New JAM global analysis of spin-dependent PDFs

Wally Melnitchouk

Jefferson Lab Angular Momentum (JAM) Collaboration
Nobuo Sato, Jacob Ethier, Alberto Accardi
(Pedro Jimenez-Delgado)

http://www.jlab.org/JAM

JAM global analysis

- Motivation – maximally utilize high-precision, high-statistics spin data at lower (& higher) energies

→ ~ 15 experiments completed at JLab, with data straddling resonance & DIS regions

→ explore systematics of lowering kinematic cuts down to $Q^2 > 1\ \mathrm{GeV}^2, \quad W^2 > 3.5\ \mathrm{GeV}^2$

($cf.$ CJ, JR, ABM unpolarized PDFs analyses)

→ control of nuclear and finite-Q^2 corrections

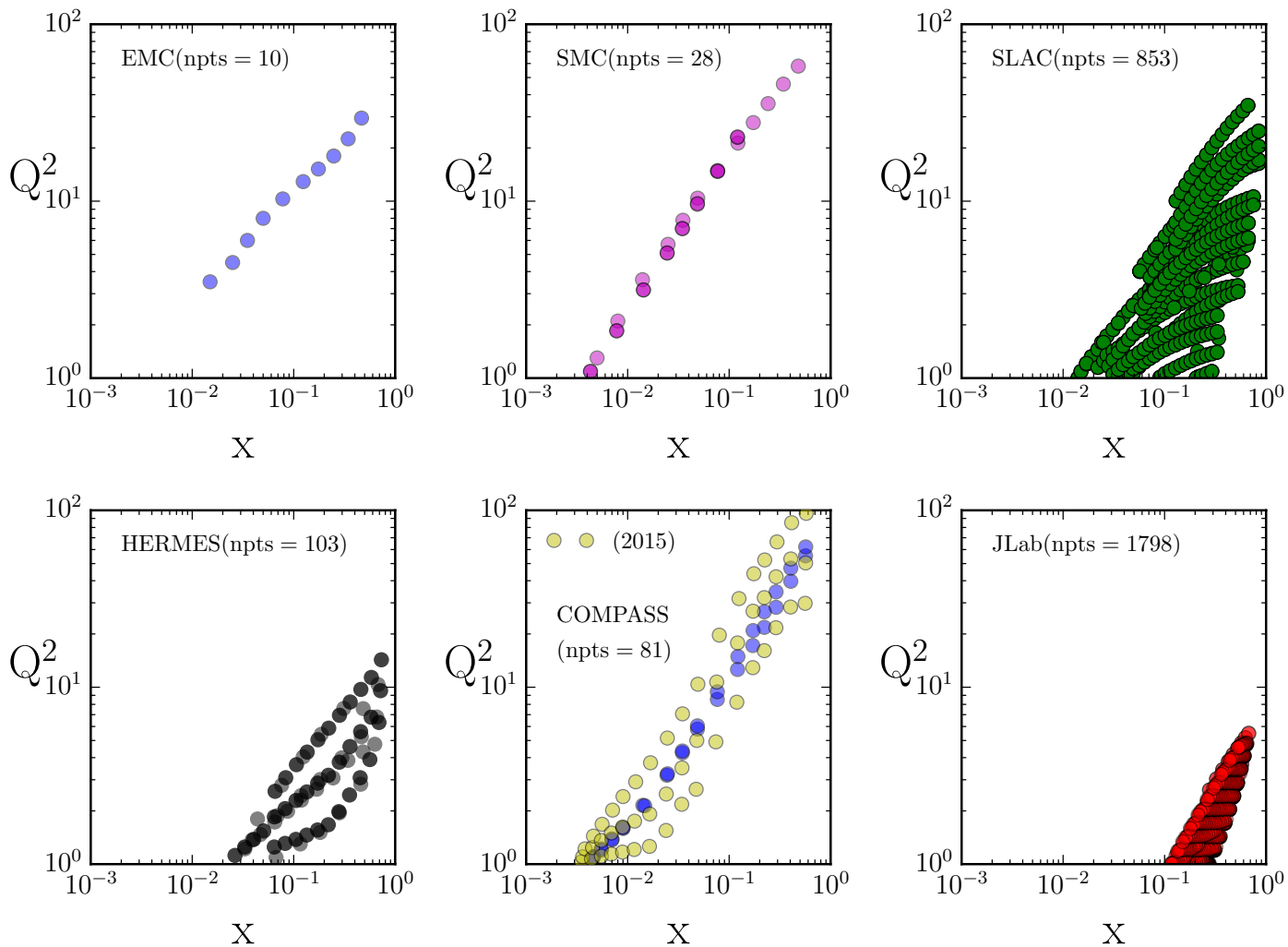
→ perform fit to unpolarized PDFs under similar set of conditions (no assumptions about R)

