The JAM fits of polarized PDFs

<u>Alberto Accardi</u>
P. Jimenez-Delgado, W. Melnitchouk
(for the JAM collaboration)

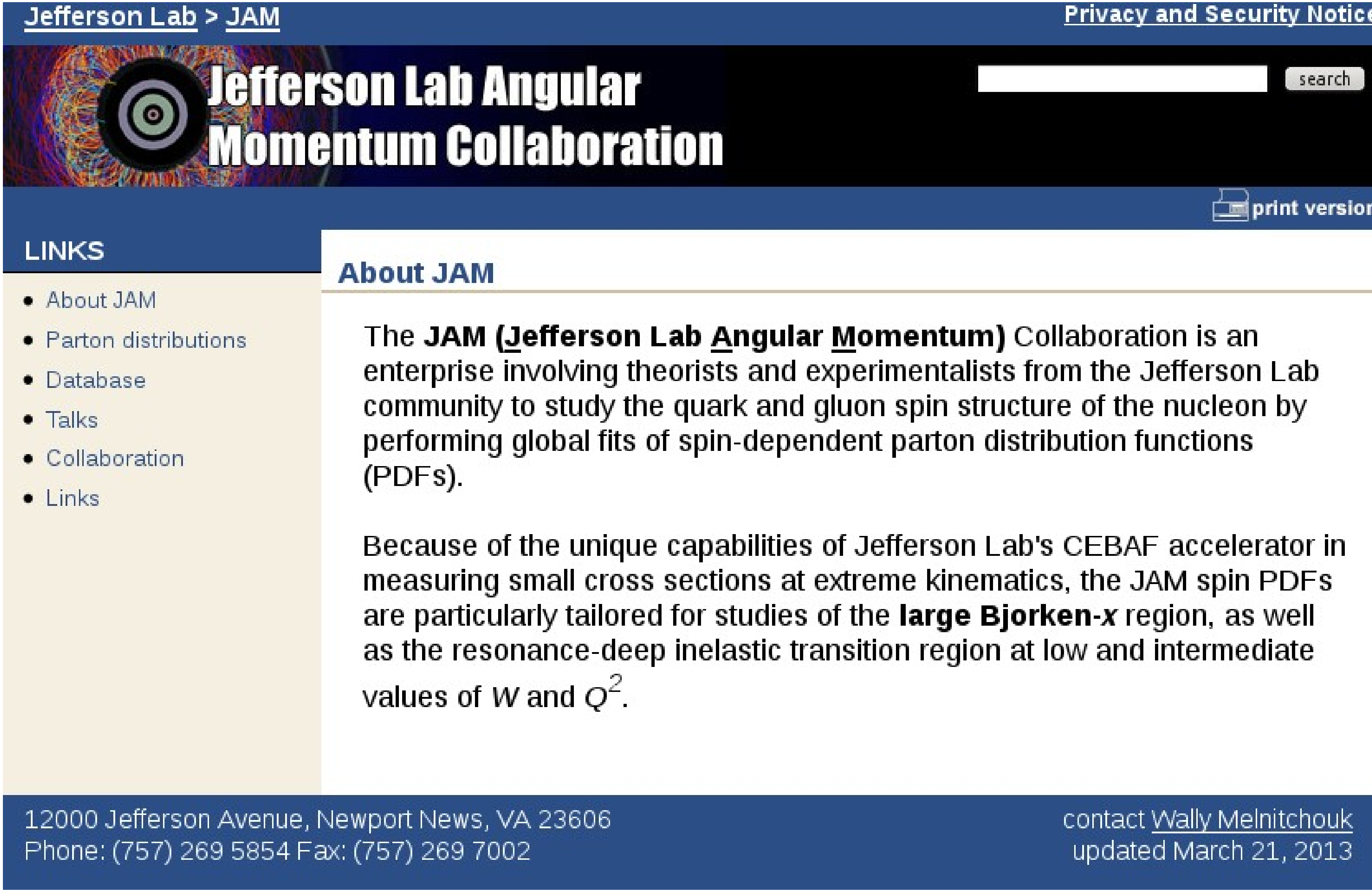
Jimenez-Delgado, Accardi, Melnitchouk, PRD89 (2014) 034025

HAMPTON UNIVERSITY

Jefferson Lab

The JAM collaboration

www.jlab.org/jam



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Jefferson Lab Angular Momentum 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.

12000 Jefferson Avenue, Newport News, VA 23606
Phone: (757) 269 5854 Fax: (757) 269 7002

contact Wally Melnitchouk
updated March 21, 2013

Parallel effort to our unpolarized PDFs: CJ and JR

Who's who

www.jlab.org/jam

Theory:

- Pedro Jimenez-Delgado *(JLab)*
- Alberto Accardi *(Hampton U. / JLab)*
- Jacob Ethier *(William and Mary)*
- Wally Melnitchouk *(Jlab)*
- Nobuo Sato *(soon at JLab)*

Experiment:

- Harut Avakian *(JLab)*
- Peter Bosted *(JLab / William&Mary)*
- Jian-ping Chen *(JLab)*
- Keith Griffioen *(William&Mary)*
- Sebastian Kuhn *(Old Dominion U.)*
- Yelena Prok *(Old Dominion U.)*
- Oscar Rondon *(U. of Virginia)*
- Brad Sawatzky *(JLab)*

The JAM database

www.jlab.org/jam

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

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Experiments

- All data
- proton
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- 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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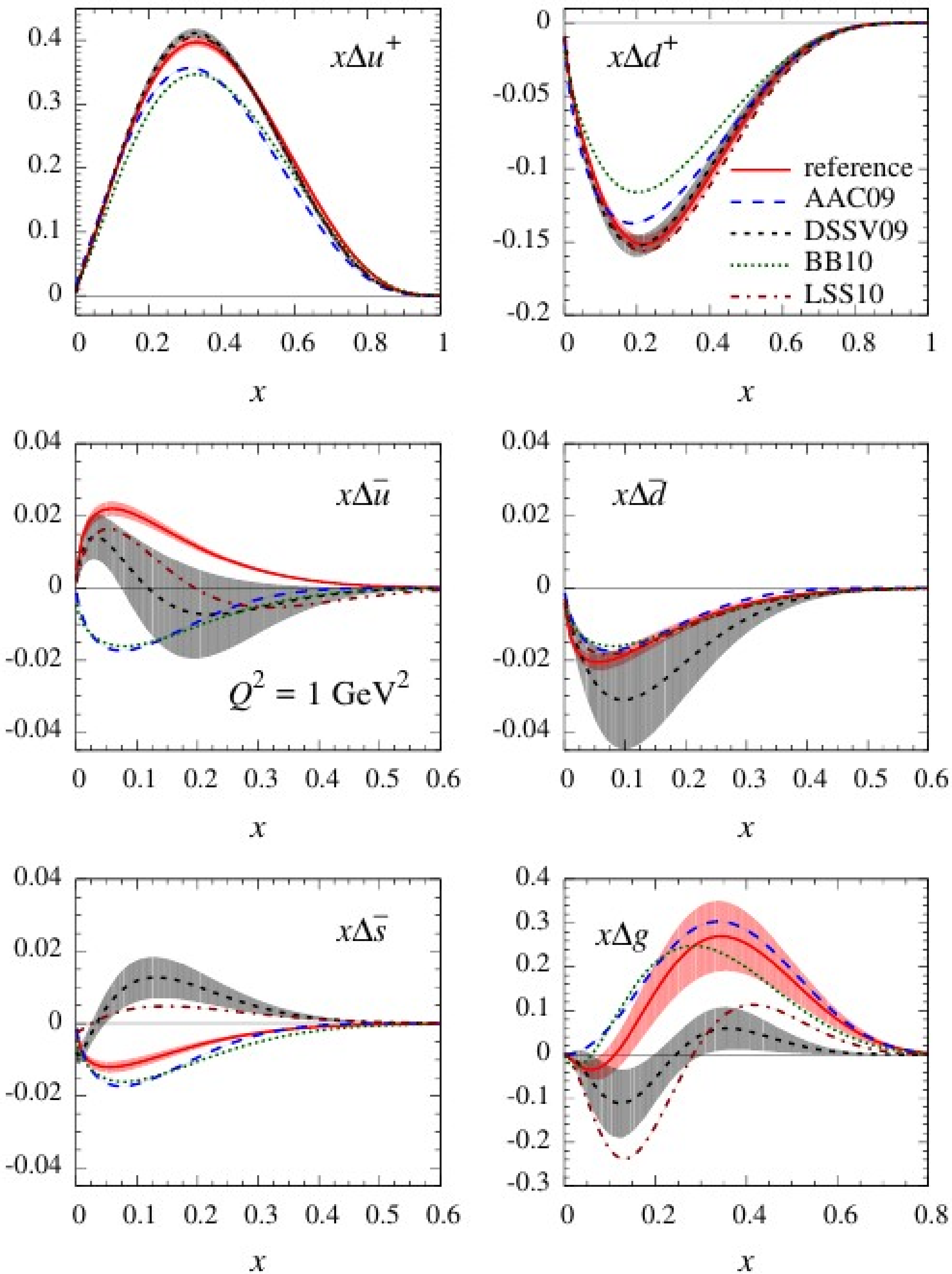
Data and theory comparison with other groups

	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	✓		(π^0 in 2014)	✓	✓	✓	✓

Presently concentrating on DIS theoretical description

Long-term objective: tick all the boxes (include SIDIS and collider data)

Current status of polarized PDFs



Worse known than the unpolarized

$\Delta u^+ = \Delta u + \Delta\bar{u}$ and
$\Delta d^+ = \Delta d + \Delta\bar{d}$ best 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)

NOTES:
Red: JAM reference (LT, no corrections)
Updated DSSV gluon in arXiv:1404.4293

Data considered at this (first) stage

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

Mainly using *measured* asymmetries:

