, 079902 (2000)
	COMPASS: V.Yu. Alexakhin et al., Phys. Lett. B **647**, 8 (2007)
	SLAC E143: K. Abe et al., Phys. Rev. D **58**, 112003 (1998)
	SLAC E155: P.L. Anthony et al., Phys. Lett. B **463**, 339 (1999)
	Phys. Lett. B **458**, 529 (2000)
	SLAC E155x: P.L. Anthony et al., Phys. Lett. B **553**, 18 (2003)
	HERMES: A. Airapetian et al., Phys. Rev. D **75**, 012007 (2007)
	JLab Hall B (EG1b): Y. Prok et al., Phys. Lett. B **672**, 12 (2009)
HELIUM-3	**SLAC E142:** P.L. Anthony et al., Phys. Rev. D **54**, 6620 (1996)
	SLAC E154: K. Abe et al., Phys. Rev. Lett. **79**, 26 (1997)
	Yu. Kolomensky, Ph.D. thesis, U. Massachusetts (1997),SLAC-Rep-503
	HERMES: K. Ackerstaff et al., Phys. Lett. B **404**, 383 (1997)
	JLab Hall A (E99-117): X. Zhang et al., Phys. Rev. Lett. **92**, 012004 (2004)
	Phys. Rev. C **70**, 065207 (2004)
	JLab Hall A (E97-103): K. Kramer et al., Phys. Rev. Lett. **95**, 142002 (2005)
	K. Kramer, Ph.D. thesis, Coll. of William & Mary (2003)
	JLab Hall A (E01-012): P. Solvignon et al., Phys. Rev. Lett. **101**, 182502 (2008)

Mainly on *measured* asymmetries:

$$A_{\|} = D(A_1 + \eta A_2)$$

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

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

Underlying QCD description

Asymmetries from (un)polarized structure functions:

$$A_1 = (g_1 - \gamma^2 g_2)\frac{2x}{(1+\gamma^2)F_2 - F_L} \qquad A_2 = \gamma(g_1 + g_2)\frac{2x}{(1+\gamma^2)F_2 - F_L}$$

Leading-twist structure functions in OPE from NLO QCD computations:

$$g_1^{\tau=2}(n, Q^2) = \frac{1}{2}\sum_{q,\bar{q}} e_q^2 \left(\Delta C_{qq}^1 \Delta q + \Delta C_g^1 \Delta g\right)$$

$$g_2^{\tau=2}(n, Q^2) = g_2^{WW} = -\frac{n-1}{n} g_1(n, Q^2)$$ [Wandzura, Wilczek 77]

Calculations and RGE evolution implemented in the space of complex Mellin *moments* (truncated solutions)

$$f(n) = \int_0^1 dx\, x^{n-1} f(x)$$

Parametrization

Only *two* independent combinations of quark distributions contribute:

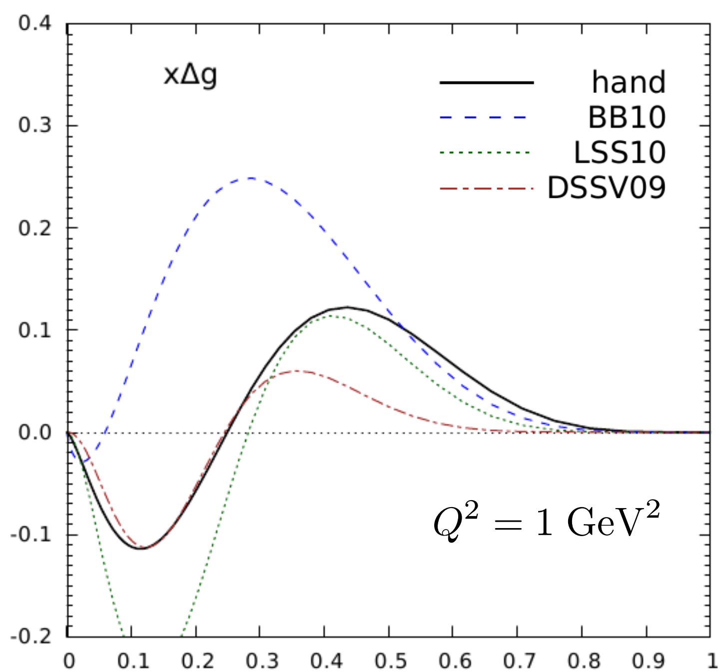
$$x\Delta u^+(x,Q_0^2) = N_u\, x^{a_u}(1-x)^{b_u}(1+A_u\sqrt{x}+B_u\,x) \qquad \Delta q^+ \equiv \Delta q + \Delta\bar{q}$$

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

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 ($\lim_{x\to 0}\Delta\bar{q} = 2\lim_{x\to 0}\Delta q^+$ and counting rules)



Formally Δg enters at second order, but in practice our fits are *not very sensitive*:

$$\Delta\chi^2 \ll \Delta\chi^2_{1\sigma}$$

DIS data provide only rather *mild* constrains

Since it is not the current object of study, it has been fixed to a reasonable function (hand) (in the following plots, now also released)

Statistical estimation

Nominally 12 (LT) + 16 (HT) = 28 parameters to be determined

Least-squares estimator with a *complete treatment* of systematic uncertainties (equivalent to the correlation matrix approach) [CTEQ]:

$$\chi^2 = \sum_{i=1}^{N} \frac{1}{\Delta_i^2} \left(D_i + \sum_{j=1}^{M} r_j \Delta_{ji} - T_i \right)^2 + \sum_{j=1}^{M} r_j^2$$

Here the systematic shifts are calculated *analytically*

Unfortunately most experiments do not provide all this information

Errors estimated with the *Hessian* approach (linear propagation, works well):

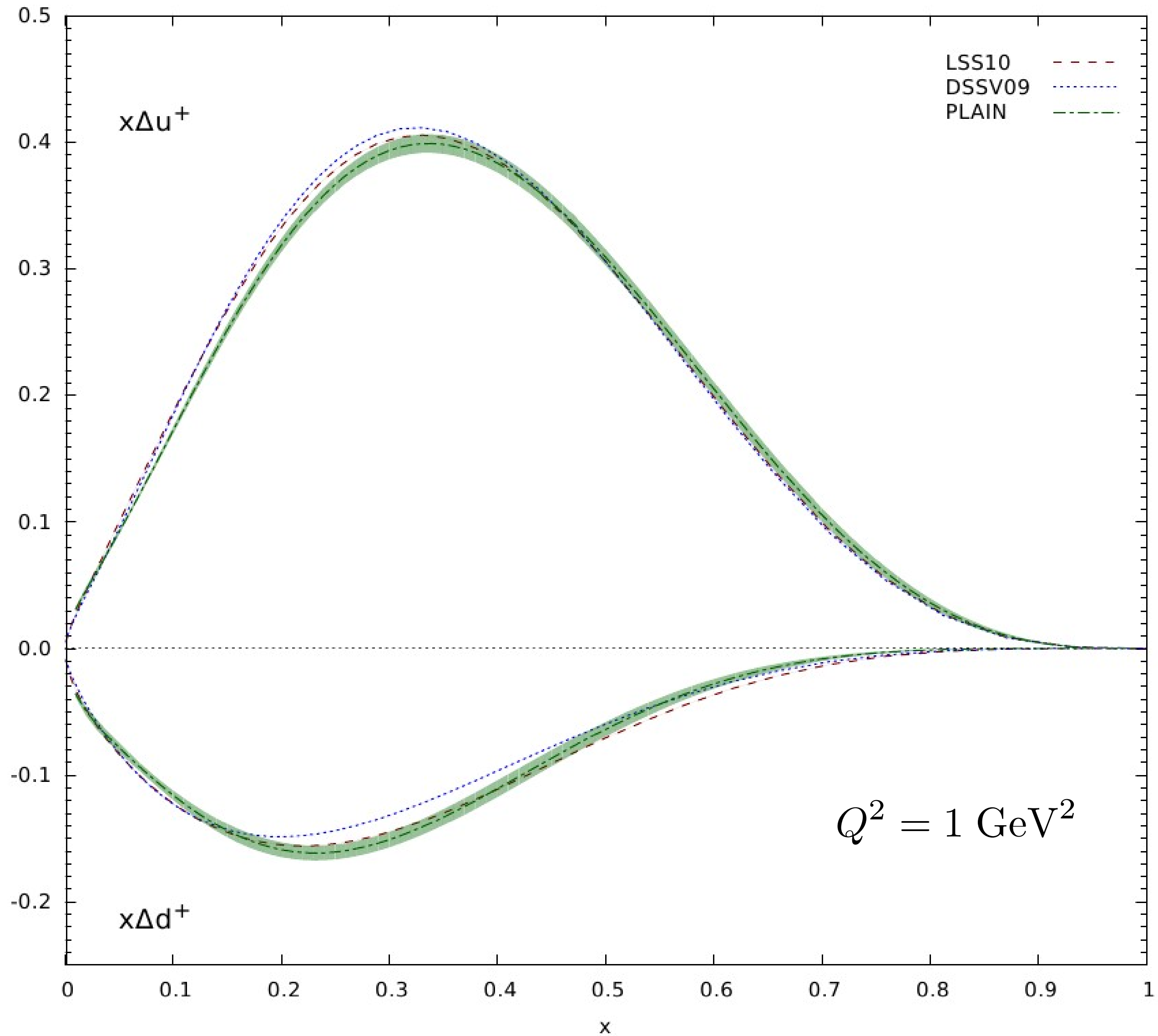
"Vicinity" of the minimum (tolerance) characterized by:

$$\Delta\chi^2 = \chi^2(p) - \chi^2(p^0) \leq T^2 = 1$$

Simple fit without further corrections: PLAIN

Nuclear targets treated with the "effective polarization" approximation:

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



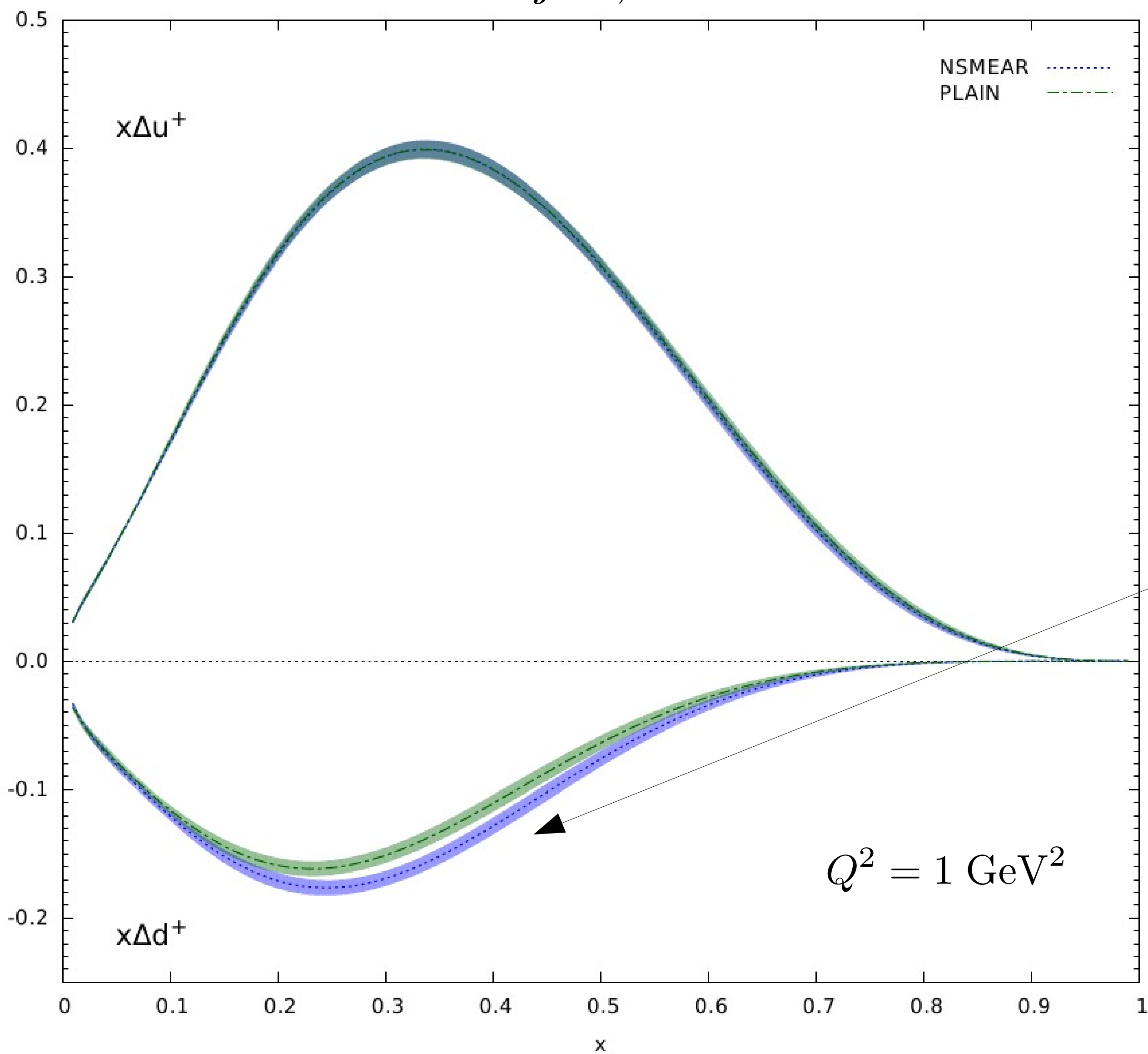
Baseline for assessing the impact of additional corrections

Improved description of nuclear targets: NSMEAR

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]