→ constrain (poorly-determined) PDFs at large x

→ extract higher twist (twist-3) distributions

JAM global analysis

- Complete collection of world's inclusive polarized DIS data (interactive database at http://www.jlab.org/JAM)



→ soon to be extended to SIDIS & polarized *pp* data

JAM global analysis

- Complete collection of world's inclusive polarized DIS data (interactive database at http://www.jlab.org/JAM)

- Fit experimental asymmetries (longitudinal & transverse) rather than derived structure functions

$$A_{\parallel} = \frac{\sigma^{\uparrow\Downarrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\uparrow\Downarrow} + \sigma^{\uparrow\Uparrow}} = D(A_1 + \eta A_2)$$

$$A_{\perp} = \frac{\sigma^{\uparrow\Rightarrow} - \sigma^{\uparrow\Leftarrow}}{\sigma^{\uparrow\Rightarrow} + \sigma^{\uparrow\Leftarrow}} = d(A_2 - \xi A_1)$$

where $A_1 = (g_1 - \gamma^2 g_2)\dfrac{2x}{(1+\gamma^2)F_2 - F_L}$

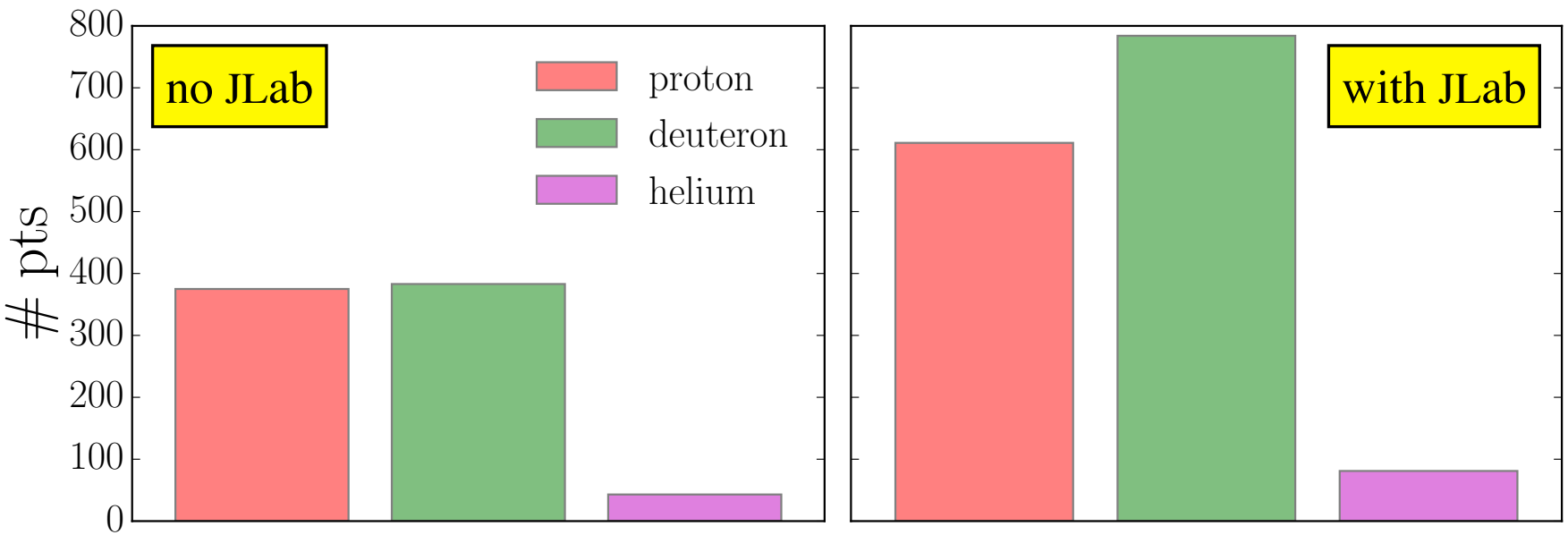
$$A_2 = \gamma(g_1 + g_2)\frac{2x}{(1+\gamma^2)F_2 - F_L}$$