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

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

Note: D, d depend on

$$R = \frac{F_L}{(1+\gamma^2)F_2 - F_L} \qquad \gamma^2 = 4\frac{M^2}{Q^2}x^2$$

$\longrightarrow$ We *consistently* develop our own Unpolarized analysis in parallel (JR)

experiment	reference	observable	target	$N_{\rm data}$	$\chi^2({\rm LT})/N_{\rm dat}$	$\chi^2({\rm JAM})/N_{\rm dat}$
EMC	[1]	A_1	p	10	0.42	0.39
SMC	[30]	A_1	p	12	0.36	0.36
	[30]	A_1	d	12	1.59	1.66
	[31]	A_1	p	8	1.37	1.35
	[31]	A_1	d	8	0.54	0.56
COMPASS	[32]	A_1	p	15	0.95	0.97
	[33]	A_1	d	15	0.57	0.51
SLAC E80/E130	[34]	$A_{\parallel}$	p	23	0.52	0.54
SLAC E142	[35]	A_1	^{3}He	8	0.58	0.70
	[35]	A_2	^{3}He	8	0.70	0.70
SLAC E143	[36]	$A_{\parallel}$	p	85	0.85	0.81
	[36]	$A_{\perp}$	p	48	0.95	0.91
	[36]	$A_{\parallel}$	d	85	1.05	0.85
	[36]	$A_{\perp}$	d	48	0.92	0.91
SLAC E154	[37]	$A_{\parallel}$	^{3}He	18	0.43	0.42
	[37]	$A_{\perp}$	^{3}He	18	1.00	1.00
SLAC E155	[38]	$A_{\parallel}$	p	73	1.00	0.92
	[38, 39]	$A_{\perp}$	p	66	1.00	0.96
	[40]	$A_{\parallel}$	d	73	0.98	0.97
	[39, 40]	$A_{\perp}$	d	66	1.51	1.49
SLAC E155x	[41]	$\tilde{A}_{\perp}$	p	117	2.17	1.64
	[41]	$\tilde{A}_{\perp}$	d	117	0.90	0.84
HERMES	[42]	$A_{\parallel}$	p	37	0.38	0.39
	[42]	$A_{\parallel}$	d	37	0.86	0.85
	[43]	A_1	"n"	9	0.29	0.30
	[44]	A_2	p	20	1.07	1.16
JLab E99-117	[45]	$A_{\parallel}$	^{3}He	3	0.62	0.06
	[45]	$A_{\perp}$	^{3}He	3	1.08	0.87
COMPASS	[49]	$\Delta g/g$	p	1	5.27	2.71
total				1043	1.07	0.98
JLab E97-103*	[46]	$A_{\parallel}$	^{3}He	2	—	—
	[46]	$A_{\perp}$	^{3}He	2	—	—
JLab EG1b*	[48]	A_1	p	766	—	—
(prelim.)	[48]	A_1	d	767	—	—

Impact of high-statistics data from JLab is being analyzed

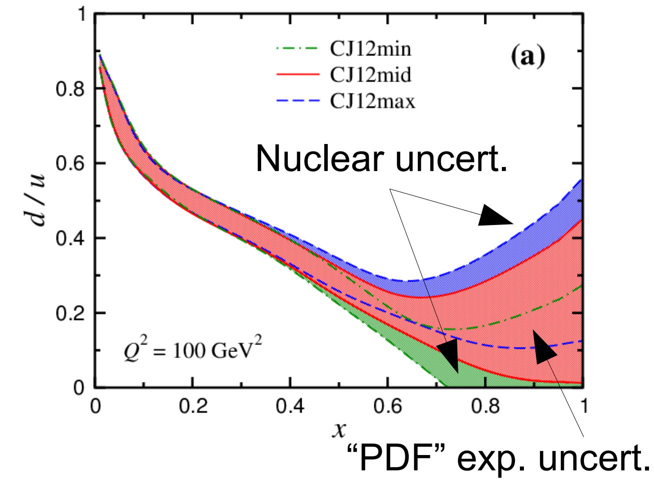
Jlab EG1-dvcs: g_1/F_1 fresh from the web arXiv:1404.6231

Unpolarized PDF fits with large-x corrections

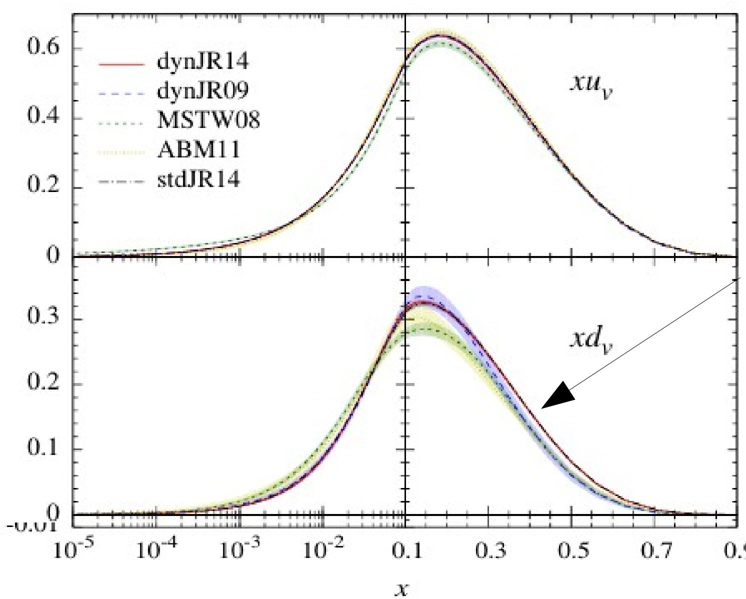
- Unpolarized PDF needed to calculate denominators of helicity asymmetries

- Fits developed in parallel to JAM; similar philosophy, focus

→ **CJ12** [CTEQ-JLab] – *Owens, Accardi, Melnitchouk PRD87 (2013) 094012*
  - HT, TMCs
  - Nuclear, off-shell corrections
  - ***Nuclear uncertainties quantified***



→ **JR14** – *Jimenez-Delgado, Reya, arXiv:1403.1852*
  - HT, TMCs
  - Nuclear (Paris w.fn. only), off-shell
  - ***Used in JAM fits***



→ see also **ABM 12** –

Alekhin, Bluemleim, Moch, PRD86 (2012) 054009

Underlying QCD description

Asymmetries from (un)polarized structure functions:

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

Calculations and RGE evolution using Mellin *moments* (truncated solutions)

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

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]

Parametrization

Only *two* independent combinations of **quark distributions** contribute:

$$x\Delta u^+(x,\mu_0^2) = N_u\, x^{a_u}(1-x)^{b_u}(1 + A_u\sqrt{x} + B_u\, x)$$
$$x\Delta d^+(x,\mu_0^2) = N_d\, x^{a_d}(1-x)^{b_d}(1 + A_d\sqrt{x} + B_d\, x)$$

$\Delta q^+ \equiv \Delta q + \Delta\bar{q}$

Constrains from hyperon decays relate N_u and N_d and fix N_s

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

Sea quarks shape fixed by counting rules and imposing

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

For the **gluons** we leave only Ng and Bg as free parameters

→ in practice current DIS data give only mild constraints

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

Statistical estimation

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

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

Unfortunately most experiments do not provide enough information

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

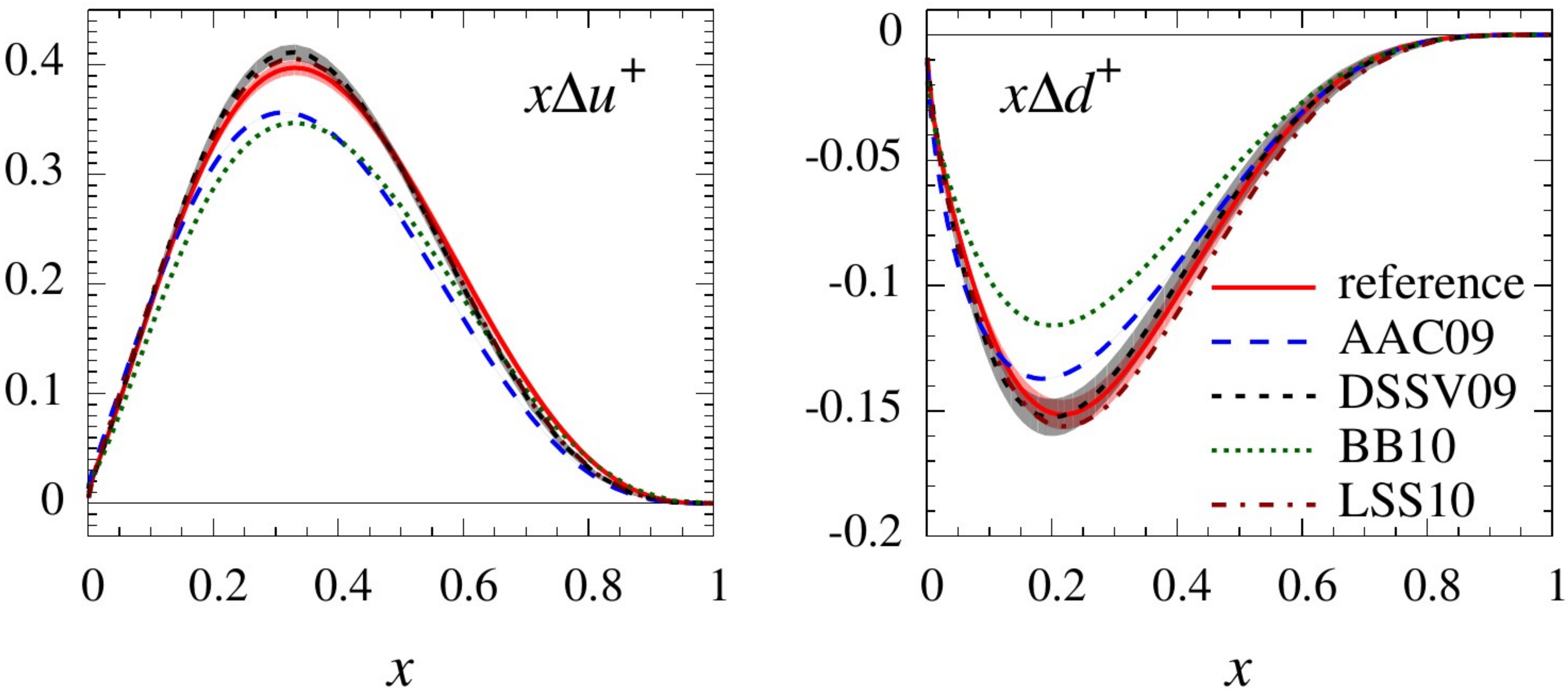
"Vicinity" of the minimum (tolerance) characterized by:

$$\Delta\chi^2 = \chi^2 - \chi^2_{min} \leq T^2 = 1$$

Simple fit without further corrections: REFERENCE

Nuclear targets treated within the "effective polarizations" approximation

$$g_1^d = (1 - \tfrac{3}{2}0.06)(g_1^p + g_1^n) \qquad g_1^{He3} = 0.86\, g_1^n - 0.059\, g_1^p$$