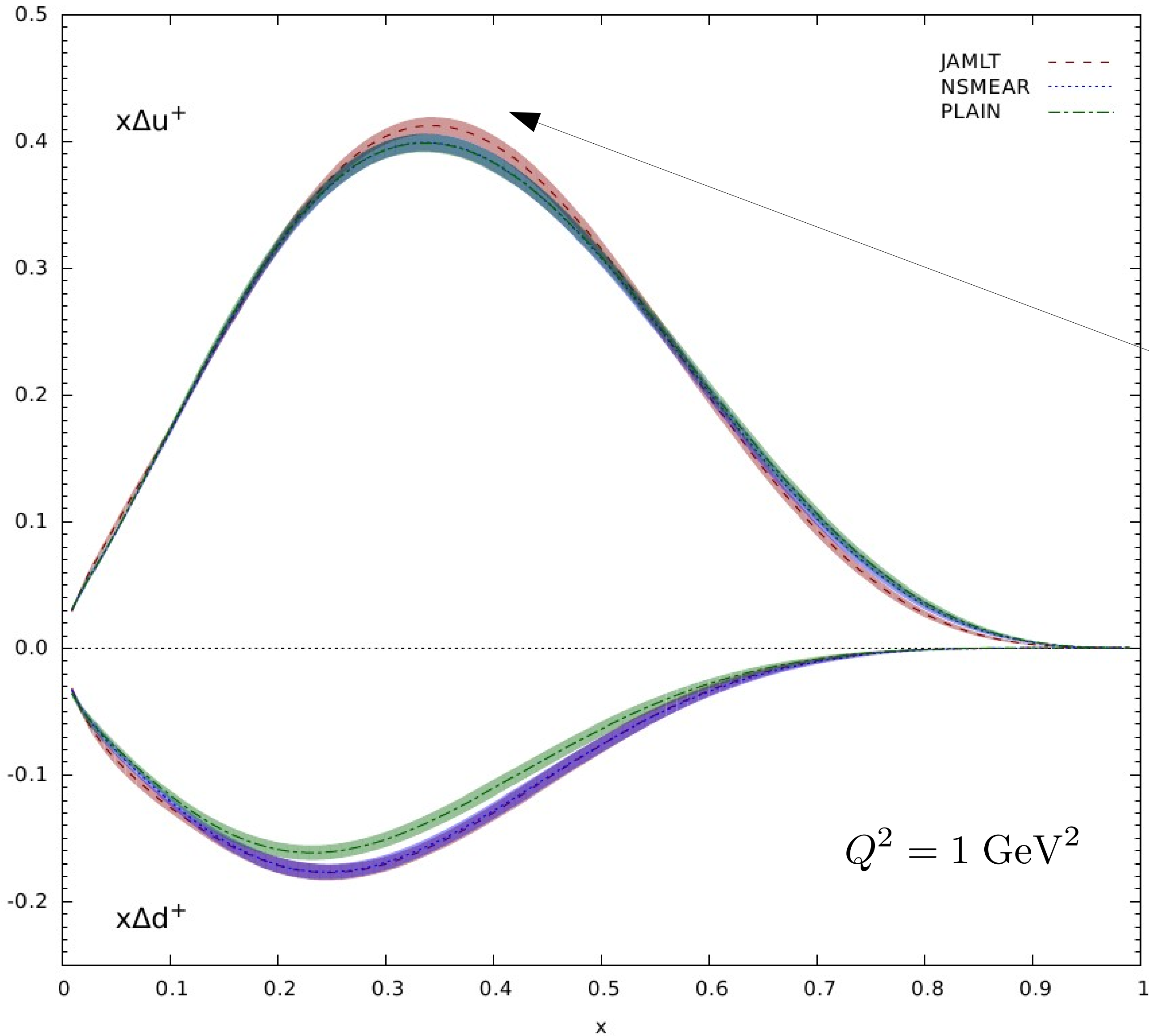
Relevant for Δd in the medium- to large-x region

Plus target-mass corrections: JAMLT

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]



Note that the Wandzura-Wilzceck relation holds also after TMCs

Relevant for Δu in the medium- to 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:

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

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

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 :

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

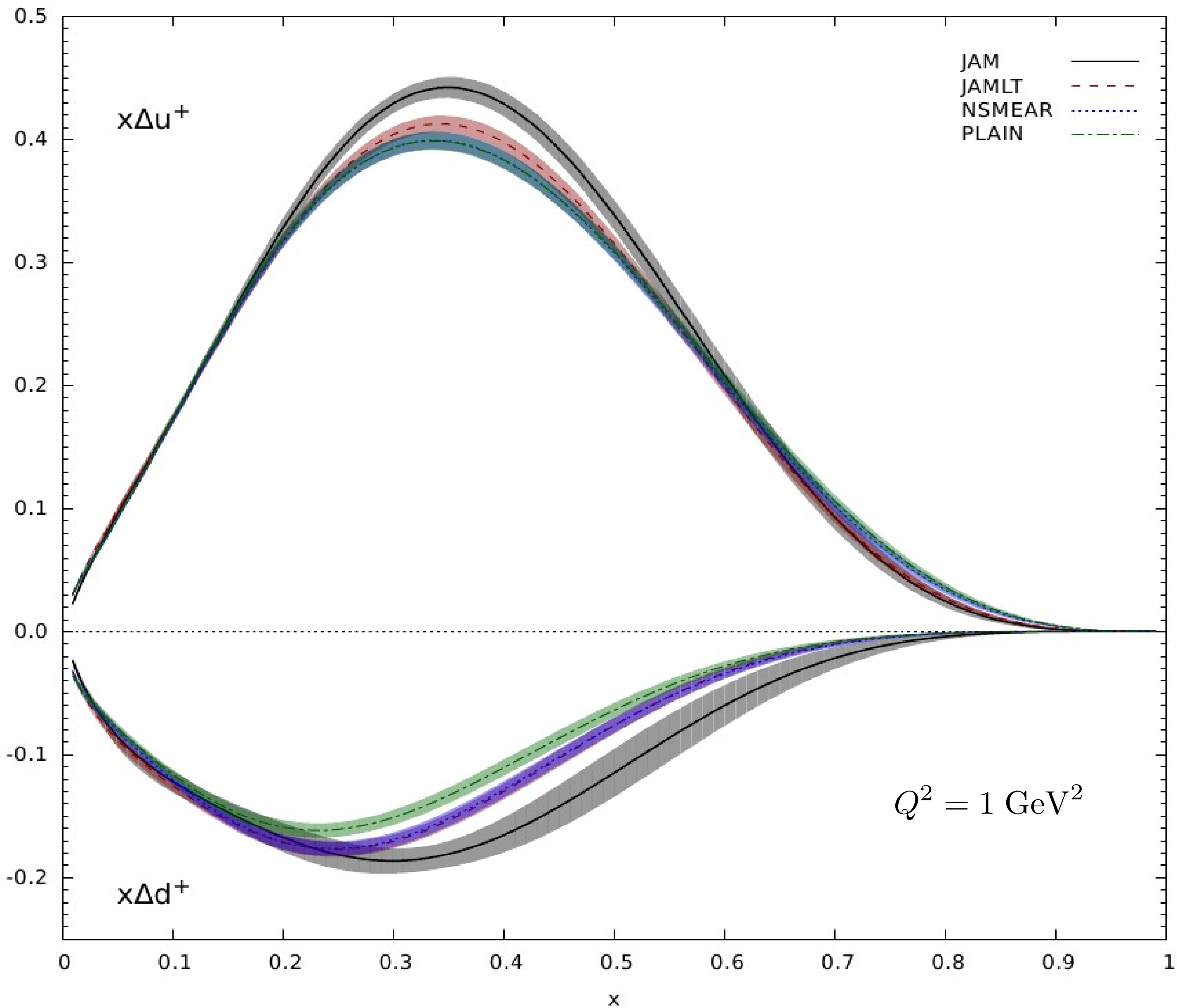
[Braun *et al.* 09]

And a splines approximation for: $g_1^{\tau=4} = \dfrac{h(x)}{Q^2}$ $\qquad \int_0^1 dx\, g_2^{\tau=3} = 0$

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

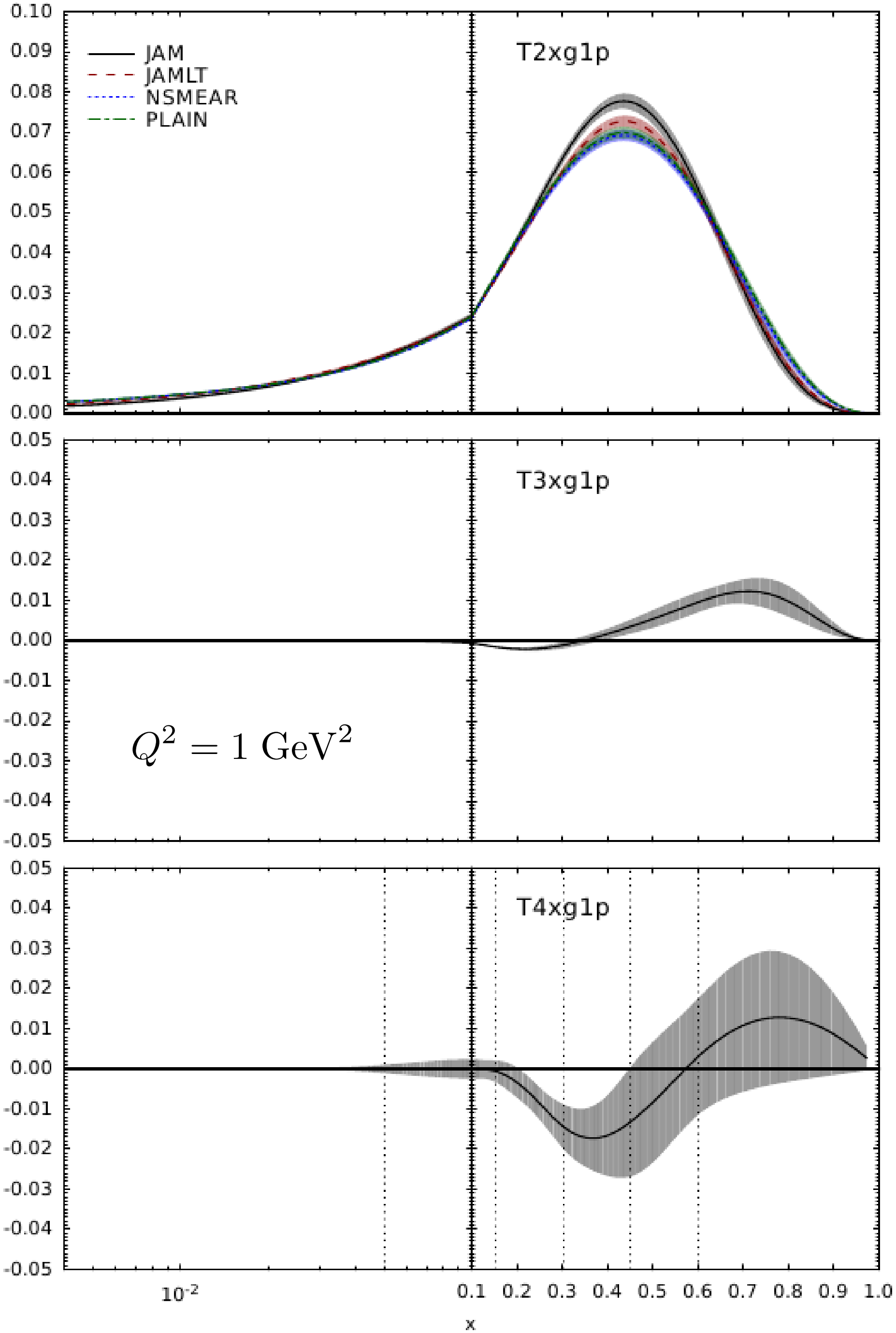
Including all these corrections: JAM

Considerable improvement of χ^2 for some sets (globally $1.07 \to 0.95\,,\ 3\sigma$)