$\longrightarrow$ remove assumptions about $R = \sigma_L/\sigma_T$ ratio

JAM global analysis

- Complete collection of world's inclusive polarized DIS data (interactive database at http://www.jlab.org/JAM)

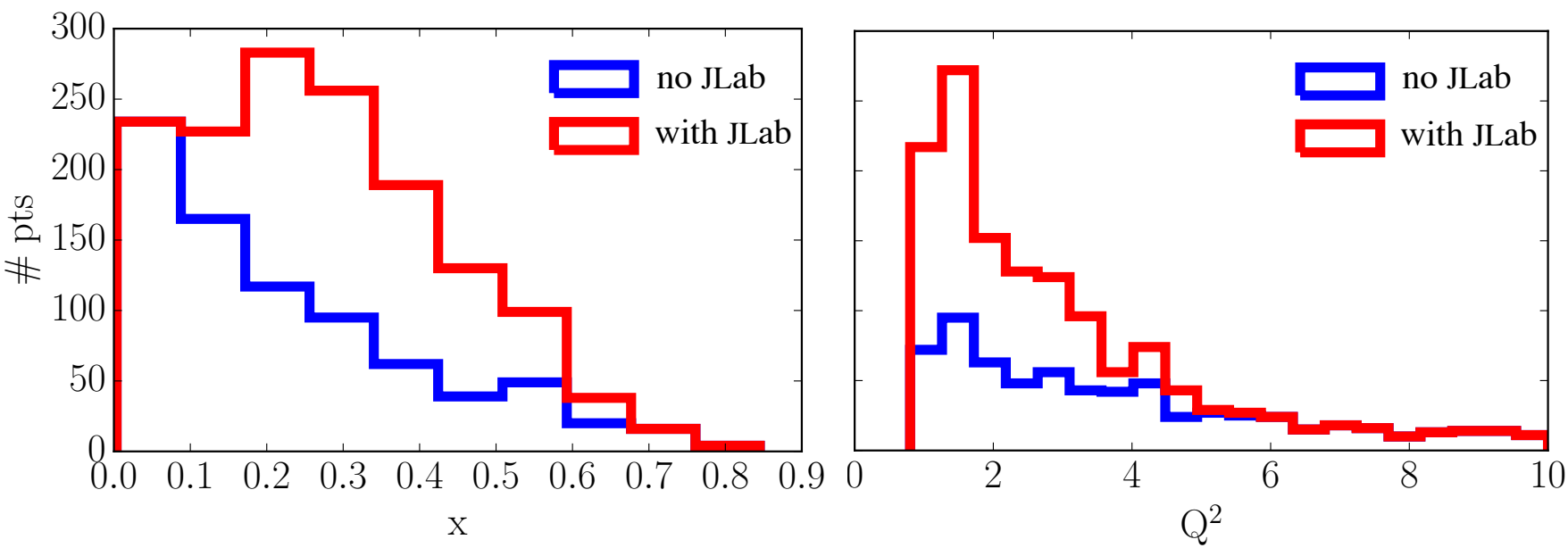
- Significant contribution of JLab data to global database



JAM global analysis

- Complete collection of world's inclusive polarized DIS data (interactive database at http://www.jlab.org/JAM)