Baseline for assessing impact of theoretical corrections

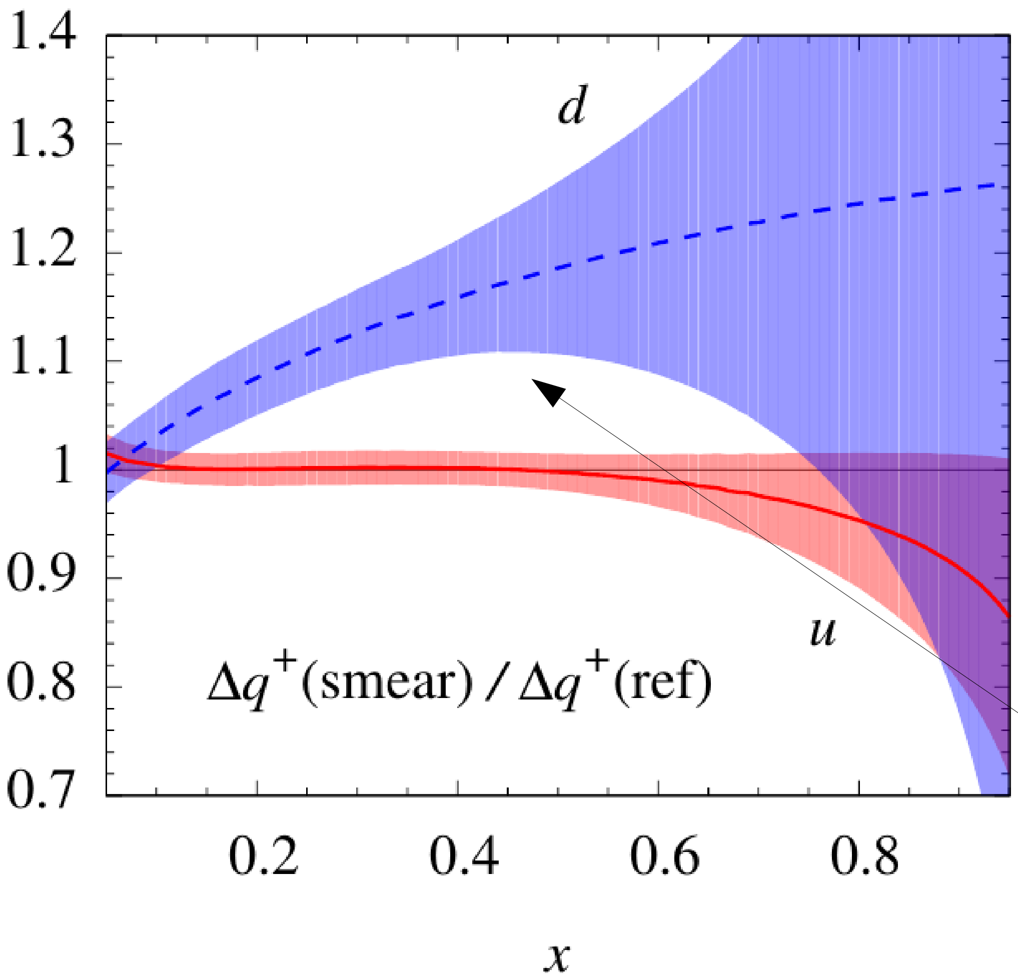
→ More similar to DSSV, LSS than to others

Improved description of nuclear targets

Binding, Fermi motion included in "smearing" formalism [Kulagin, Petti 06]

$\longrightarrow$ smearing functions f_{jN} derived from nuclear spectral functions

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



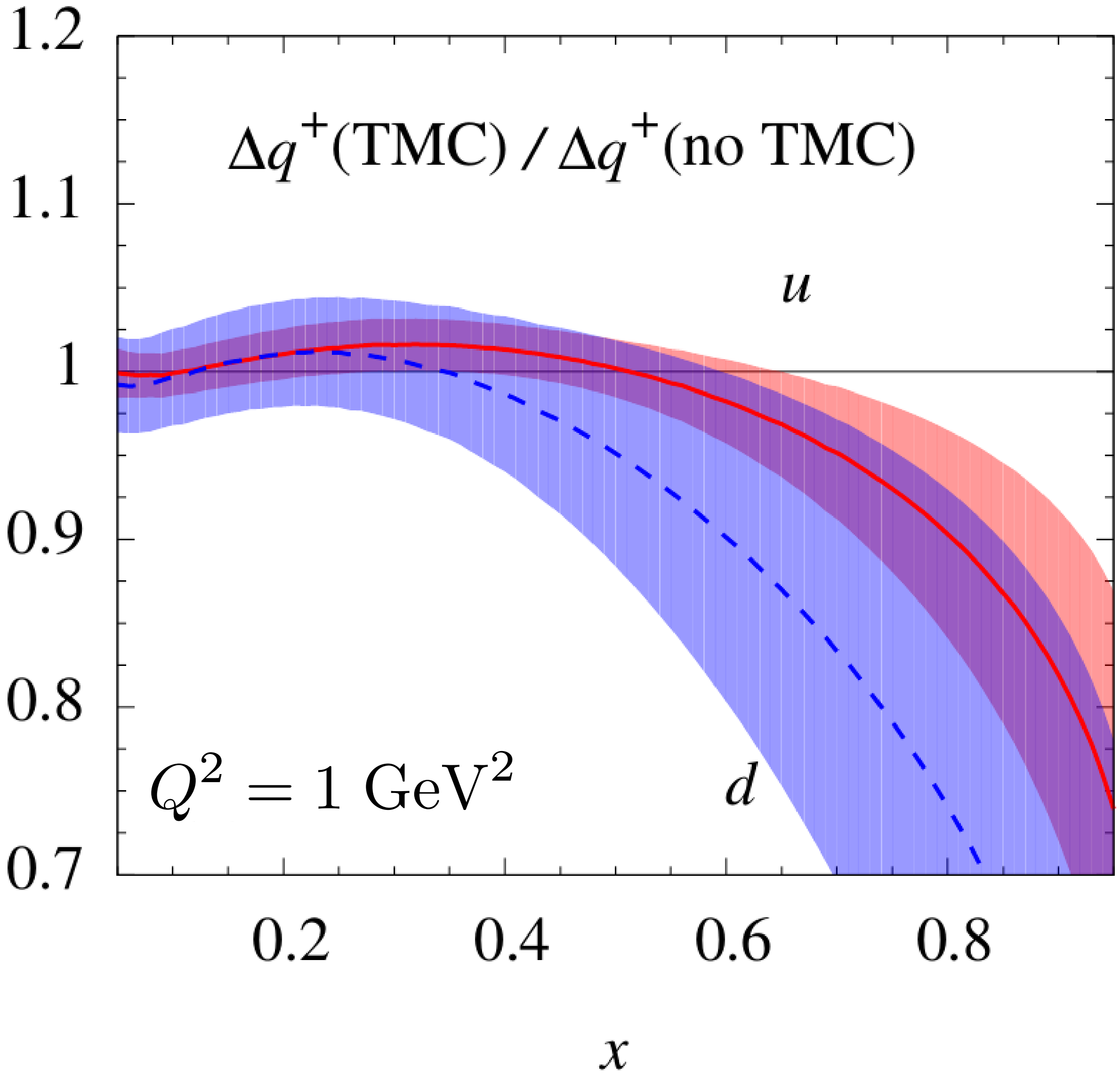
Relevant **for Δd in the medium- to large-*x* region**

Plus target-mass corrections

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

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

[Bluemlein, Tkabladze 99]



Note that the Wandzura-Wilzceck relation holds also after TMCs

Relevant* for both Δu and Δd at large-*x

Both nuclear and TMC corrections should be included in global fits

Plus higher twist contributions

We consider also corrections from higher twist contributions:

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

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

where $g_1^{\tau=3}$ depends on $g_2^{\tau=3}$ [Bluemlein, Tkabladze 99]

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

Flexible phenomenological parametrization for g_2 inspired by [Braun *et al.* 09]