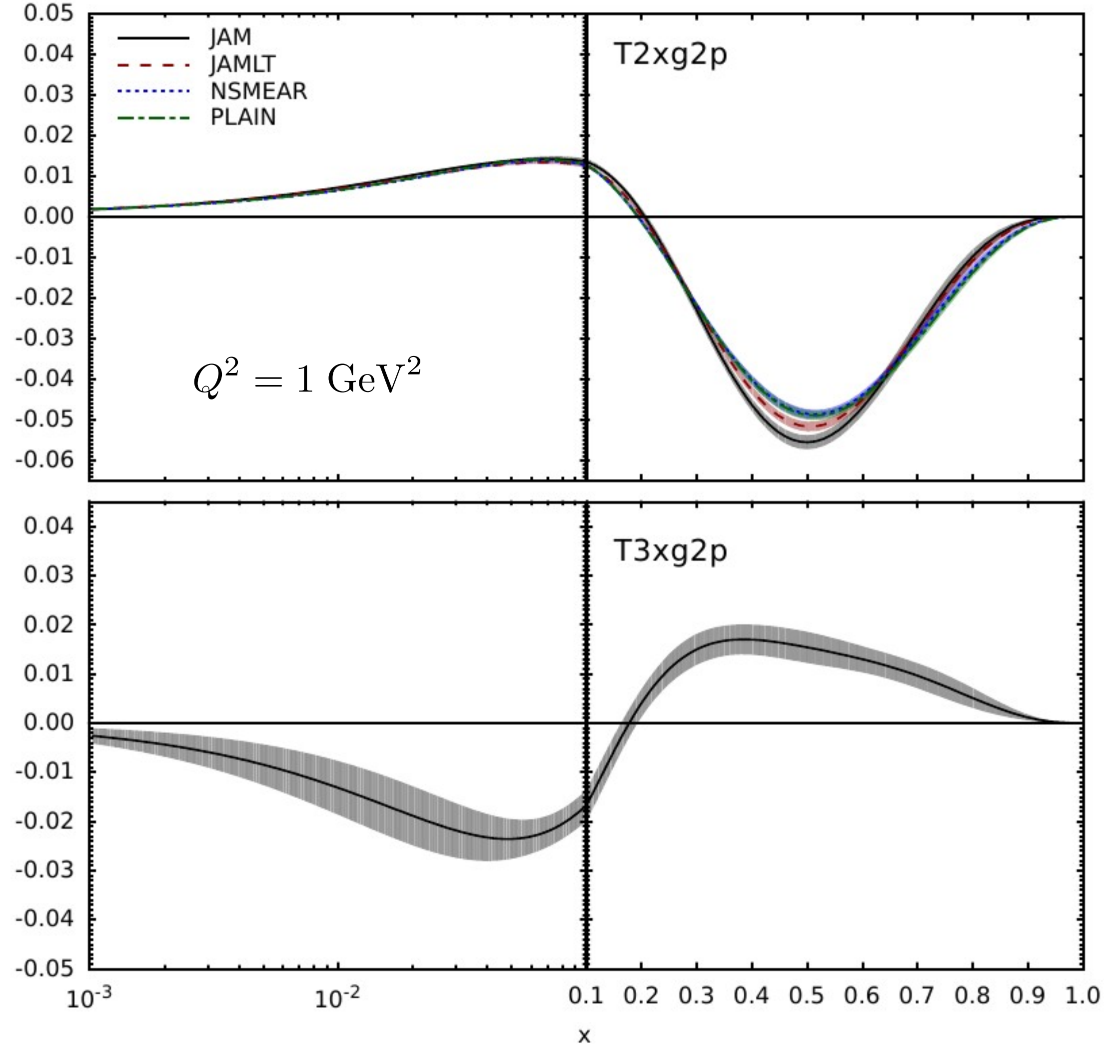


Higher twist contributions are *manifestly important* for PDF extractions

Including all these corrections: JAM



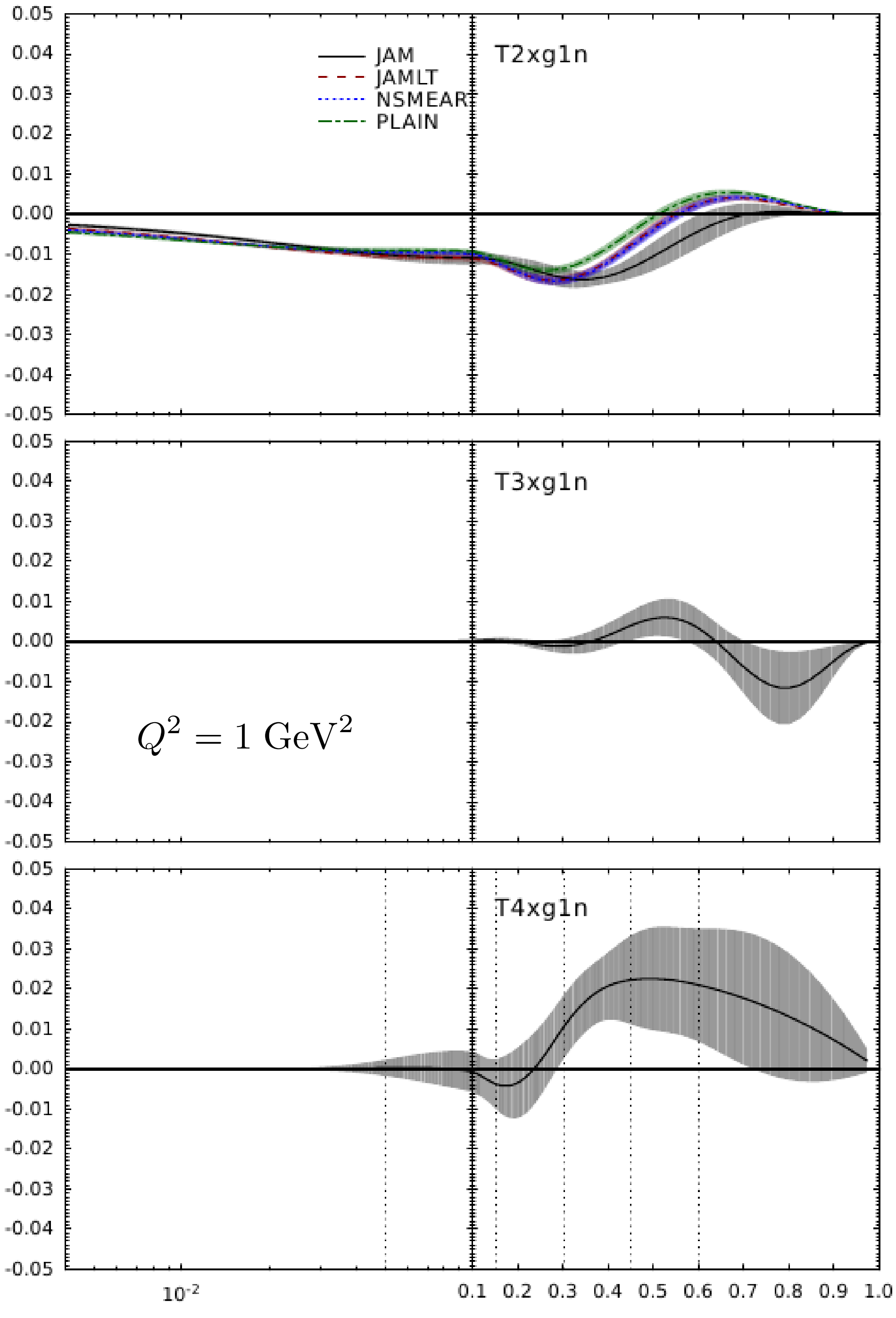
It is possible to determine *simultaneously* higher-twist contributions for g_1 and g_2



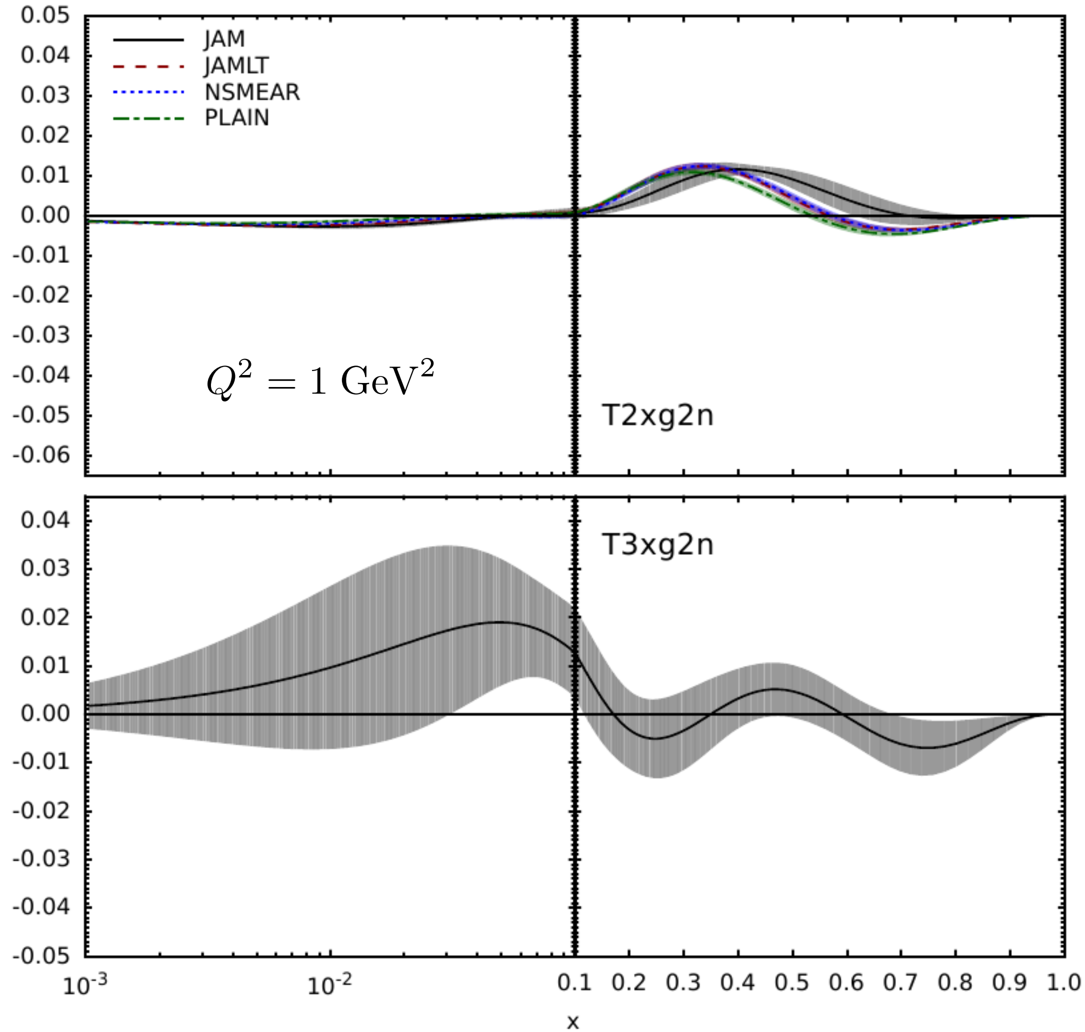
Qualitative agreement with [LSS 10] on g_1 and [BB 12], [ABMS 09] on g_2

[Accardi, Bacchetta, Melnitchouck, Schlegel 09]

Including all these corrections: JAM



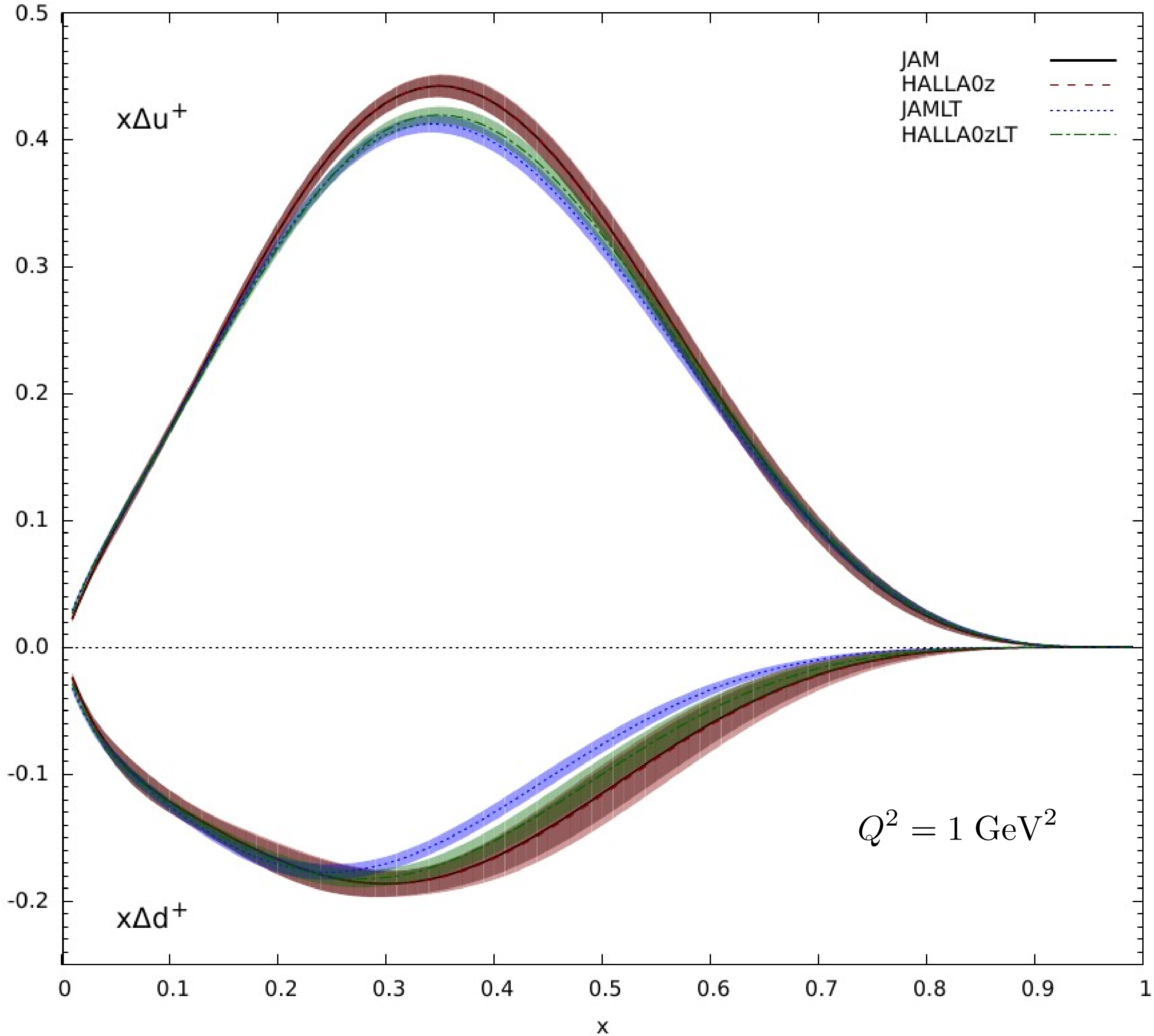
As well as for proton and neutron (which are rather different)



Disagreement with [LSS 10] on g_1 ;
g_2 is more or less compatible with zero

Impact of Jefferson Lab data: HALLA0z

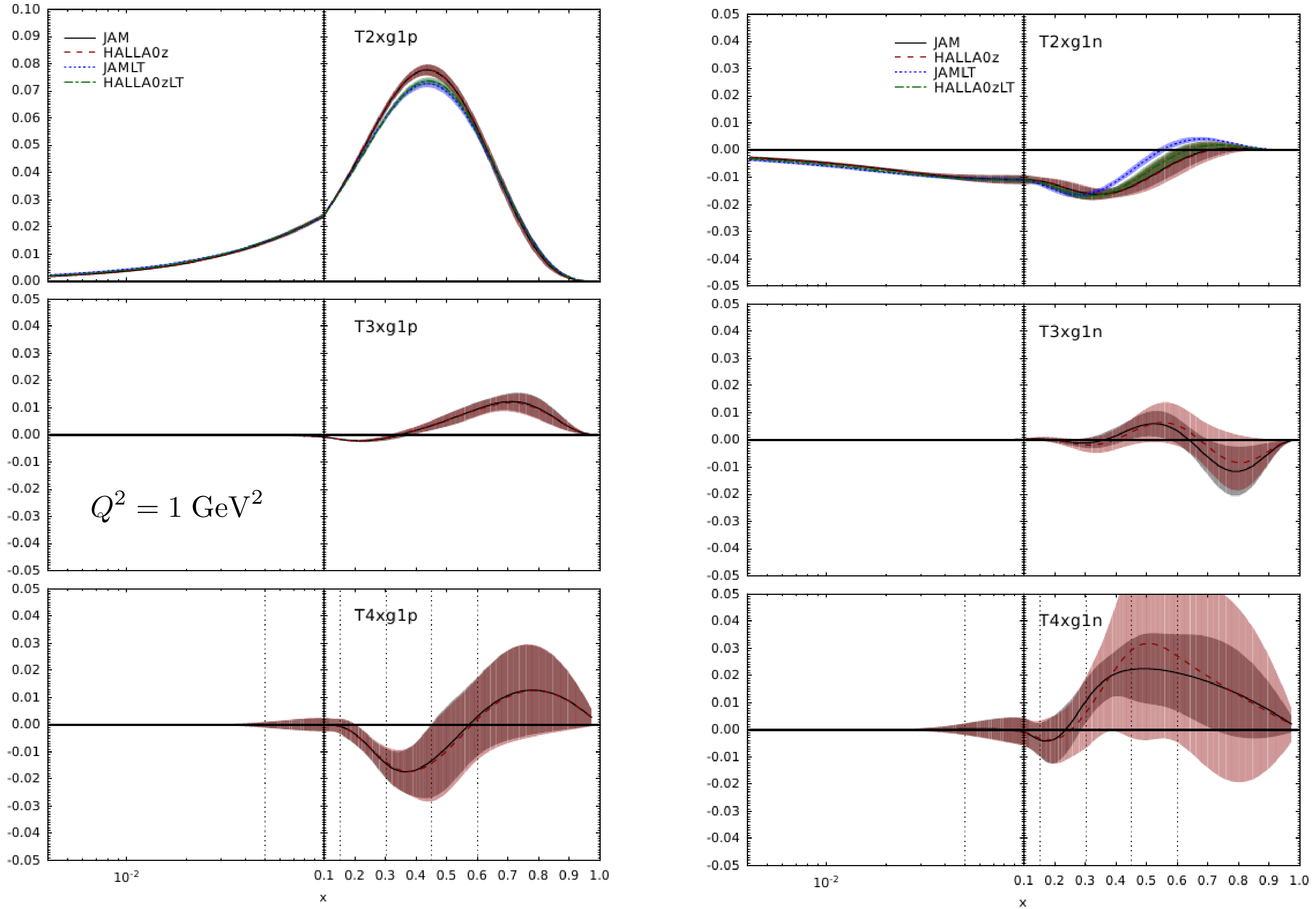
What happens if we remove E99-117 [X. Zhang et al., Phys. Rev.Lett. **92**, 012004 (2004)] ?