- Significant contribution of JLab data to global database

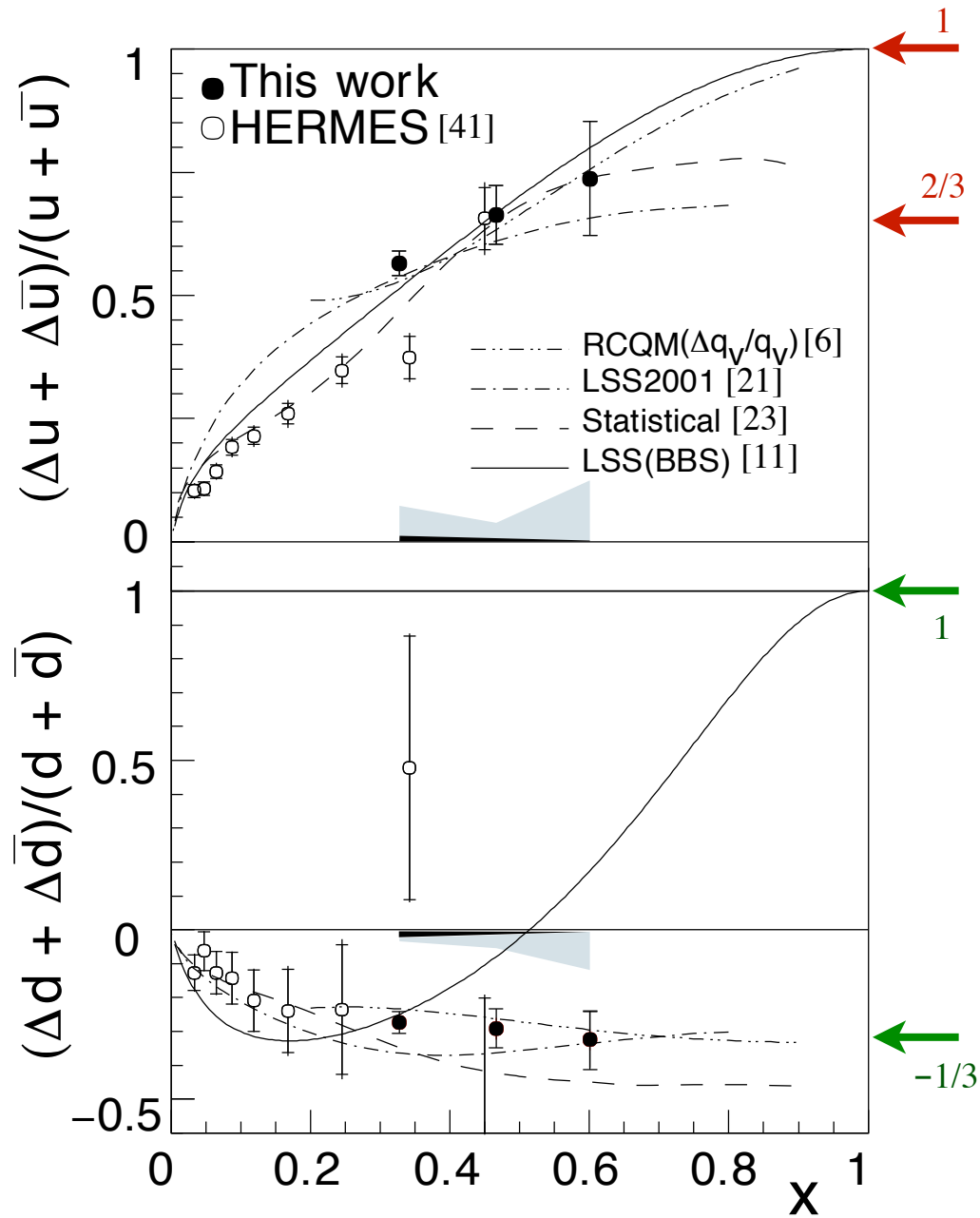


→ especially at high x $(0.1 < x < 0.6)$ and low Q^2 $(1 < Q^2 < 3\ \mathrm{GeV}^2)$