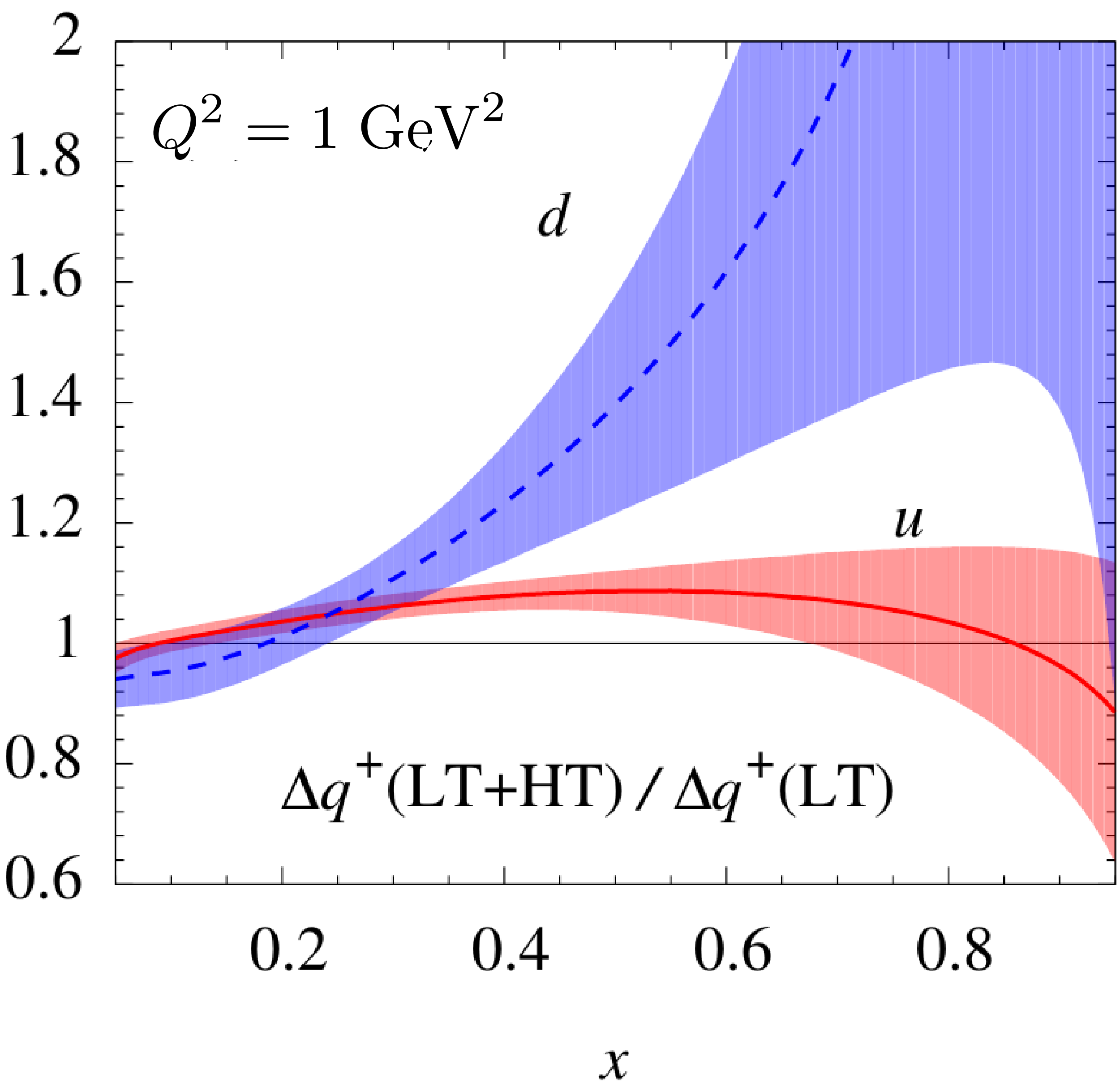
$$g_2^{\tau=3} = A[\ln x + (1-x) + \tfrac{1}{2}(1-x)^2] + (1-x)^3[B + C(1-x) + D(1-x)^2 + E(1-x)^3]$$

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

Possible scale dependence in h and $g_2^{\tau=3}$ neglected compared to exp. errors

Plus higher twist contributions

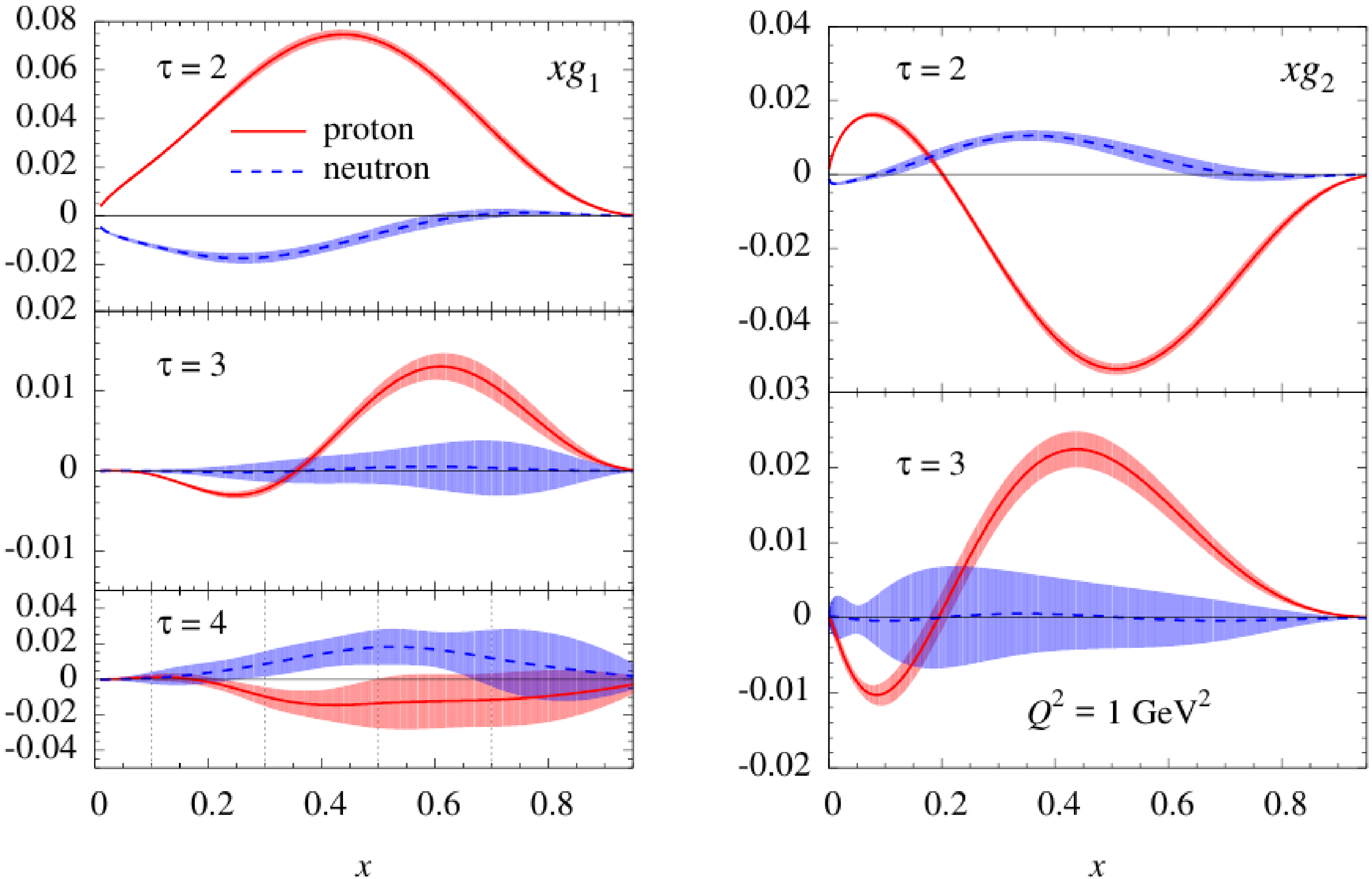
Considerable improvement of χ^2 for some sets (globally $1.07 \rightarrow 0.98$, 3σ)



Very large changes in Δd

Plus higher twist contributions

Possible to determine *simultaneously* higher-twist contributions for g_1 and g_2



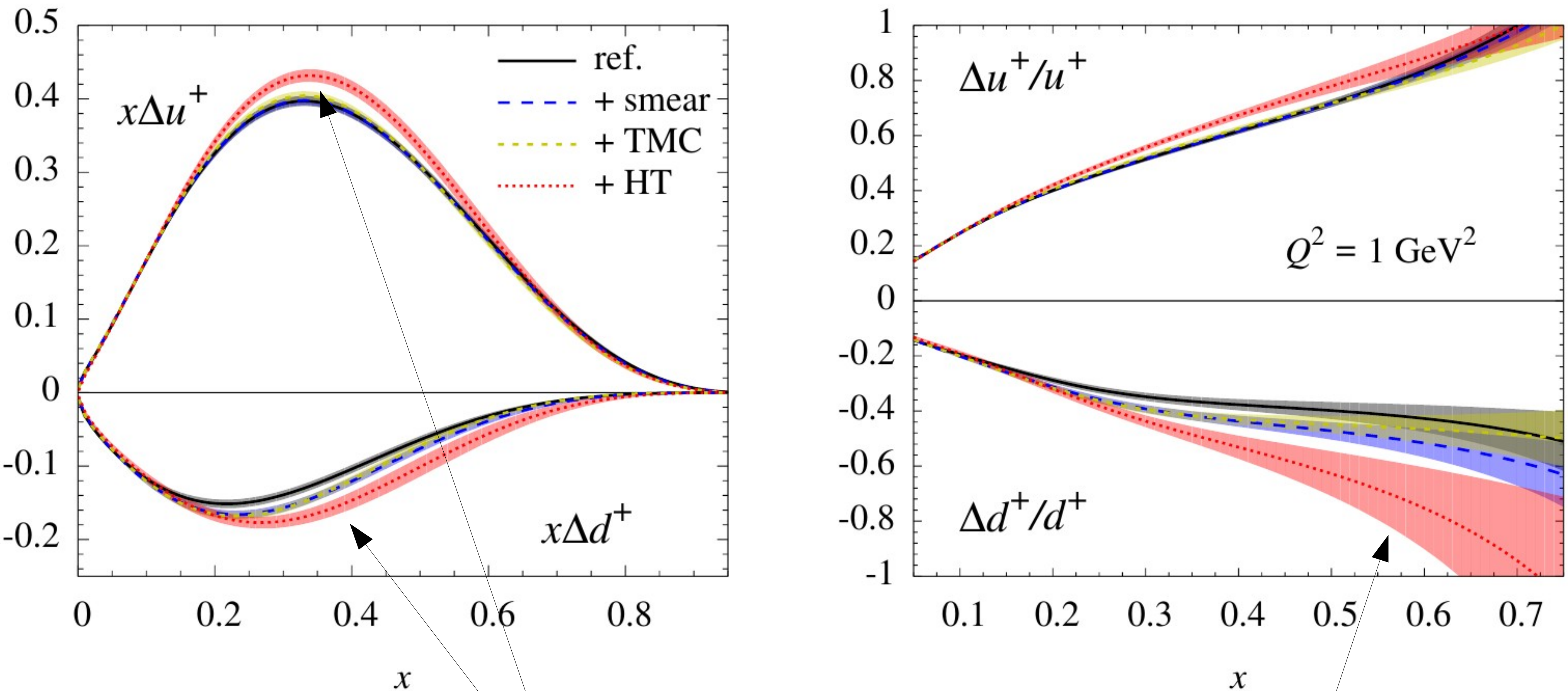
Qualitative agreement with previous (separated) determinations