Higher twist contributions stabilize results for the PDFs (leading twist)

Impact of Jefferson Lab data: HALLA0z

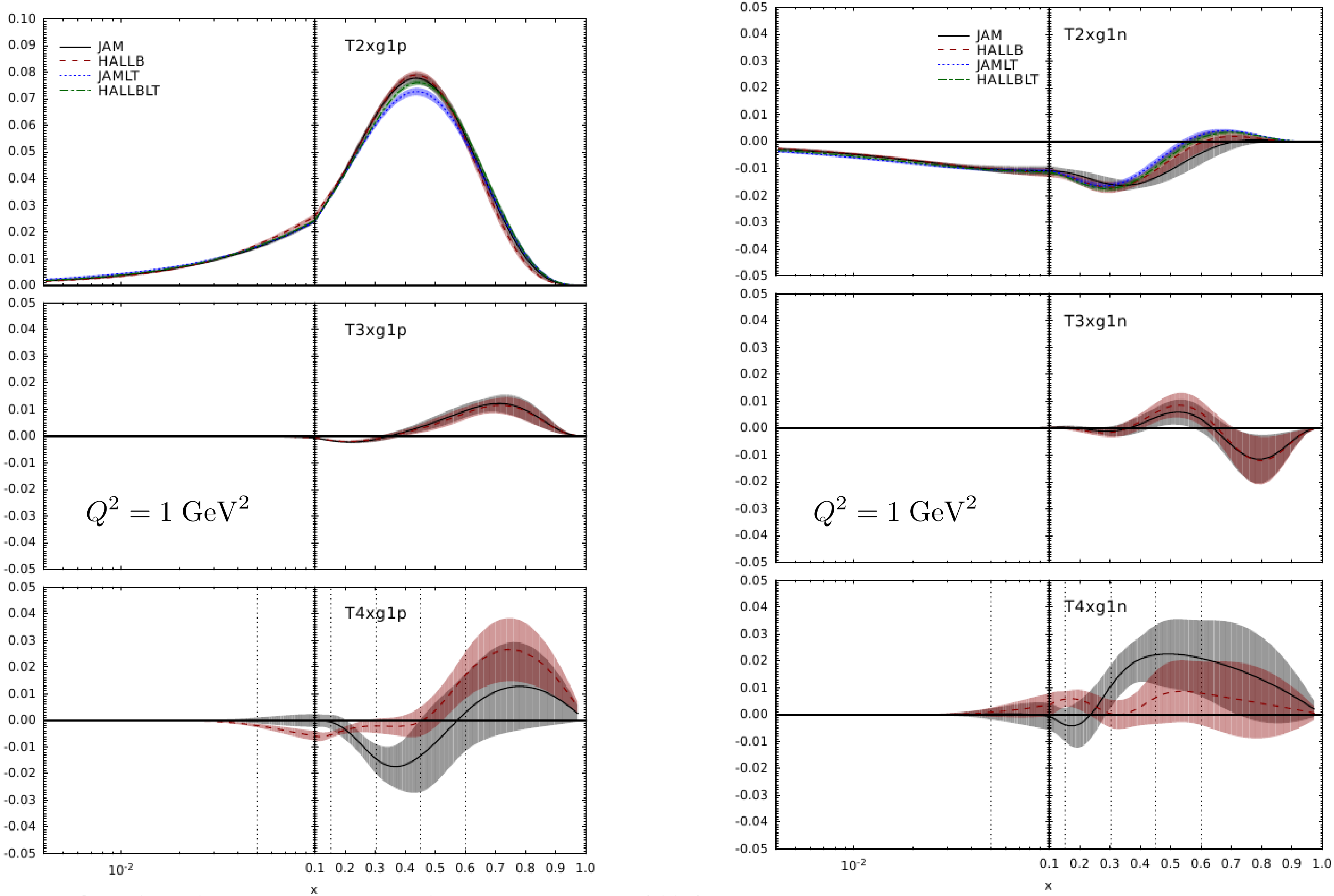
What happens if we remove E99-117 [X. Zhang et al., Phys. Rev.Lett. **92**, 012004 (2004)] ?



Very important for g_1 neutron; determine the higher contributions at large x

Impact of Jefferson Lab data: HALLB

Which impact will have future CLAS data (being analyzed at the moment)?



Impact for both, proton and neutron; will improve accuracy

… and unpolarized parton distributions functions

The dynamical approach

Parametrizations: $xf(x, Q_0^2) = Nx^a(1-x)^b \text{ function}(x)$

"function" may be polynomial, contain exponentials, neural networks, ...

We are free to (and have to) select the input scale Q_0^2

Physical motivation:

At low-enough Q^2 only "valence" partons would be resolved
⇒ *structure at higher Q^2 appears radiatively* (due to QCD *dynamics*)

Dynamical:

$Q_0^2 < 1\text{GeV}^2$ optimally determined

Valence-like structure

QCD "predictions" for small-x

More predictive, less uncertainties

"Standard":

Arbitrarily fixed $Q_0^2 \gtrsim 1\text{GeV}^2$

Fine tunning to particular data

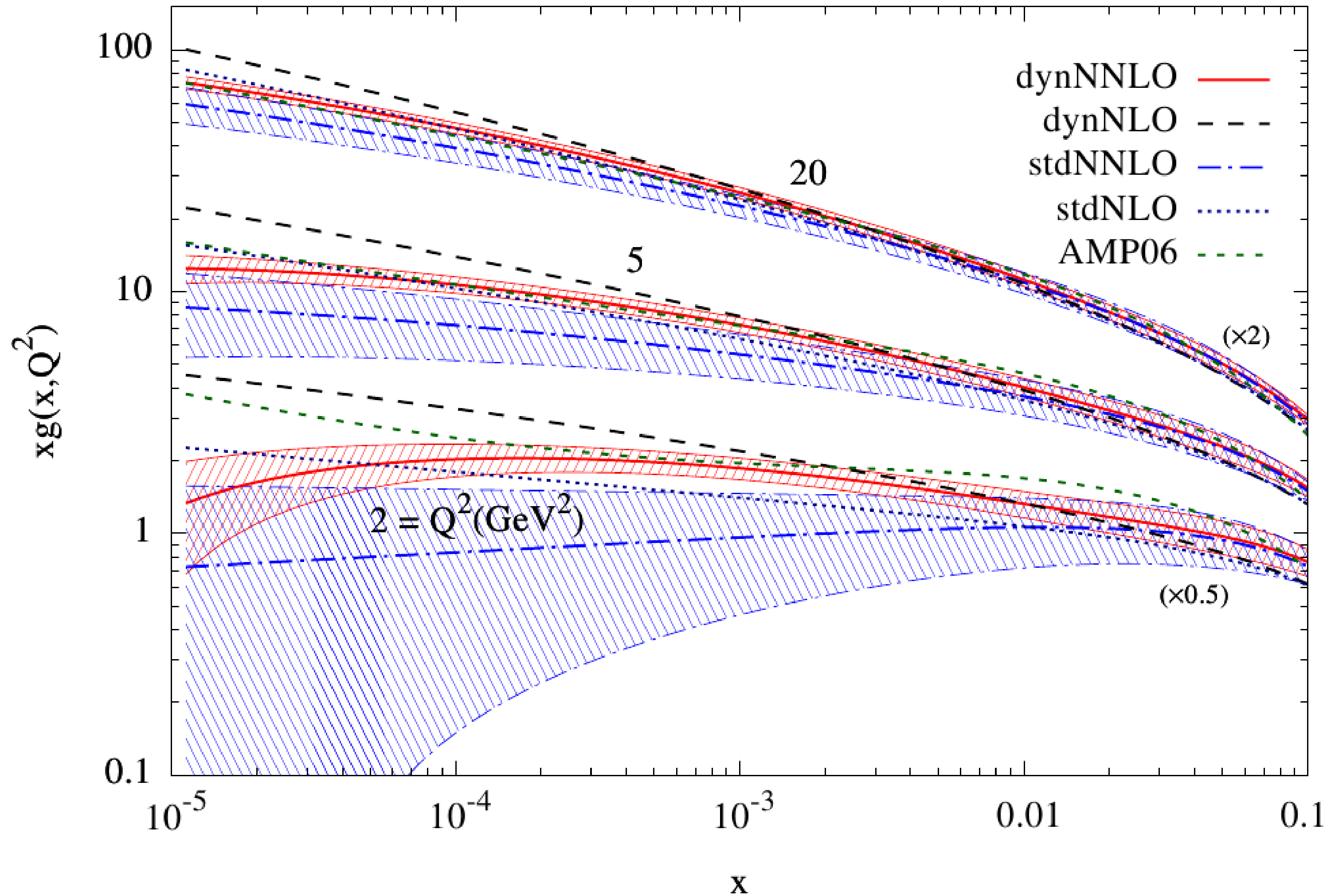
Extrapolations to unmeasured regions

More adaptable, marginally smaller χ^2

There are no extra constraints involved in the dynamical approach

Physical motivation for contour conditions ≠ non-perturbative structure

Gluon evolution from dynamical scales

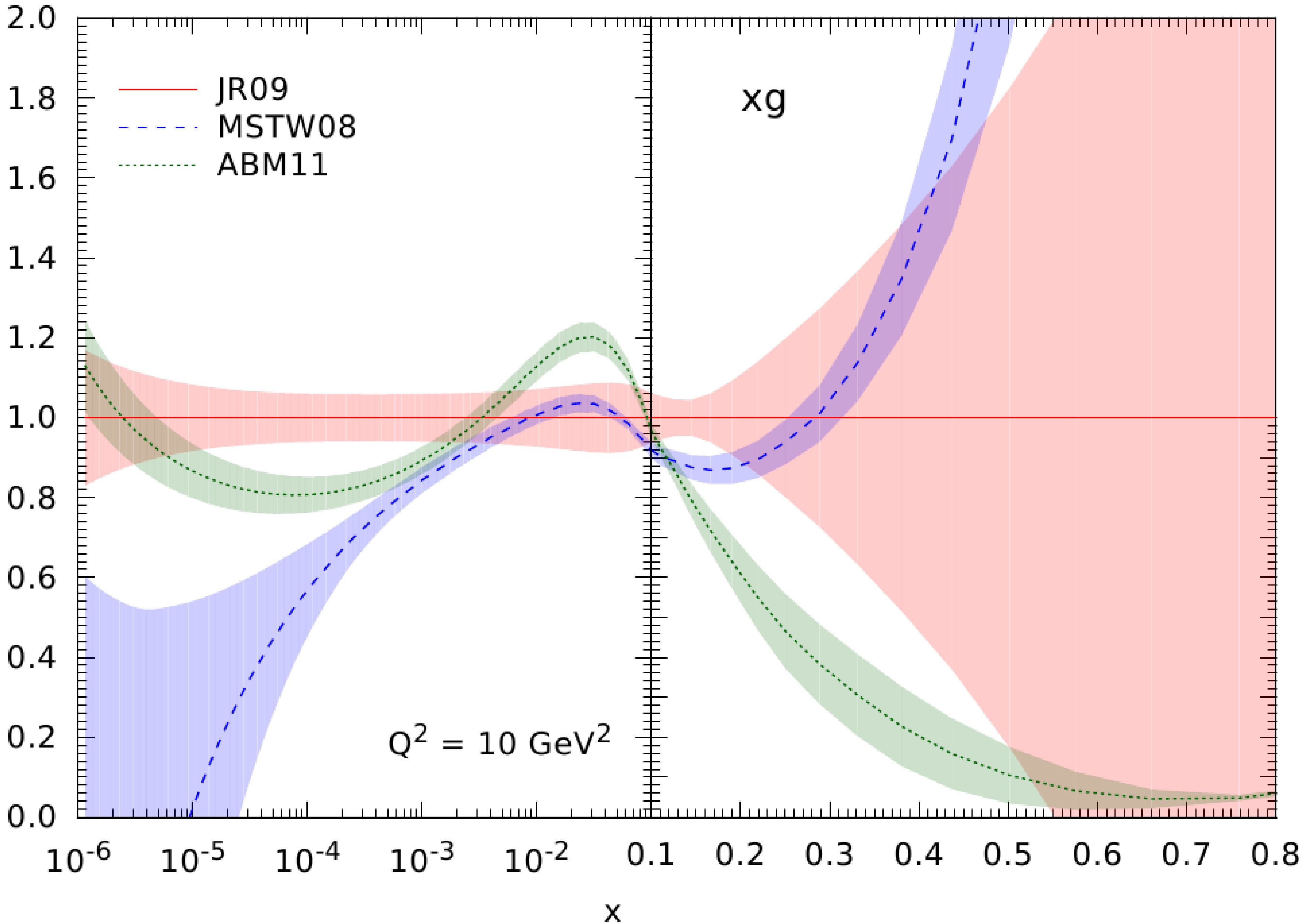


Larger “evolution distance”+ valence-like structure:

- smaller uncertainties
- steeper gluons (correspondingly smaller α_s)