Large-x PDFs

- Issues at large x
  - dearth of precision data
  - at fixed Q^2, large x means low W
  - finite-Q^2 corrections (higher twists, ...)
  - nuclear corrections (D, ^3He data)

→ PDFs poorly determined for $x > 0.5$



Zhang et al., JLab E99-117

Large-x PDFs

- SU(6) spin-flavor symmetry

  → $d/u \to 1/2$ $\quad \Delta u/u \to 2/3$ $\quad A_1^p \to 5/9$

  $\Delta d/d \to -1/3$ $\quad A_1^n \to 0$

- Symmetry broken by $e.g.$ color-spin interaction

  → scalar diquark dominance $(M_\Delta > M_N)$;

  → $d/u \to 0$ $\quad \Delta u/u \to 1$ $\quad A_1^p \to 1$

  $\Delta d/d \to -1/3$ $\quad A_1^n \to 1$

- Perturbative one-gluon exchange

  → dominance of helicity-$1/2$ configurations

  → $d/u \to 1/5$ $\quad \Delta q/q \to 1$ $\quad A_1 \to 1$

JAM QCD analysis

- Parametrization at scale $Q^2 = \mu_0^2 \; (= 1\,\mathrm{GeV}^2)$

$$x\Delta q^+(x) = N x^\alpha (1-b)^\beta \, (1+\gamma x)$$

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

→ constraints from hadronic weak decays

$$\Delta u^{+(1)} - \Delta d^{+(1)} = 1.269(3), \quad \Delta u^{+(1)} + \Delta d^{+(1)} - 2\Delta s^{+(1)} = 0.586(31)$$

- Q^2 evolution performed in moment space

$$f^{(n)}(Q^2) = \int_0^1 dx\, x^{n-1}\, f(x, Q^2)$$

- Structure function (moments) at leading twist τ (at NLO)

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

$$g_{2,\tau 2}^{(n)} = -\frac{n-1}{n} g_{1,\tau 2}^{(n)}$$

Wandzura–Wilczek relation

JAM QCD analysis

- Inclusive DIS data constrain Δu^+ & Δd^+ distributions

  → mostly insensitive to polarized strangeness and glue

  → for inclusive-only analysis, fix shape of Δs^+, Δg using results from DSSV; normalization free

  → total of 10 shape parameters for leading twist PDFs

- Assume g_1, g_2 can be described as sum of $\tau = 2$ and higher twist terms

$$g_1 = g_1^{\tau 2(\mathrm{TMC})} + g_1^{\tau 3(\mathrm{TMC})} + g_1^{\tau 4}$$

$$g_2 = g_2^{\tau 2(\mathrm{TMC})} + g_2^{\tau 3(\mathrm{TMC})}$$

Target mass corrections (twist-2)

→ use standard OPE derivation, *e.g.* in closed form

$$g_1^{\rm TMC}(x) = \frac{x}{\xi\,\rho^3}\,g_1^{(0)}(\xi) + \frac{(\rho^2-1)(x+\xi)}{\xi\,\rho^4}\int_\xi^1 \frac{d\xi'}{\xi'}\,g_1^{(0)}(\xi')$$

$$-\frac{(\rho^2-1)(3-\rho^2)}{2\rho^5}\int_\xi^1 \frac{d\xi'}{\xi'}\int_{\xi'}^1 \frac{d\xi''}{\xi''}\,g_1^{(0)}(\xi'')$$