⟶ [Leader, Sidorov, Stamenov 2010] on g_1

⟶ [Accardi, Bacchetta, Melnitchouk, Schlegel 2009] [Bluemlein, Bottcher 2012] on g_2

Including all corrections: JAM13

Jimenez-Delgado, Accardi, Melnitchouk, PRD89 (2014) 034025



No trace of $\Delta d/d \longrightarrow 1$ at $x \longrightarrow 1$ as expected in pQCD

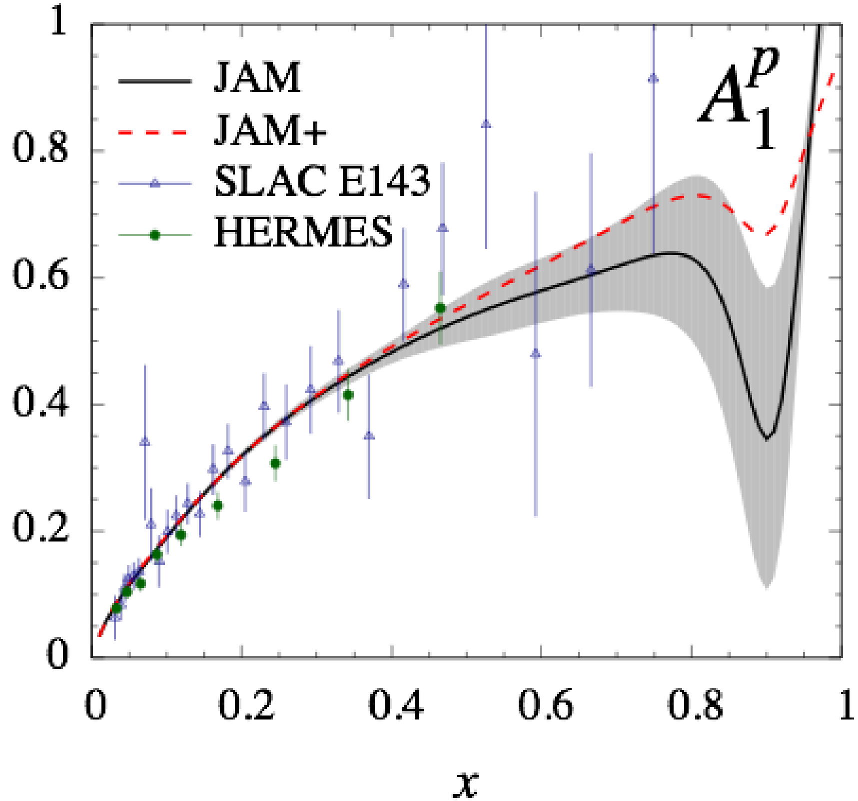
Relevant **for both** Δu **and** Δd

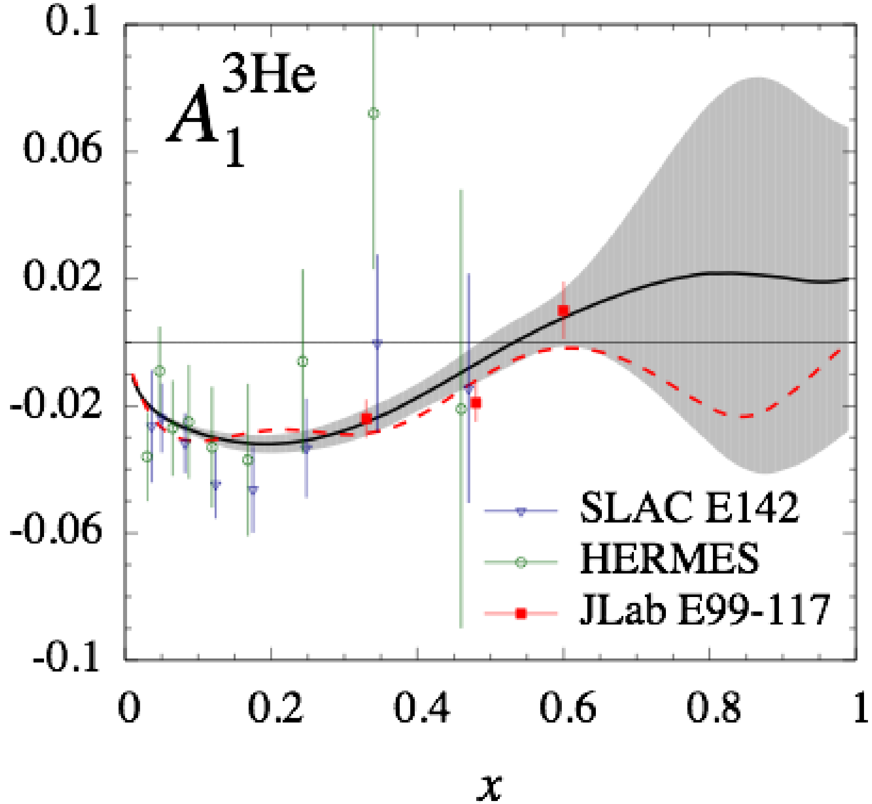
HT contributions are manifestly important for current DIS data

Constraints at large *x*

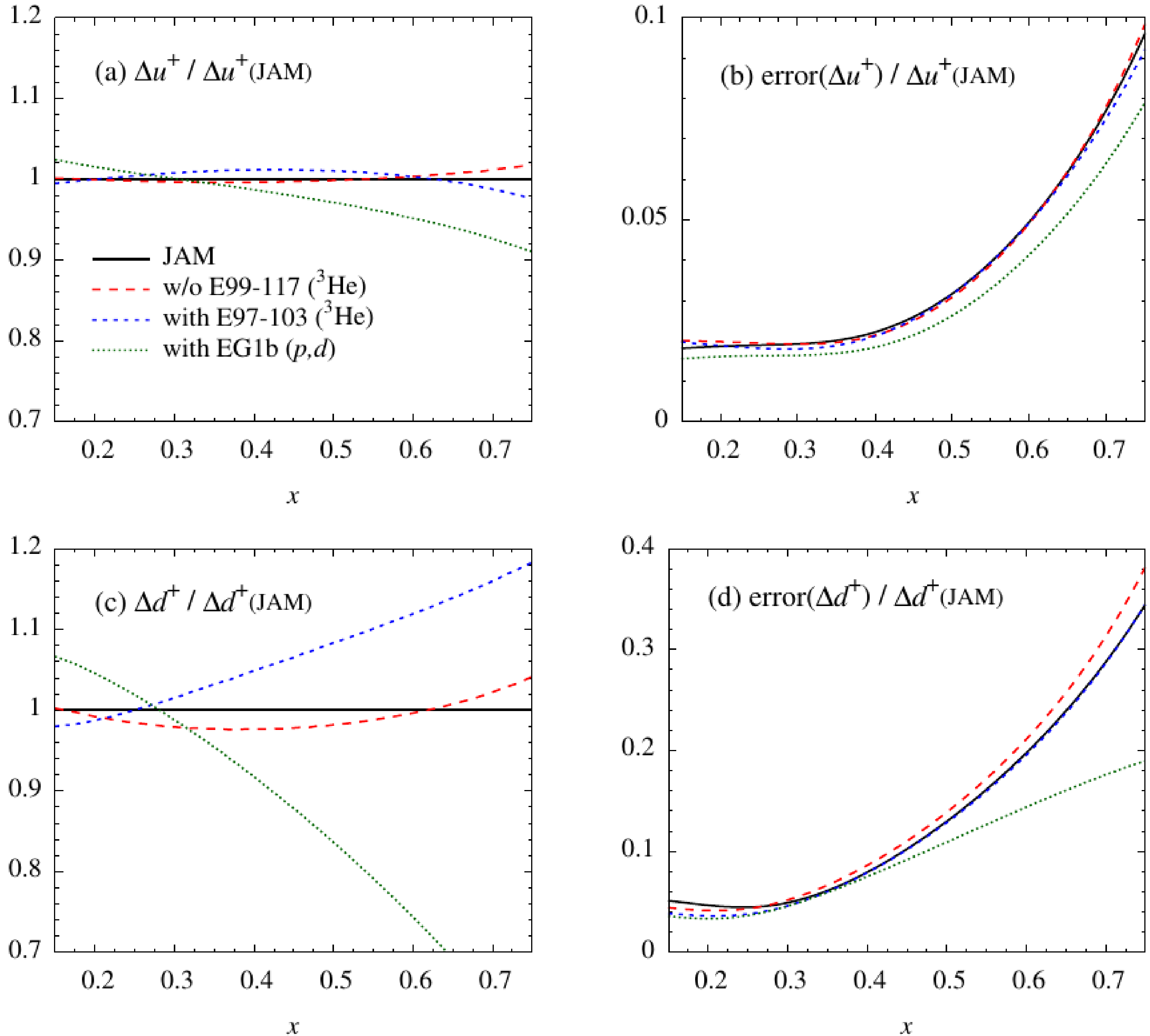
- Current data cannot discriminate different $\Delta u/u$ and $\Delta d/d$ behaviors
- Try and impose $x \rightarrow 1$ pQCD constraints by hand: **"JAM+" fit**
  - Large systematic (parametrization) uncertainty
  - **More data needed at large *x*!**
    (e.g., JLab EG1-dvcs, EG1b and JLab12 in near future)