Fine tunning marginal (e.g. for DIS in JR09 $\chi^2_{dyn} = 0.90$, $\chi^2_{std} = 0.87$)

Status of gluon distributions



Large differences at small and large x

Constraints on the gluon and data selection

Gluon only enters directly (at LO) in:

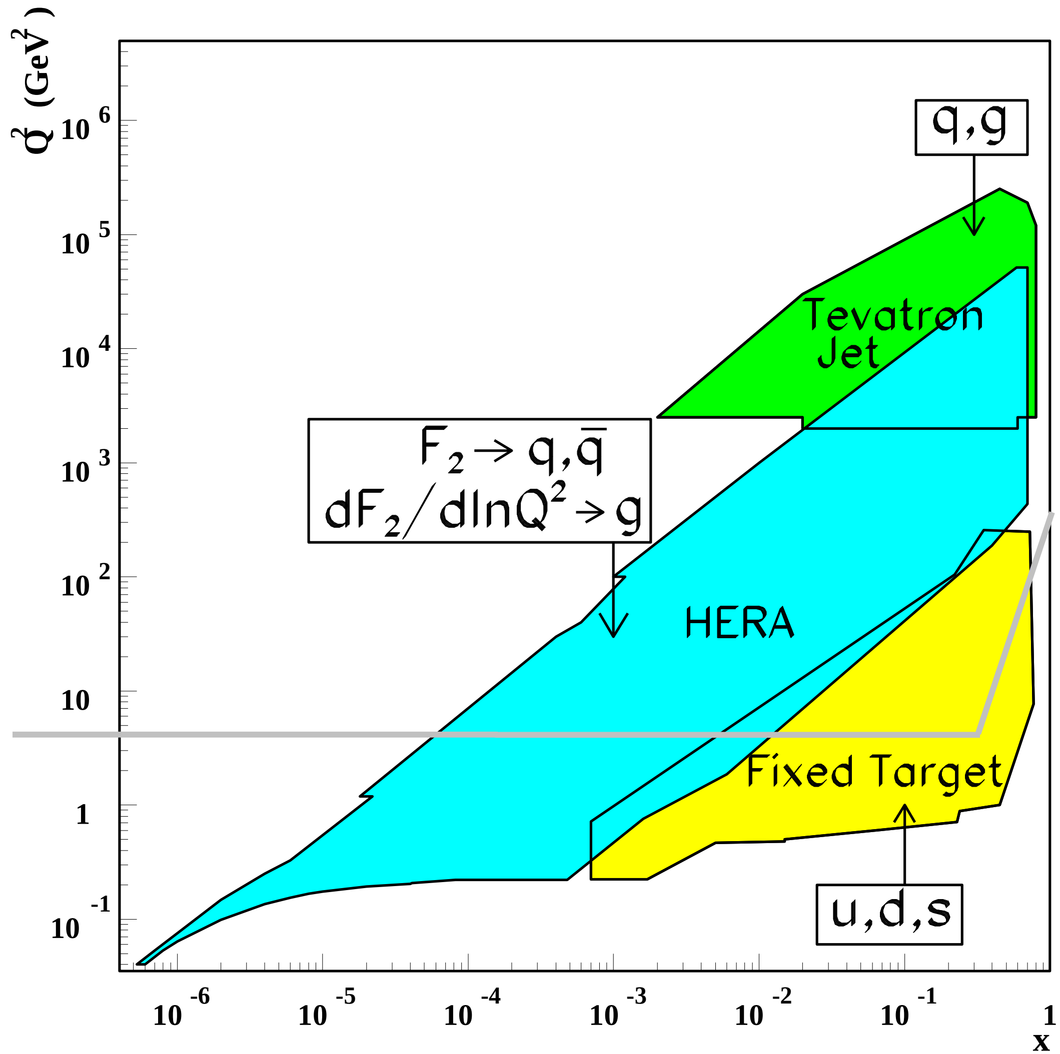
- F_L (both small and large x)
- HQ electroproduction (small x)
- jet production (medium to large x)

But constrained via scaling violations in the small x region

Momentum sum rule correlates small and large x

DIS data often excluded from fits:

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



[Particle Data Group]

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

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

(NNLO corrections are large)

Updating the JR parton distribution functions

Significant changes in data:

- F_2 replaced for cross-section for SLAC and NMC [ABM 2010]; BCDMS excluded
- From 30 points on p/n ratios to an equal-footing treatment of p and d FT DIS
- Dimuon data included in nominal fits
- JLab proton and deuteron DIS data also included (need lower *W* cuts)
- Switched to HERA combined NC σ_r, σ_r^c and included CC
- Inclusion of Rosenbluth separated (F_2, F_L) data from H1, and from BCDMS, SLAC, EMC and Jlab [Monaghan et al. 2012]

Theory improvements:

- Switched to $\overline{\mathrm{MS}}$ scheme for heavy quark masses [ABM 2010]
- NNLOapp for heavy quark contributions to structure functions [ABM 2010]
- Target mass corrections included also for F_L (in addition to F_2)
- Nuclear corrections for deuteron data [CJ 2010]
- Determination of higher-twist contributions for structure functions $F_{2,L}^{p,n}$

Higher-twist contributions

Large x DIS data provide valuable information

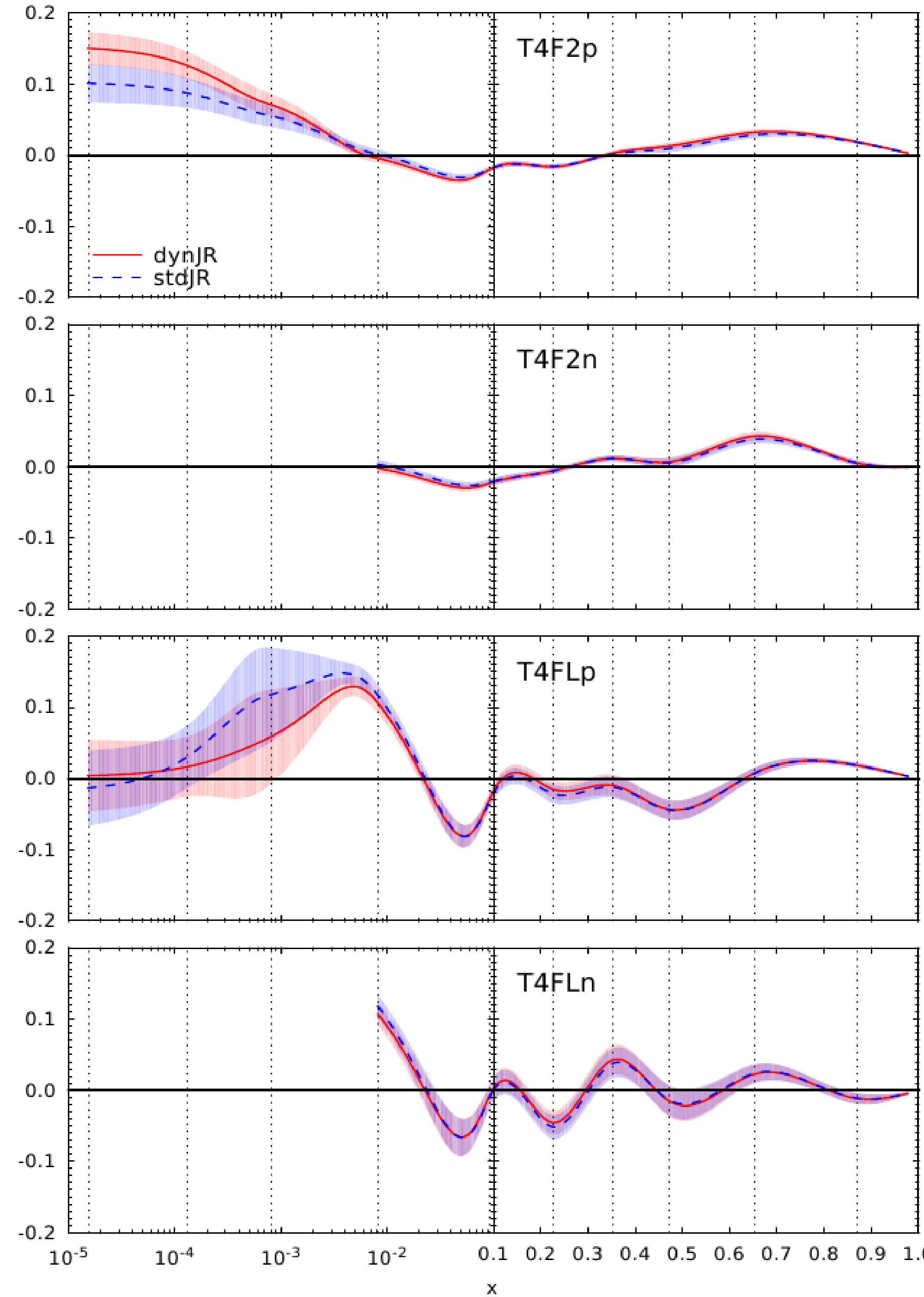
Currently we use all DIS data:

$$Q^2 \gtrsim 1 \text{ GeV}^2, \; W^2 \gtrsim 3.5 \text{ GeV}^2$$

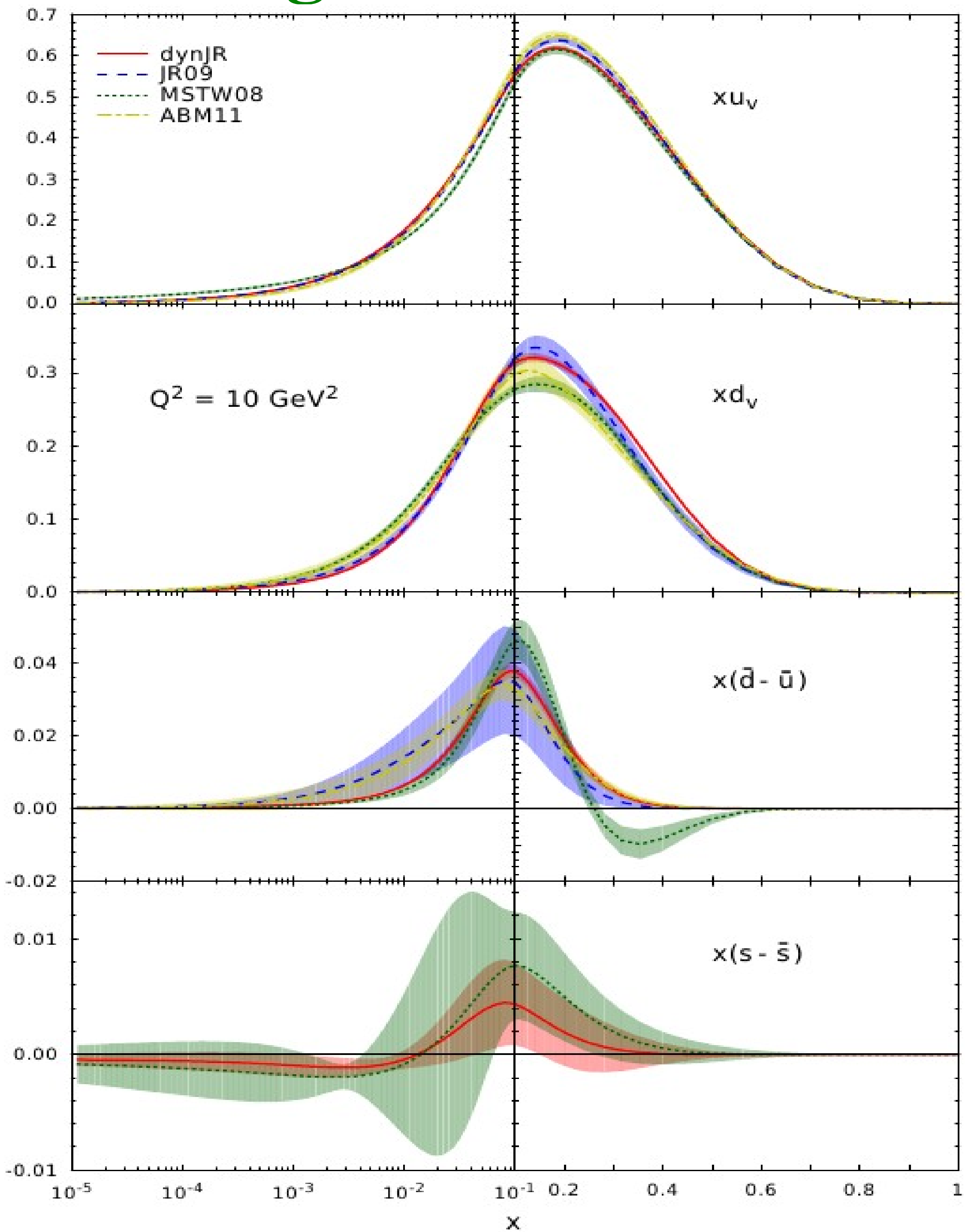
It is possible to determine higher-twist contributions together with the distributions

Including twist-4 stabilizes the PDFs (twist-2)

Including in addition twist-6 lead to compensating contributions and destabilizes the results (too much!)