$$\xi = 2x/(1+\rho) \qquad \rho^2 = 1 + 4M^2x^2/Q^2$$

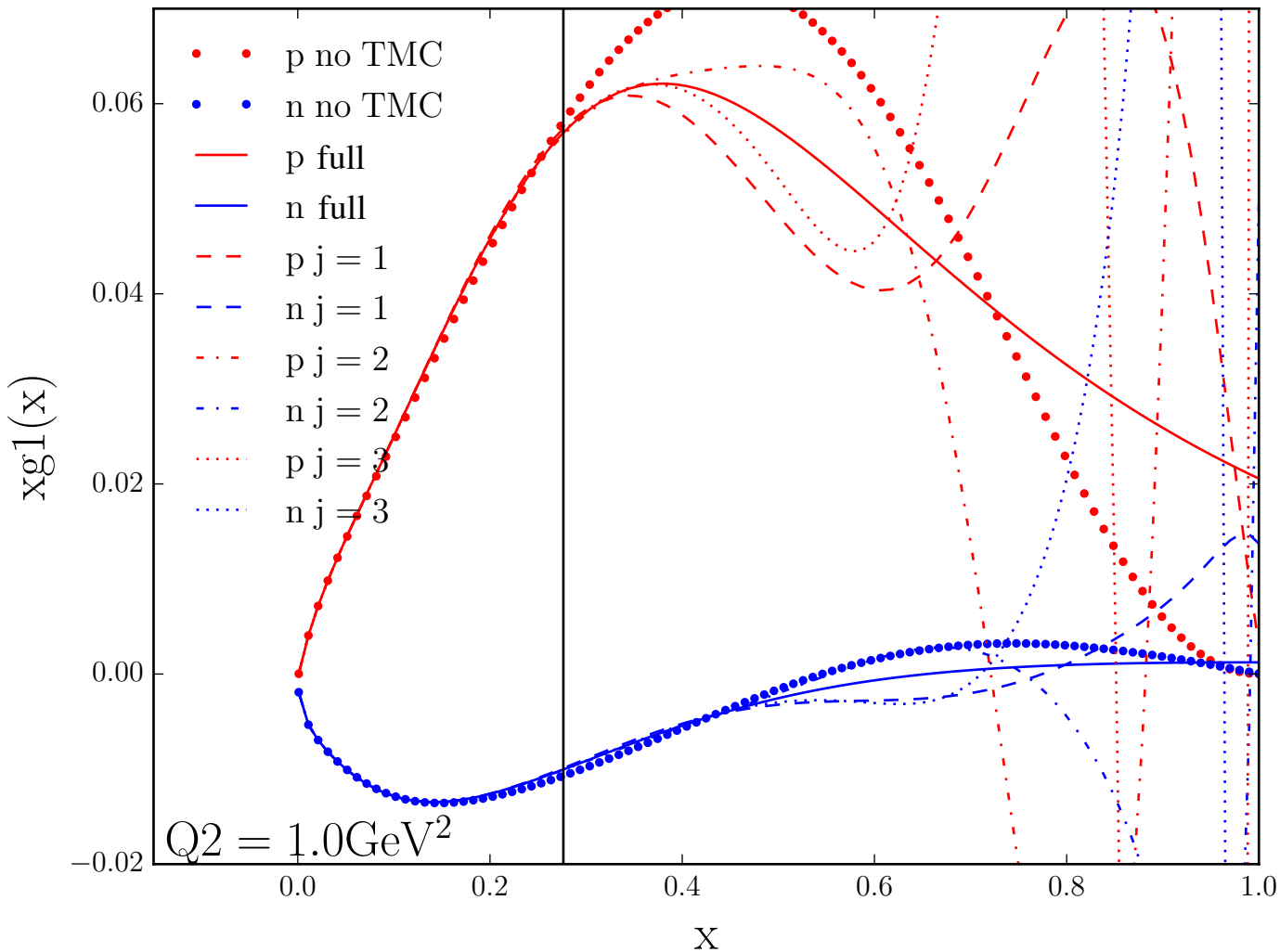
$$\lim_{M/Q\to 0} g_1^{\rm TMC}$$

or series expansion

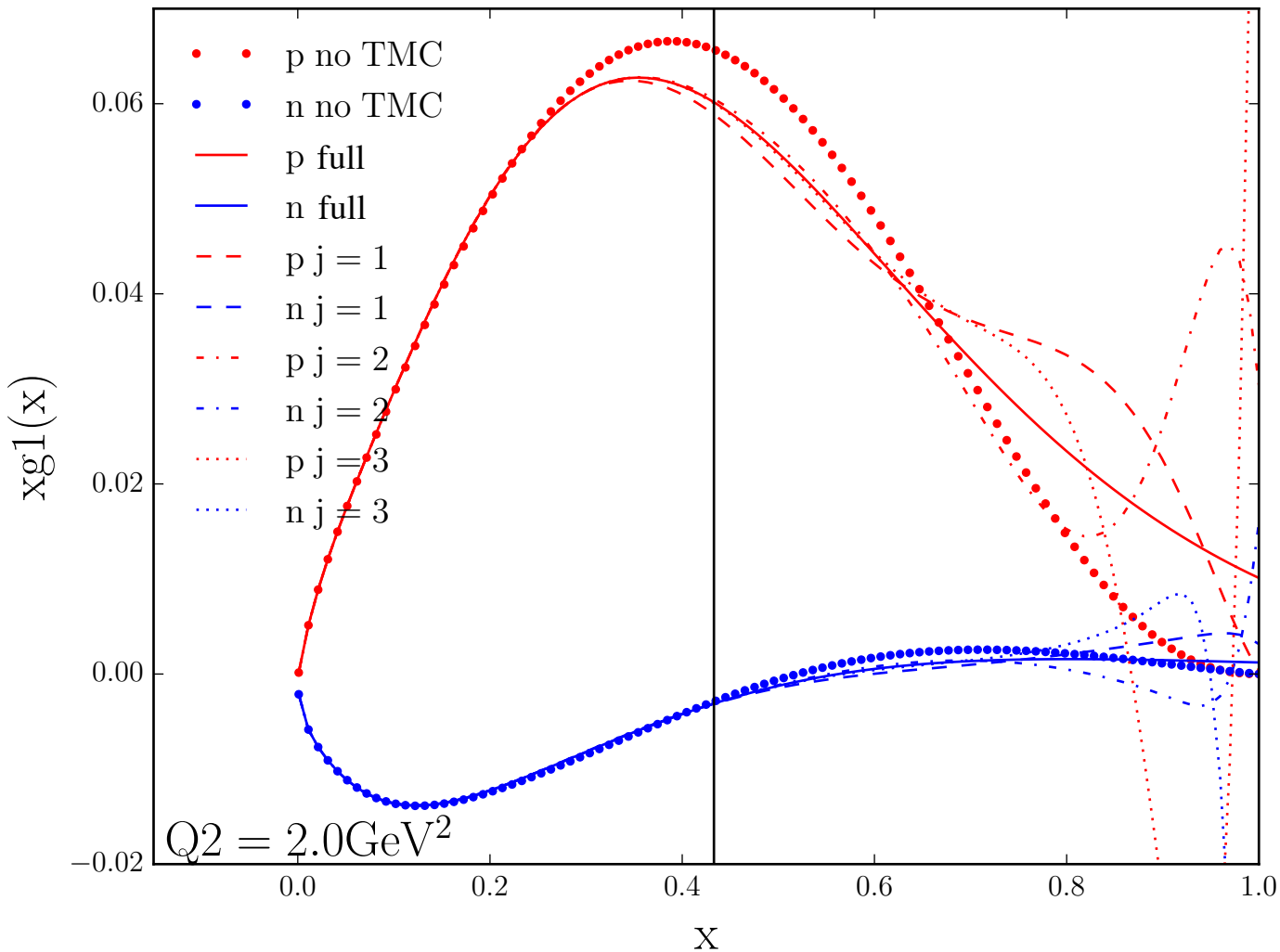
$$g_1^{\rm TMC}(x) = \sum_{j=0}^{\infty}\frac{1}{j!}\left(\frac{M^2}{Q^2}\right)^j (-x)\frac{\partial}{\partial x}\left[(-x)^{j+1}\frac{\partial^{j+1}}{\partial x^{j+1}}(x^{2j}G(x))\right]$$