Jimenez-Delgado, Avakian, Melnitchouk, arXiv:1403.3355





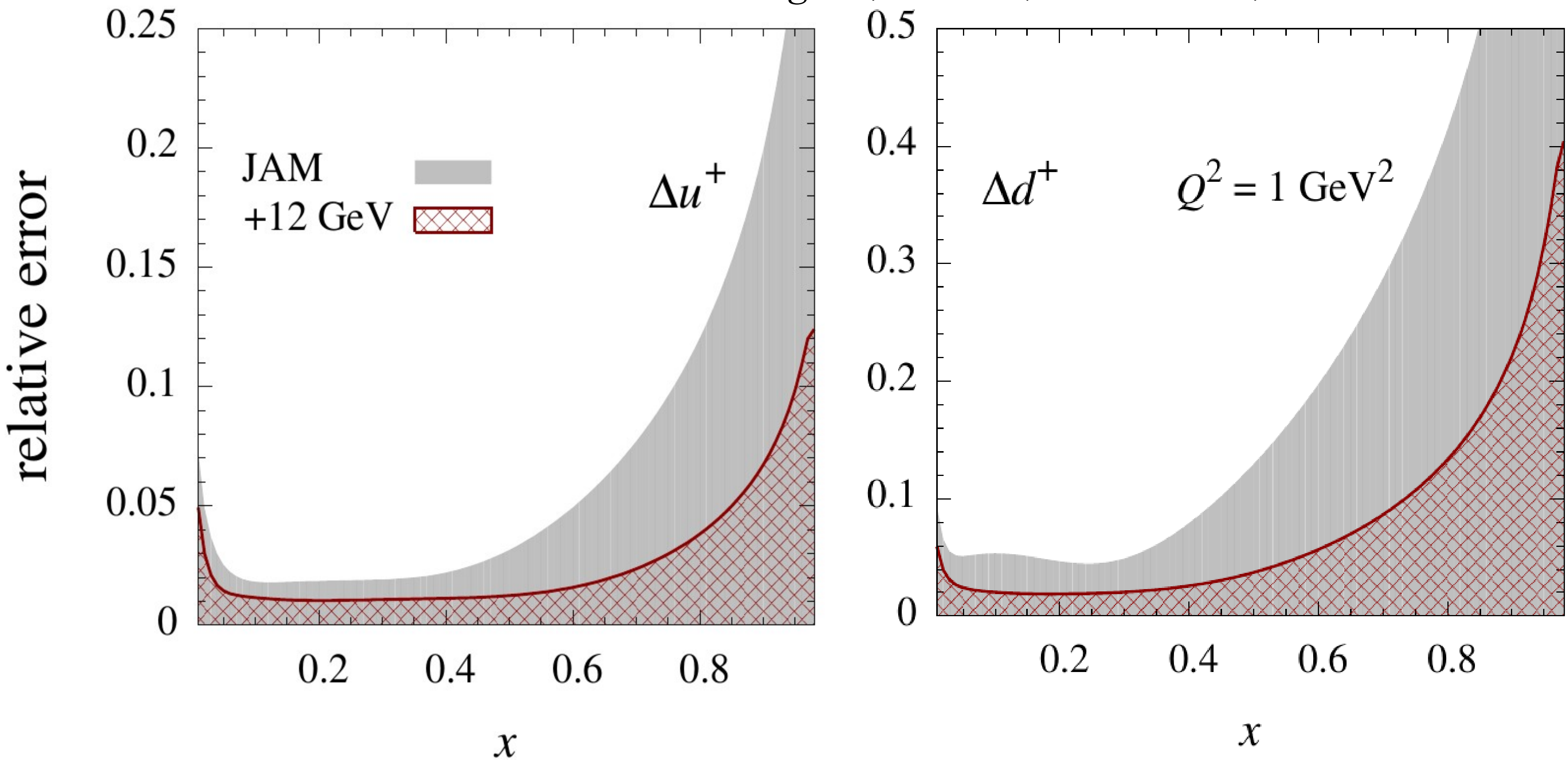
Impact of Jefferson Lab data



40%-50% uncertainty reduction

Impact of JLab 12 data

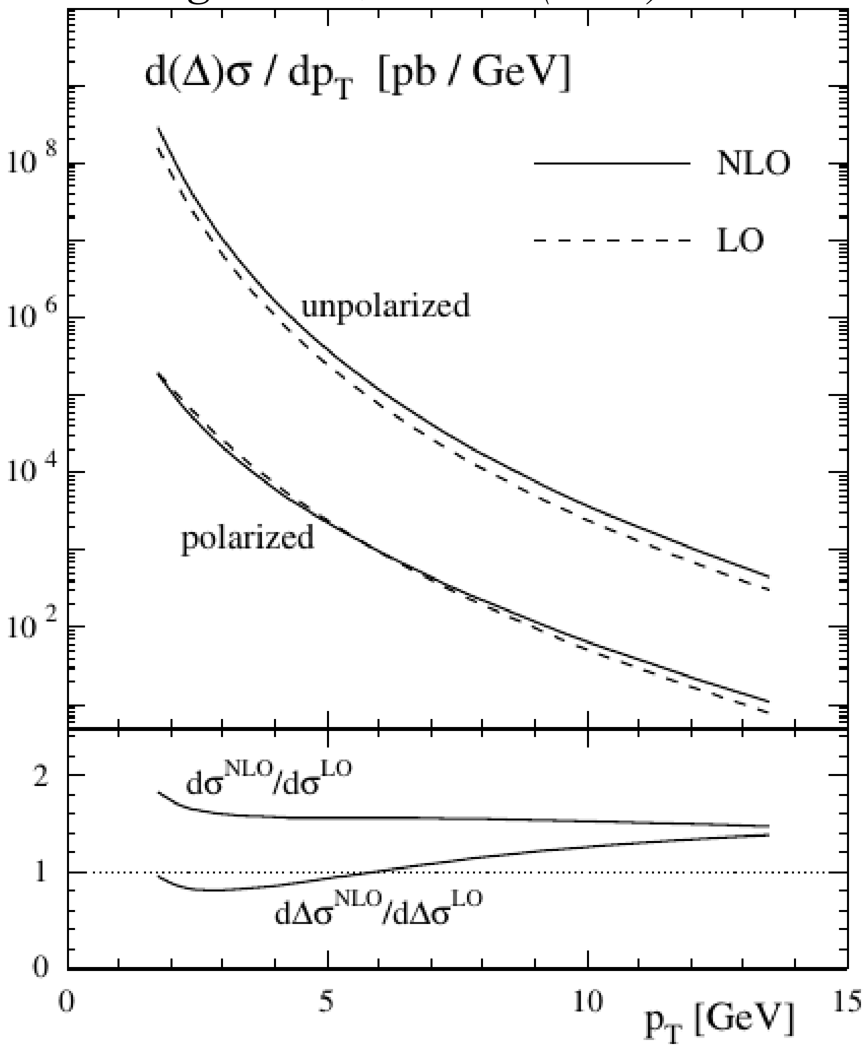
Jimenez-Delgado, Avakian, Melnitchouk, arXiv:1403.3355



60%-70% reduction of experimental uncertainty for $0.6 \leq x \leq 0.8$

Moving forward – including RHIC data

B. Jäger et al., PRD67 (2003) 054005



High-p_T pions at RHIC: $pp \to \pi^0 X$

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

We use scaled LO (K-factors):

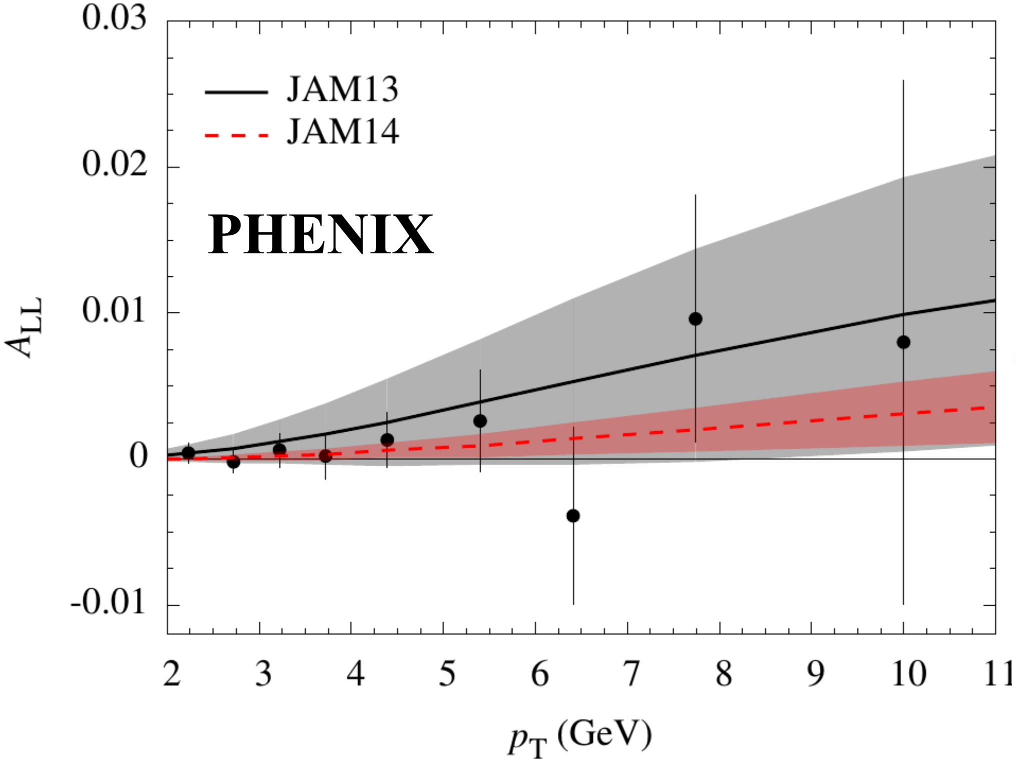
$$d\Delta\sigma^{NLO} = 1 \times d\Delta\sigma^{LO}$$