Non-singlet sector



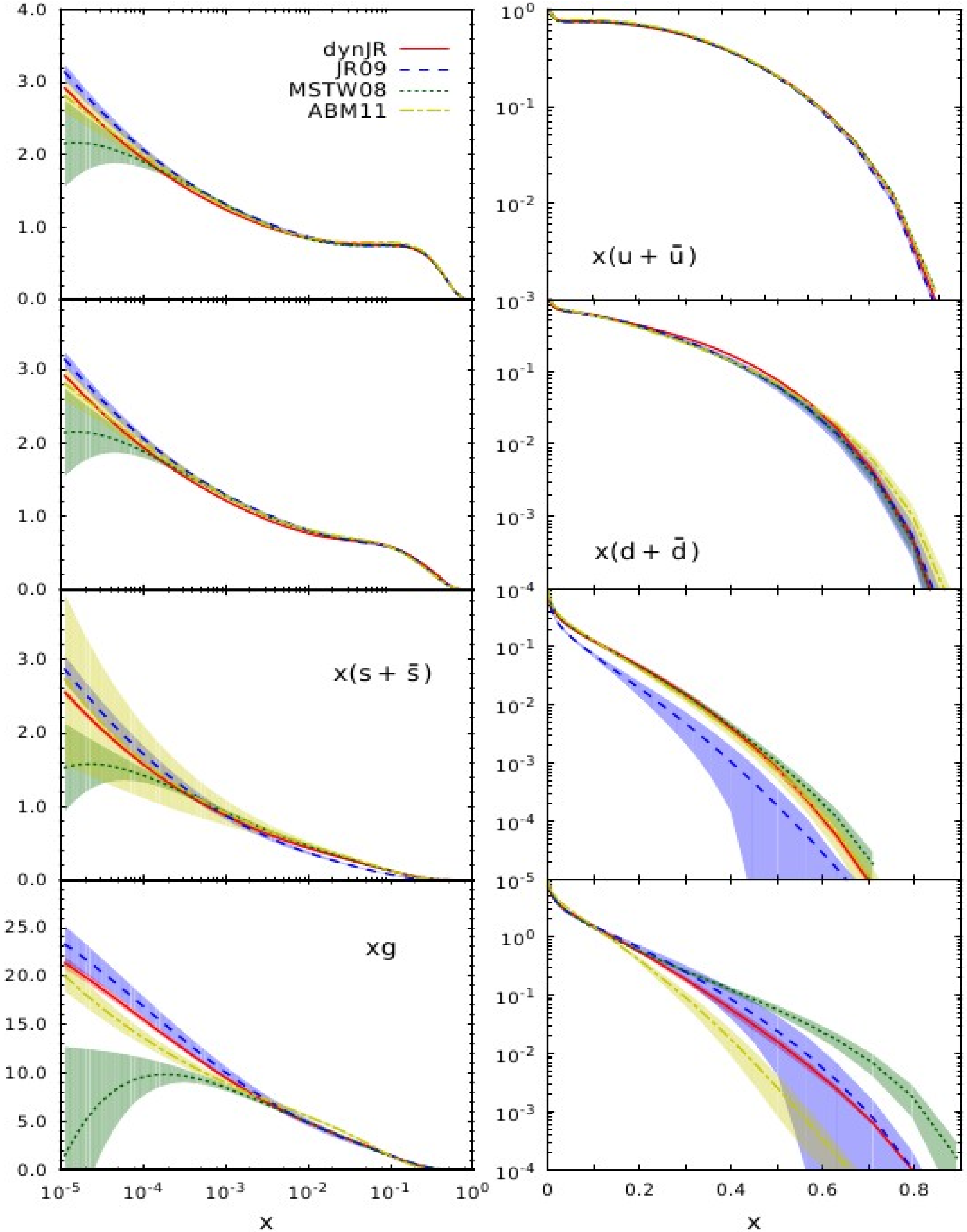
u-valence rather well determined

larger differences for d-valence, but also quite stable

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

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

Singlet sector



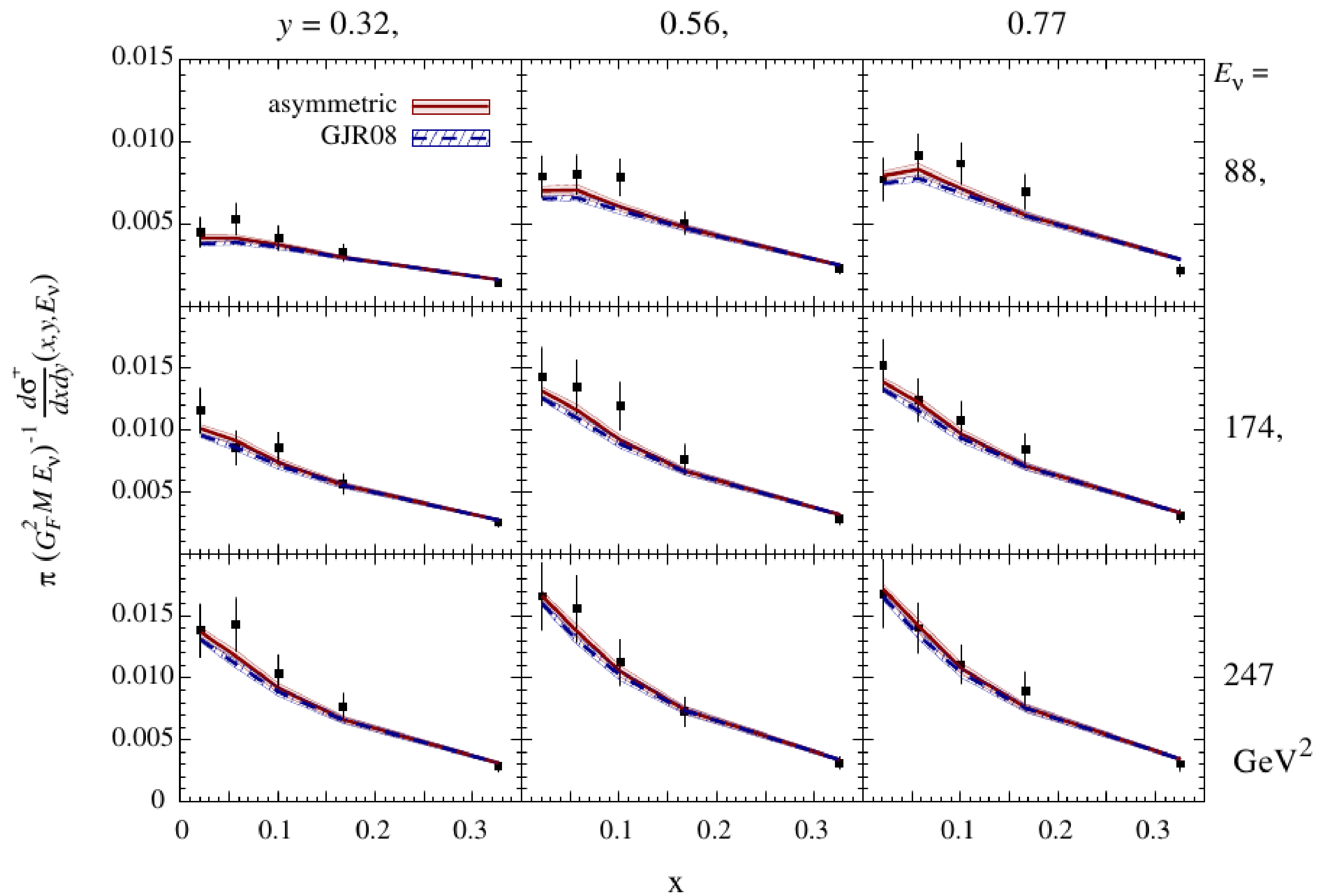
sea distributions at small x determined by the gluon via RGE evolution

d/u ratio at large x sensitive to nuclear corrections and differences parametrizations [CJ2010]

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

Largest and most relevant differences in the gluons (and α_s values)

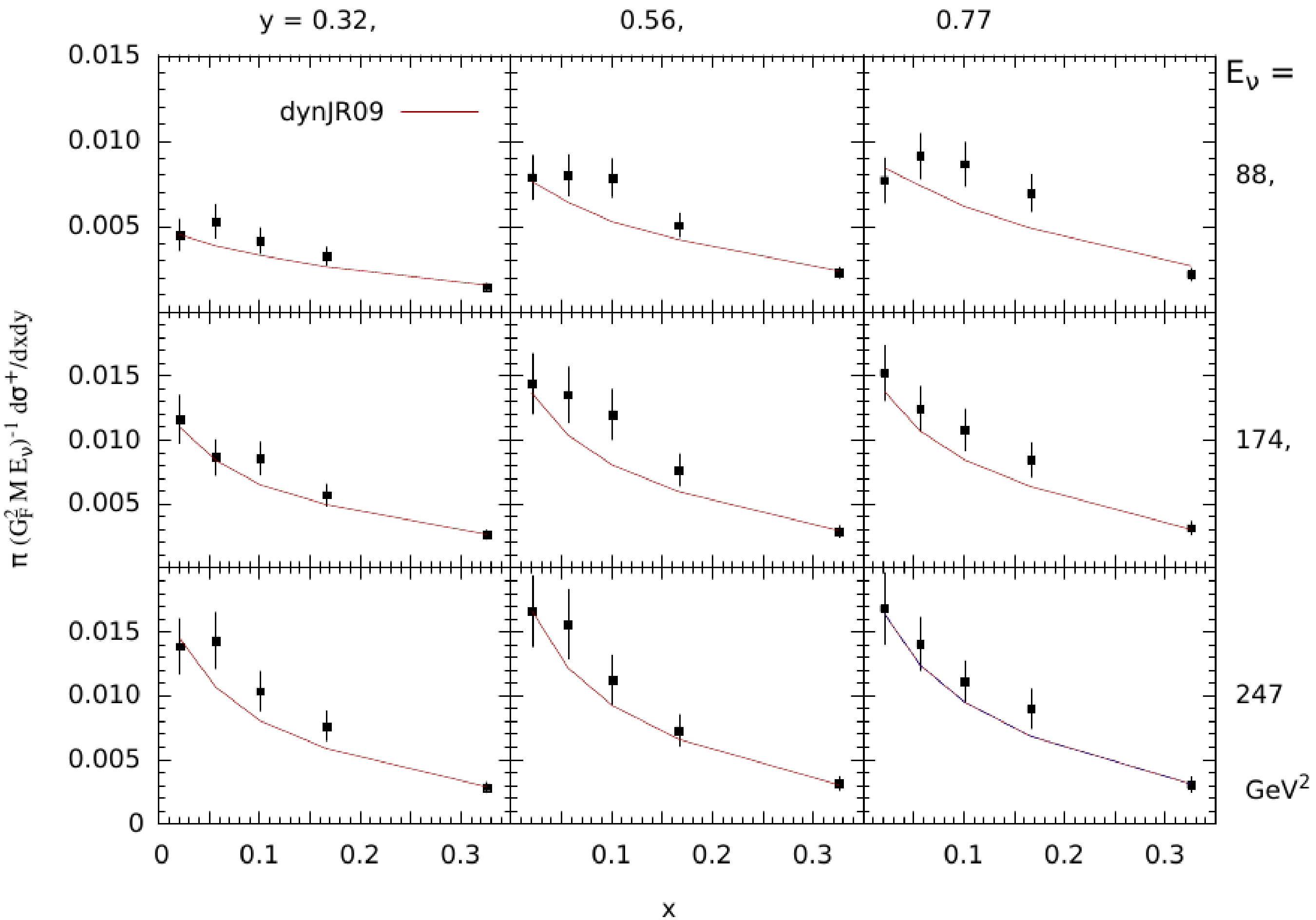
The dynamical determination of strange PDFs



Generated at NLO from $s(x,Q_0^2)+\bar{s}(x,Q_0^2)=0$ at $Q_0^2=0.5\ \mathrm{GeV}^2$

Data well described $\chi^2=65$ for 90 data points, plausible [PJD 2010]

The dynamical determination of strange PDFs



Generated at NNLO from $s(x,Q_0^2)+\bar{s}(x,Q_0^2)=0$ at $Q_0^2=0.55\ \mathrm{GeV}^2$

Not so different but predictions below data for most of the points,
now these data also included, even at NNLO (hopefully NNLO corrections are small)

The role of the input scale in PDF analysis

Any dependence is due to shortcomings of the estimation: *procedural bias*

[PJD 2012]

Typically parametrization bias

Example: backwards evolution to low scales leads to oscillating gluons

Excersise: systematic study with progresively more flexible parametrizations

$$xf(x,Q_0^2) = N_f \; x^{a_f}(1-x)^{b_f}(1+A_f\sqrt{x}+B_f x+C_f x^2)$$

Allow also for negative input gluons:

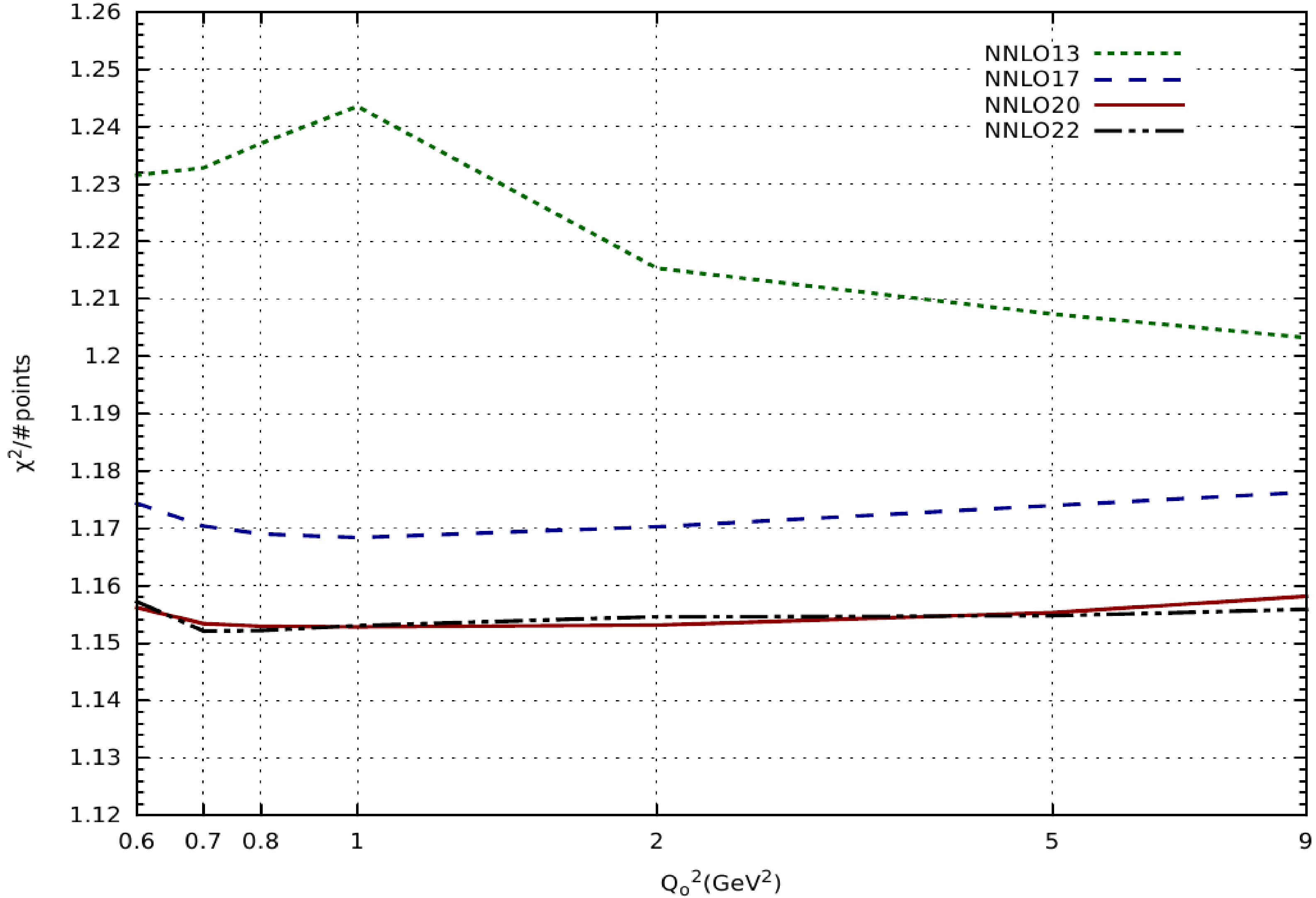
$$\mathrm{xg}(\mathrm{x},\mathrm{Q}_0^2) = N_g \; x^{a_g}(1-x)^{b_g}\left(1+N_g' \; x^{a_g'}(1-x)^{25}\right)$$