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

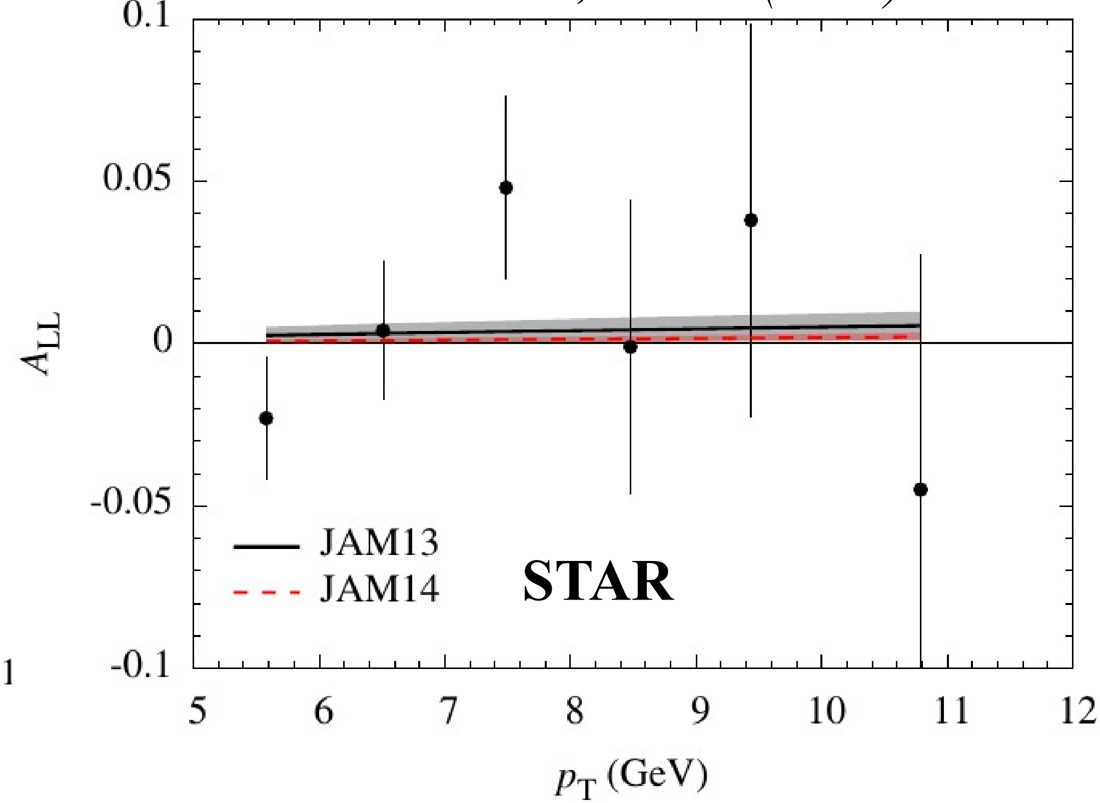
One should use the full calculation, however experimental errors are large

Moving forward – including RHIC data

PHENIX, arXiv:1402.6296



STAR, PRD89(2014)012001



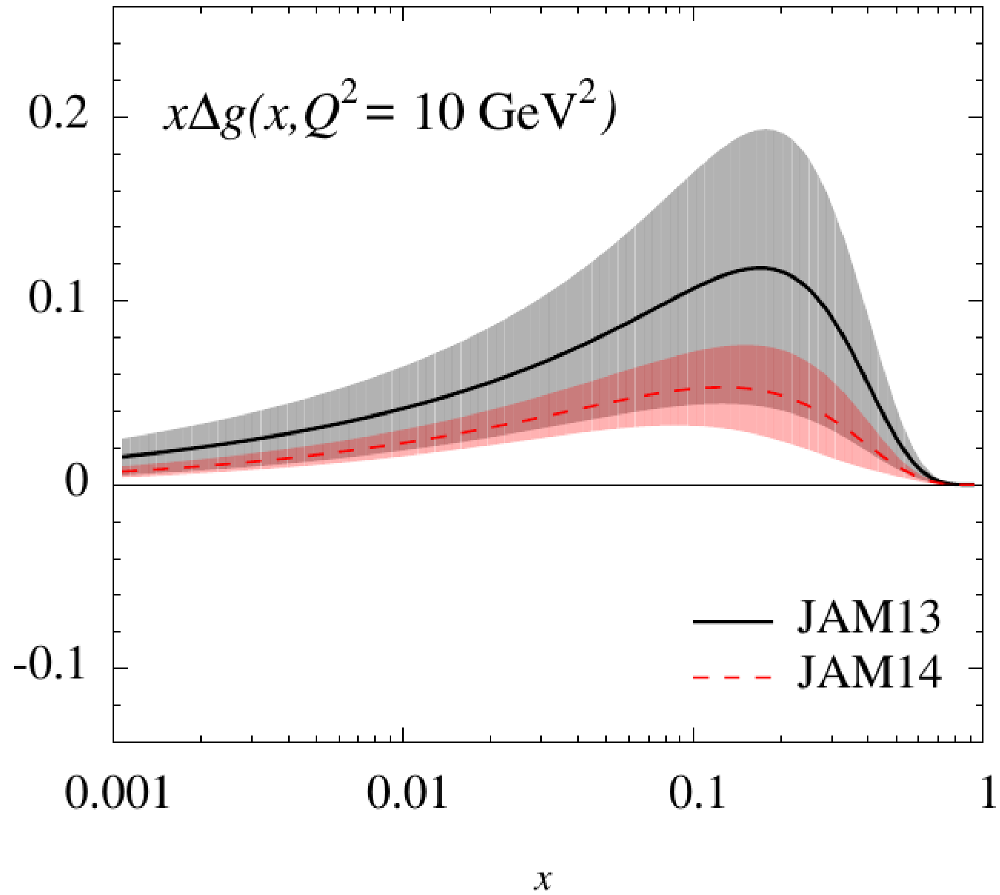
Already "well described" by central JAM13

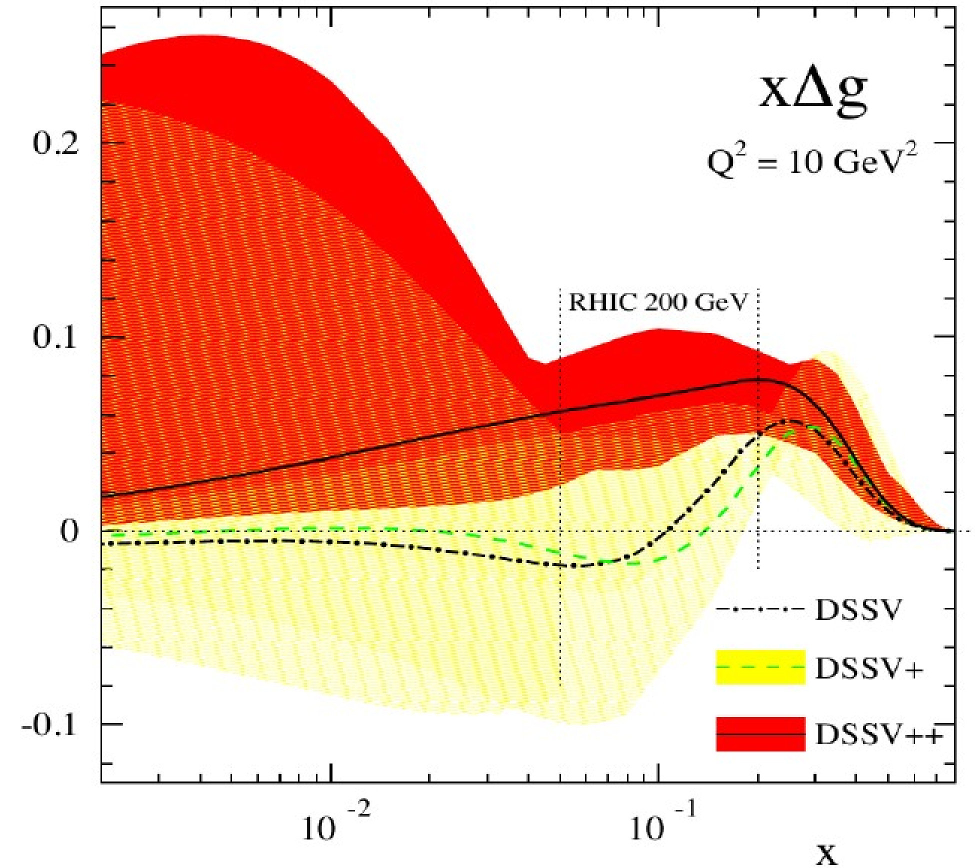
PHENIX data constrain Δg significantly

→ (without affecting quarks or DIS asymmtries)

Preliminary!!

Effect on polarized gluons





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

New polarized PDFs: JAM13

Jimenez-Delgado, Accardi, Melnitchouk, PRD89 (2014) 034025

- Nuclear corrections relevant
- Target mass corrections should be used
- Complete inclusion of higher-twists possible, manifestly important

Moving forward – JAM14:

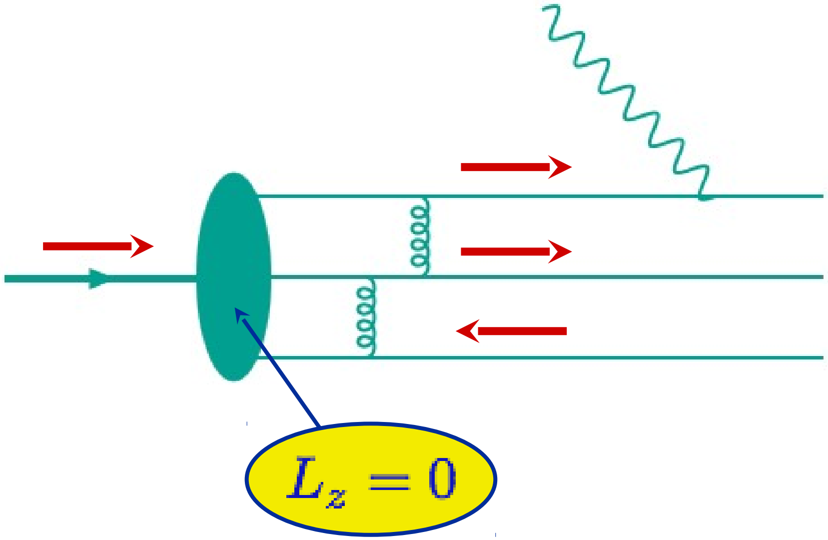
- JLab (+ future JLab12) data will impact large-*x* *u*- and *d*-quarks
- RHIC pion A_{LL} constrains medium-*x* gluons
- SIDIS data for flavor separation to be included "soon"

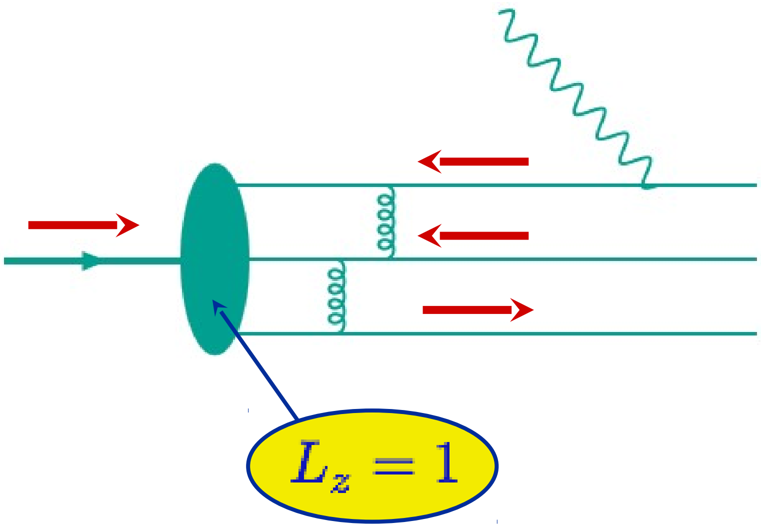
Longer term: RHIC jets & *W*, EIC, …

Backup slides

Orbital angular momentum

- Theory analysis suggested need for additional nonzero orbital ang. momentum (L_z = 1) component in nucleon wave fn.





→ Leading $(1\text{-}x)^3$ behavior from $L_z = 0$ component

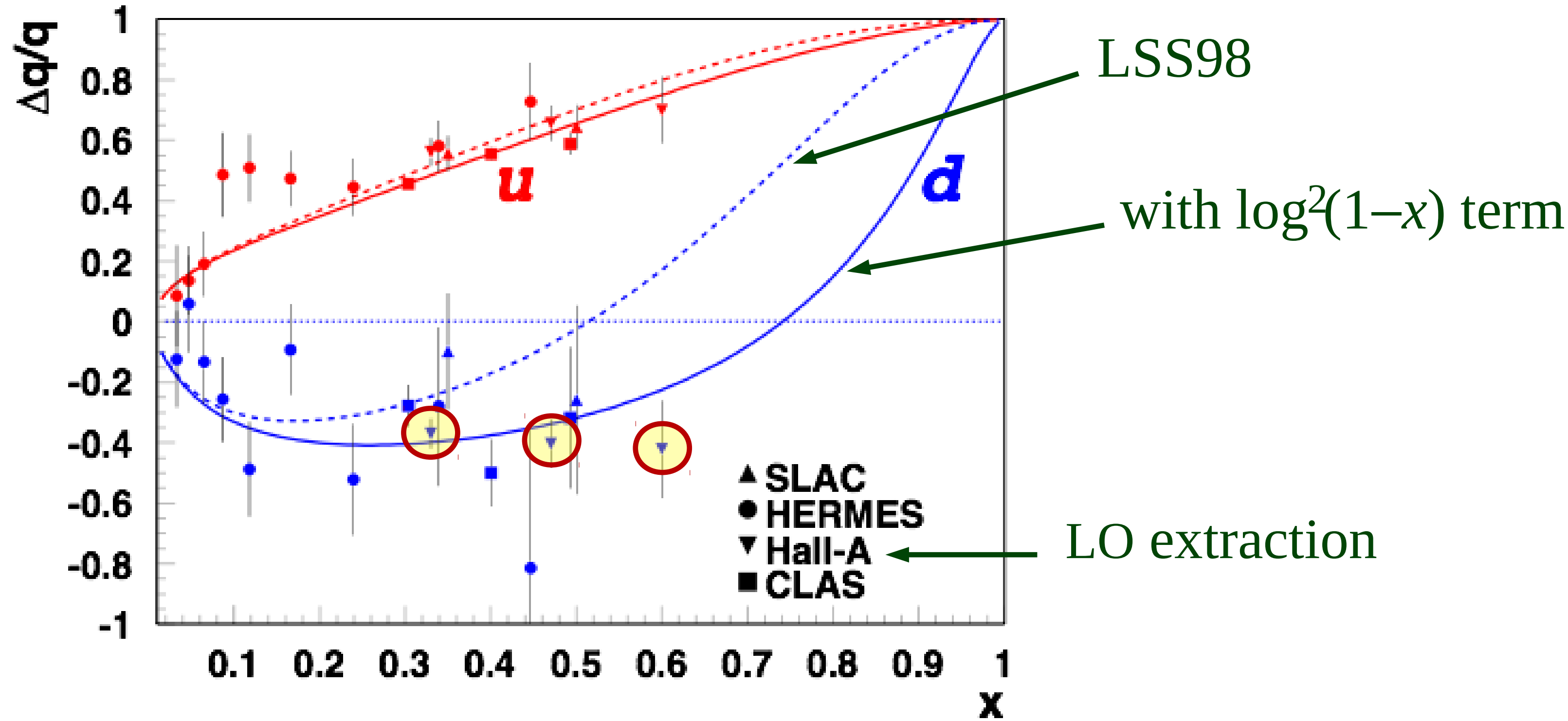
→ $L_z = 1$ gives additional $\log^2(1\text{-}x)$ enhancement of $q^{\downarrow}$

$$q^{\downarrow} \sim (1-x)^5 \log^2(1-x)$$

Avakian, Brodsky, Deur, Yuan
*PRL **99**, 082001 (2007)*

Orbital angular momentum

- Theory analysis suggested need for additional nonzero orbital ang. momentum (L_z = 1) component in nucleon wave fn.

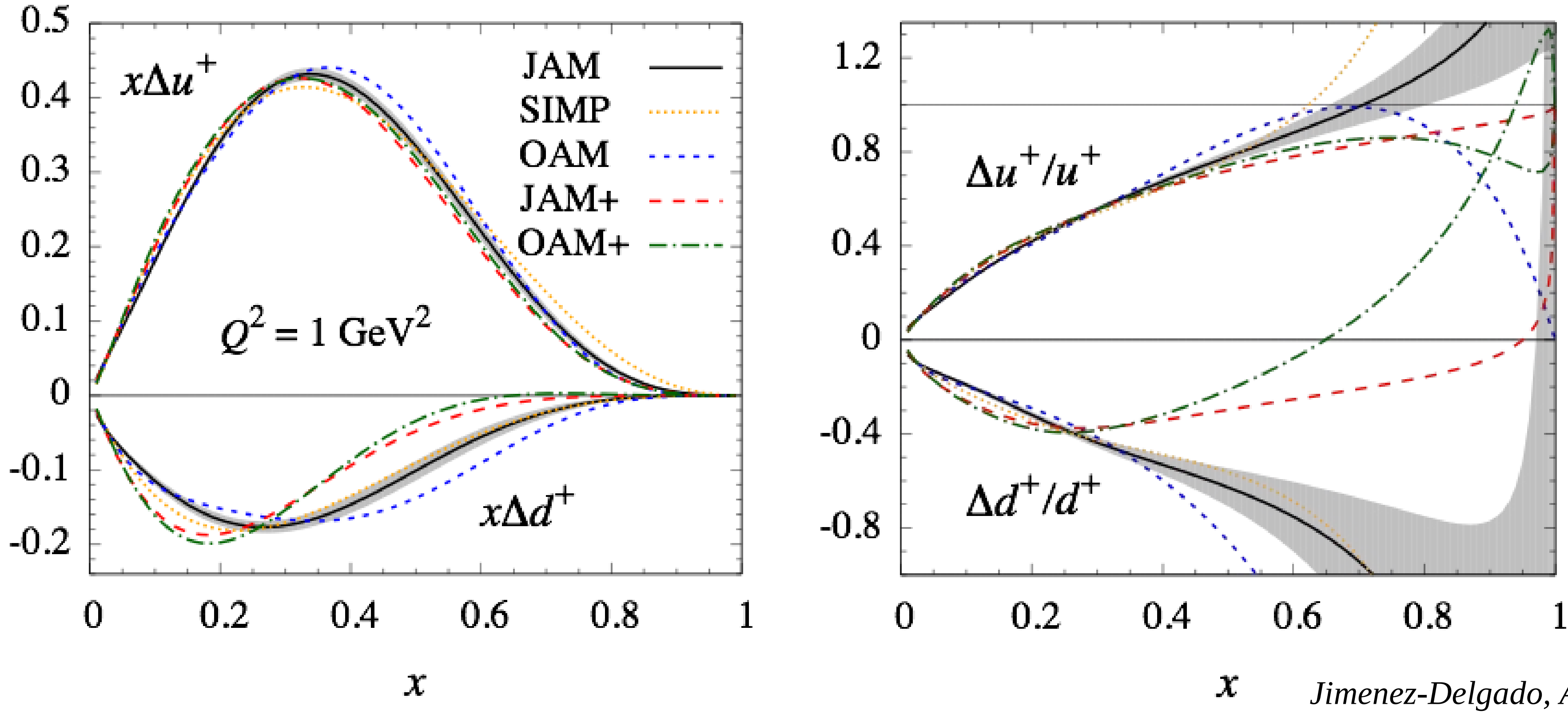


⟶ $L_Z = 1$ term needed to delay Δd turnover until larger *x*

Avakian, Brodsky, Deur, Yuan
PRL ***99****, 082001 (2007)*

Orbital angular momentum

- Global JAM & JAM+ fits can accommodate data *without* $L_z = 1$ terms



Jimenez-Delgado, Avakian, WM
arXiv:1403.3355

⟶ "OAM" and "OAM+" fits use

$$x\Delta f = Nx^\alpha(1-x)^\beta + N'x^\alpha(1-x)^5\log^2(1-x)$$

can also accommodate data, with similar overall χ^2

⟶ **MORE DATA NEEDED!**

Polarized valence quark PDFs

- Several upcoming experiments at JLab will measure
  $A_1(p, d, {}^3\mathrm{He})$ up to $x \sim 0.8$