	NNLO13	NNLO17	NNLO20	NNLO22
a_{u_v}	$\surd$	$\surd$	$\surd$	$\surd$
b_{u_v}	$\surd$	$\surd$	$\surd$	$\surd$
A_{u_v}	–	–	$\surd$	$\surd$
B_{u_v}	–	$\surd$	$\surd$	$\surd$
C_{u_v}	$\surd$	$\surd$	$\surd$	$\surd$
a_{d_v}	$\surd$	$\surd$	$\surd$	$\surd$
b_{d_v}	$\surd$	$\surd$	$\surd$	$\surd$
A_{d_v}	–	$\surd$	$\surd$	$\surd$
B_{d_v}	–	–	$\surd$	$\surd$
C_{d_v}	–	–	–	–
N_Δ	$\surd$	$\surd$	$\surd$	$\surd$
a_Δ	$\surd$	$\surd$	$\surd$	$\surd$
b_Δ	$\surd$	$\surd$	$\surd$	$\surd$
A_Δ	–	$\surd$	$\surd$	$\surd$
B_Δ	–	–	–	–
C_Δ	–	–	–	–
N_Σ	$\surd$	$\surd$	$\surd$	$\surd$
a_Σ	$\surd$	$\surd$	$\surd$	$\surd$
b_Σ	$\surd$	$\surd$	$\surd$	$\surd$
A_Σ	–	$\surd$	$\surd$	$\surd$
B_Σ	–	–	$\surd$	$\surd$
C_Σ	–	–	–	–
a_g	$\surd$	$\surd$	$\surd$	$\surd$
b_g	$\surd$	$\surd$	$\surd$	$\surd$
N_g'	–	–	–	$\surd$
a_g'	–	–	–	$\surd$

The role of the input scale in PDF analysis

χ^2 decreases at first and stabilizes at NNLO20:

allowing for negative gluons (at any scale) does *not* improve the description

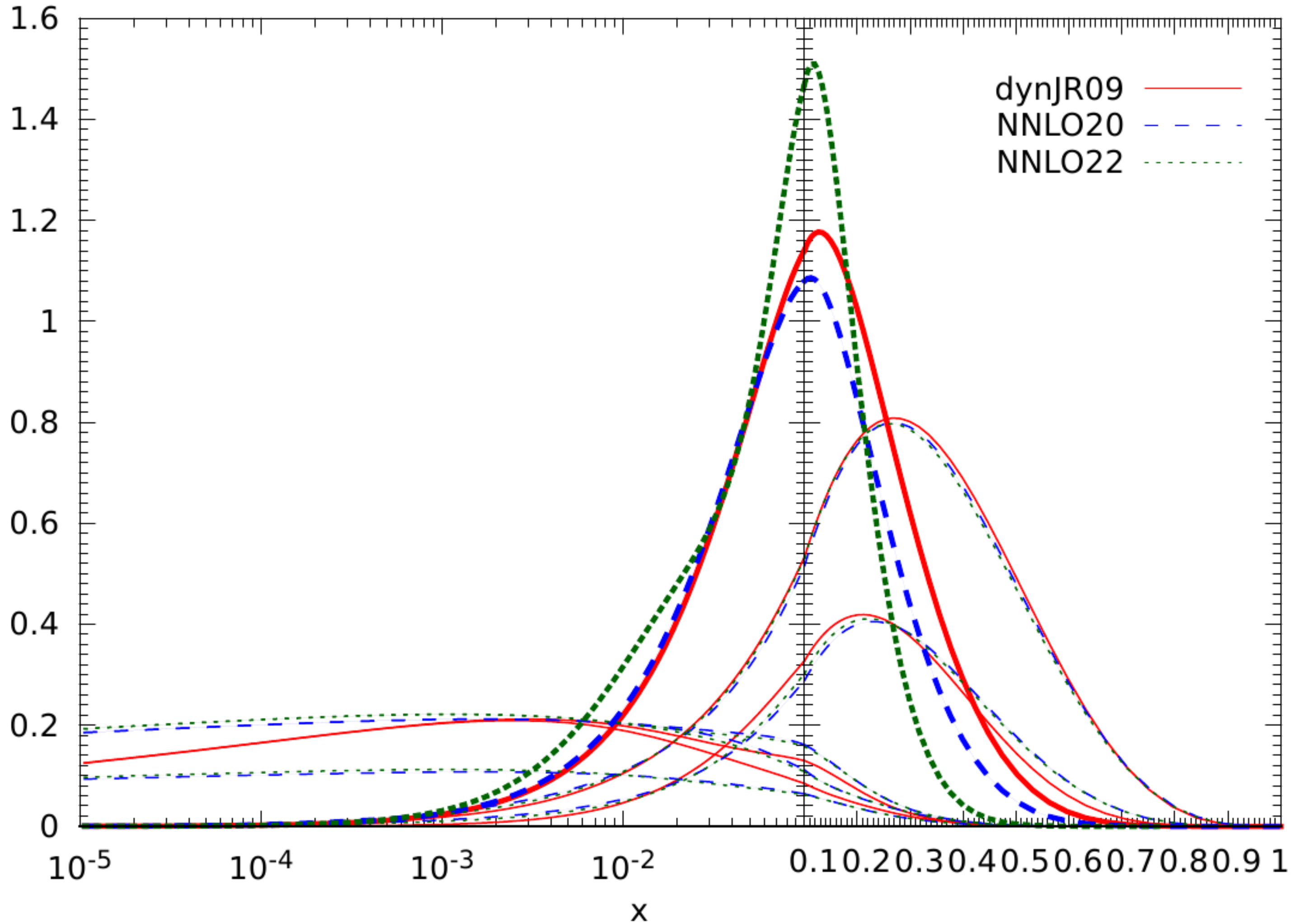


These variations can be used to estimate the procedural bias

(devise a measure: e.g. in (G)JR half the difference between dynamical and standard)

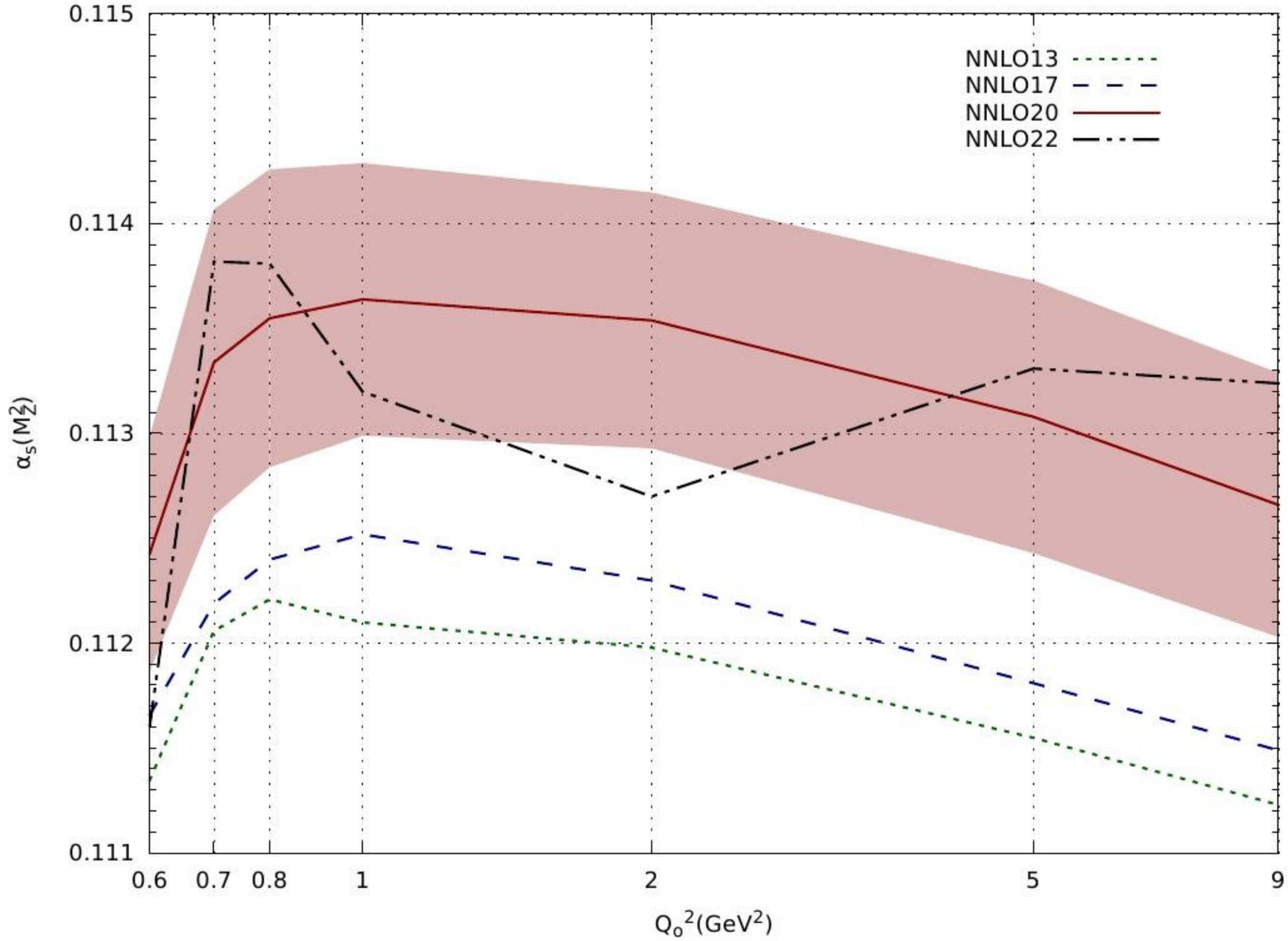
Positive input gluon distributions

NNLO22 with $Q_0^2 = 0.6\ \mathrm{GeV}^2$ does *not* turn negative, remains *valence-like* $(a_g \simeq 1, a'_g \simeq 1.2)$ ⇒ *natural tendency* of the input gluons at low scales



Uncertainties in the strong coupling

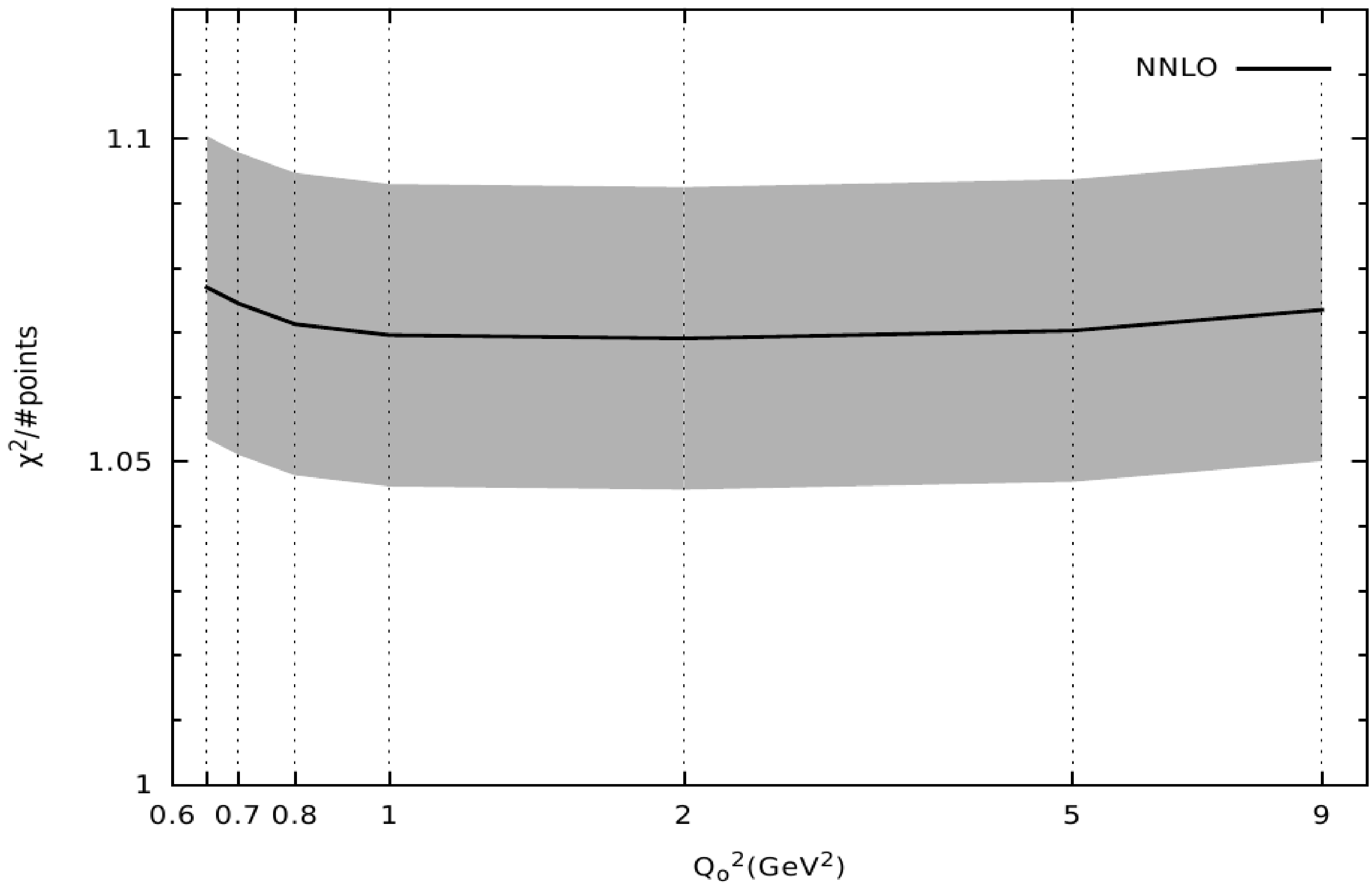
Results stabilize at NNLO20 but variations do not (substantially) decrease



Following our "recipe" we would estimate $\Delta_{\mathrm{bias}} \simeq 0.0006$

About the *same size* than the error from experimental uncertainties!

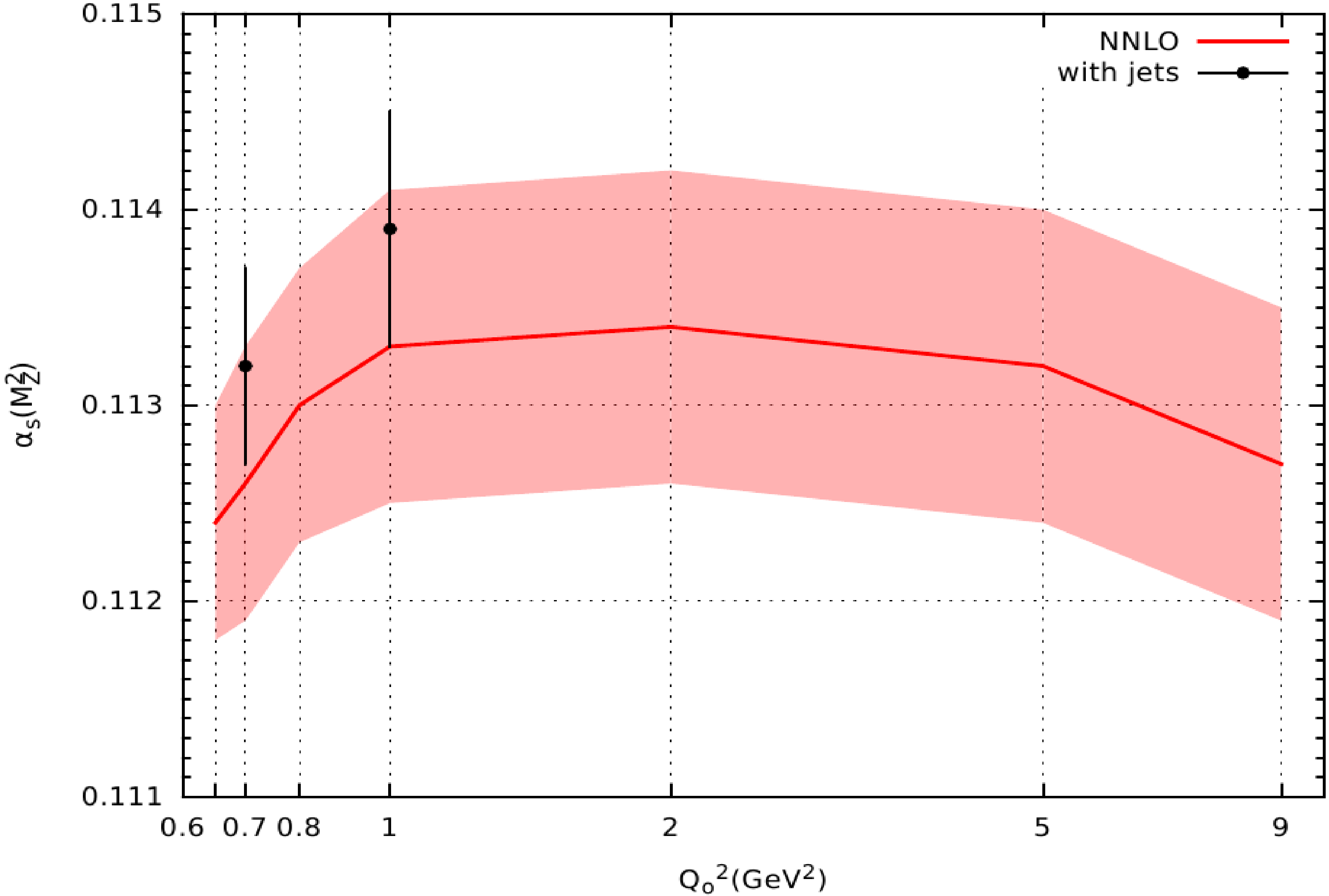
Dynamical scale in the current update (JR13)



Here error band for N points given by $\frac{\sqrt{2N}}{N}$ (parameter errors by $\Delta\chi^2 = 1$)

Fits become unstable at about $0.6\ \mathrm{GeV}^2 \Rightarrow$ new dynamical scale $0.7\ \mathrm{GeV}^2$

Strong coupling in the current update (JR13)

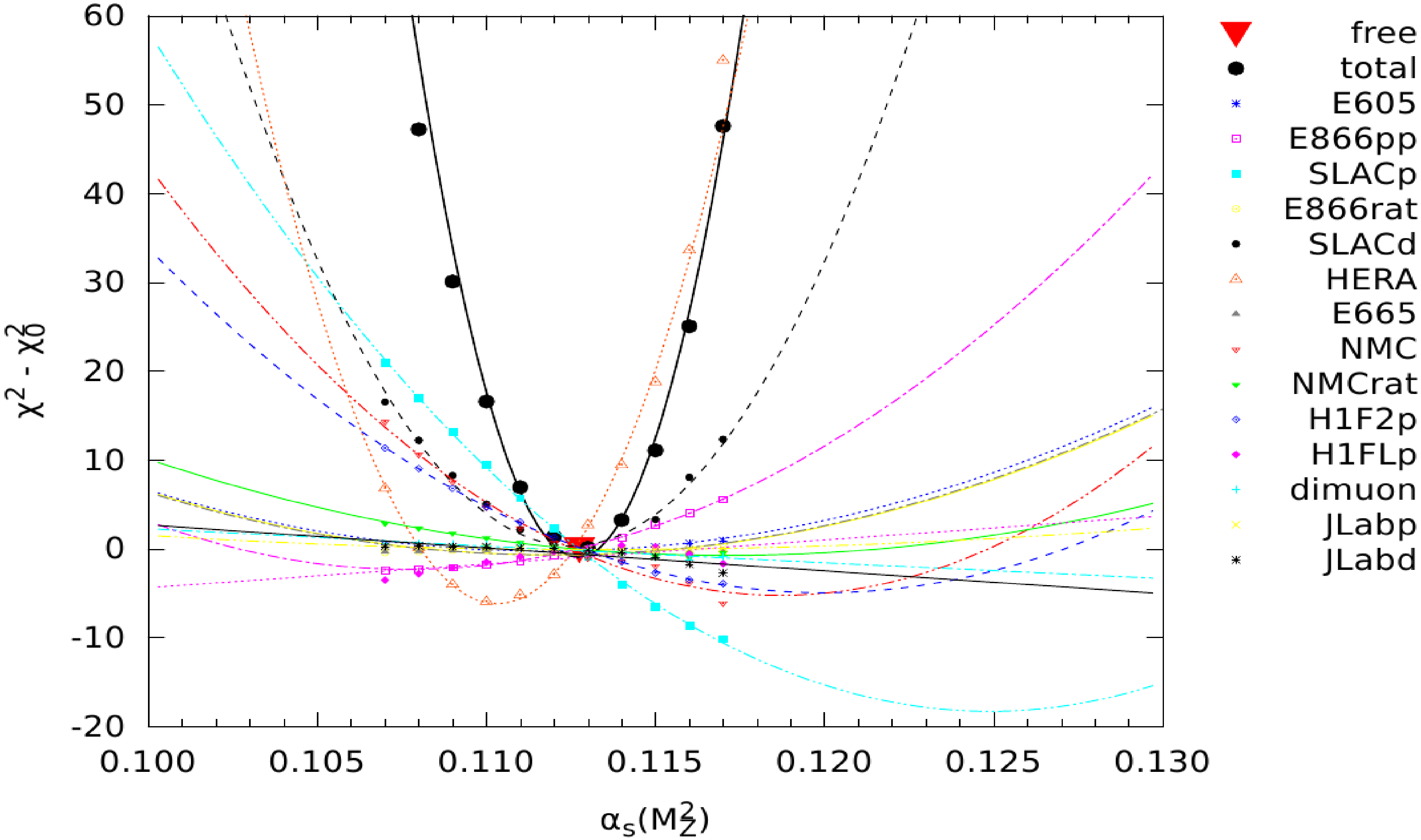


Central values in good agreement with JR09 and AB(K)M

Uncertainties: $\Delta_{\rm exp} \simeq 0.0006\,,\ \Delta_{\rm bias} \simeq 0.0005,\ \Delta_{\rm theo} \simeq ??$

Jets increase *a bit* central values but not dramatically

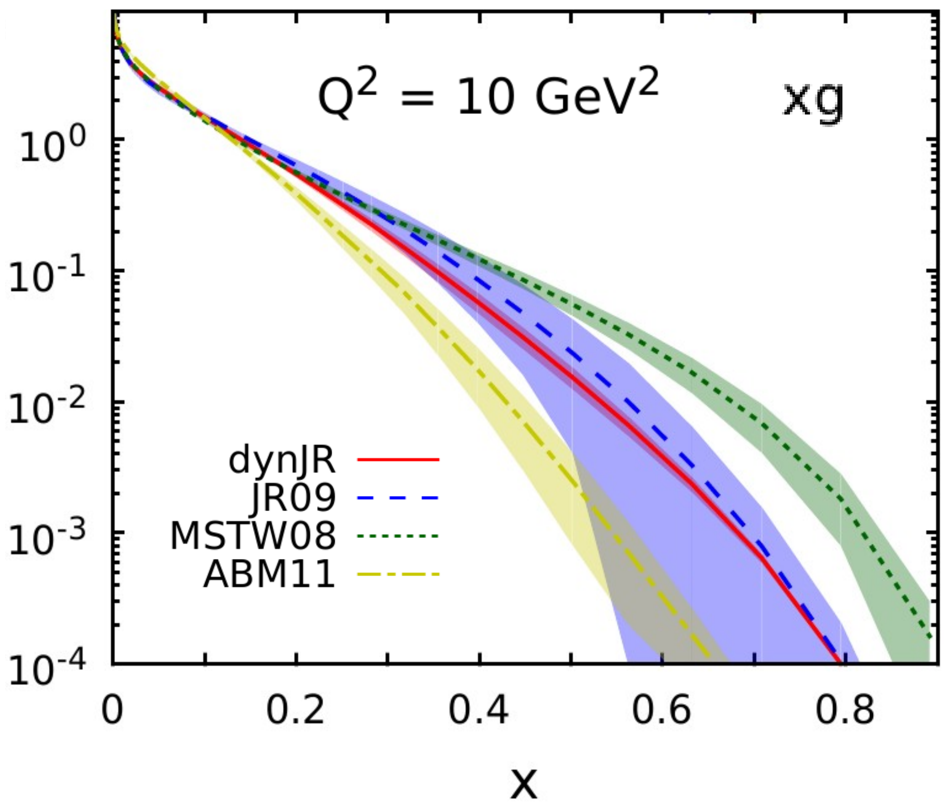
Strong coupling in the current update (JR13)

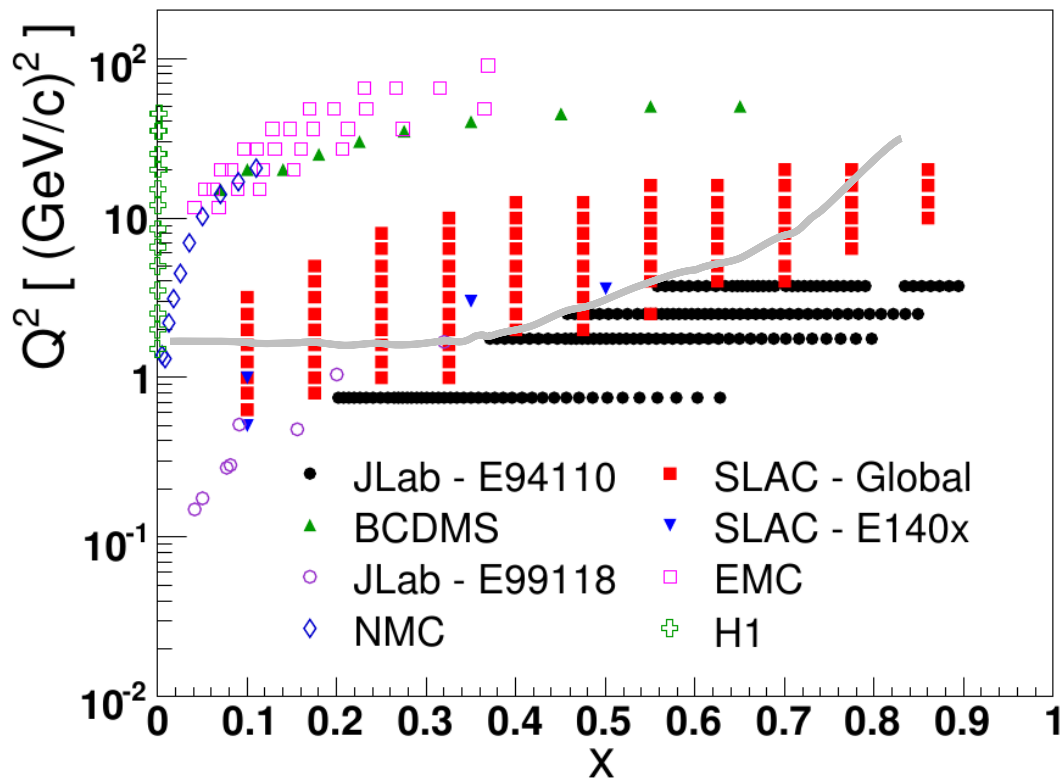


Tension between inclusive cross-sections from HERA and major fixed-target experiments (SLAC, NMC)

Fit finds a compromise: intermediate central value with reduced uncertainties (artificially? tolerance parameter?)

Major remaining difference: large-x gluons





[Monaghan et al. 2012]

The JR gluons at large x are *very stable*: not very sensitive to the inclusion of jet data and describe well the Rosenbluth separated F_L data

As a matter of fact the error has become very small, we have extended the parametrization to study this

Summary and outlook

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 analysis of the impact of JLab data

Other developments in progress or planned: symmetric sea, OAM, SIDIS, RHIC

An update of the JR unpolarized distributions currently in preparation

Preliminary results consistent with JR09 although with some improvements

At low input scales the *natural* tendency of gluons is a *valence-like* structure

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

α_s and gluon distributions rather stable; some issues still in study