$$G(x) = \int_x^1 \frac{dy}{y}\int_y^1 \frac{dy'}{y'}\,g_1^{(0)}(y')$$

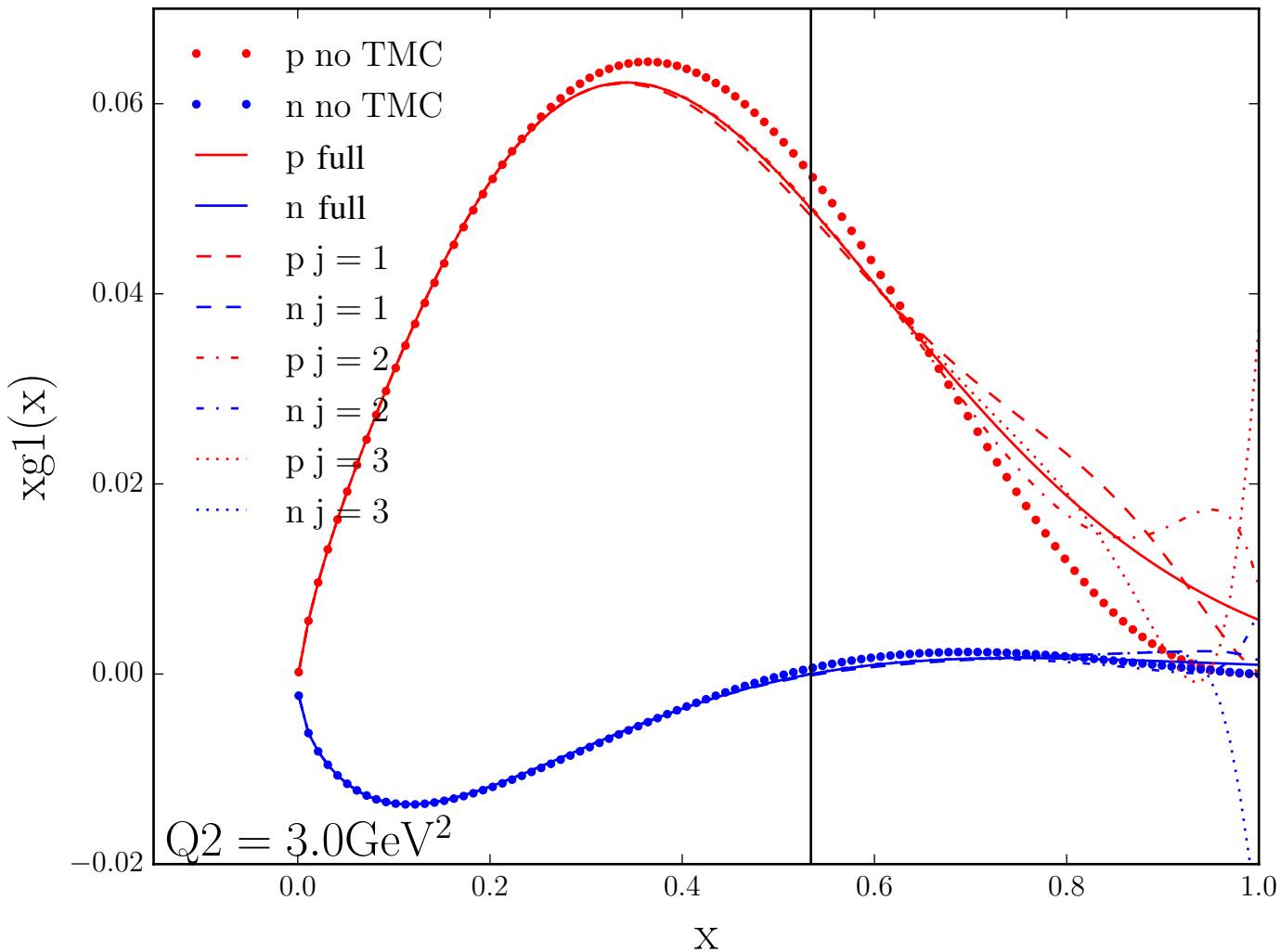
Target mass corrections (twist-2)



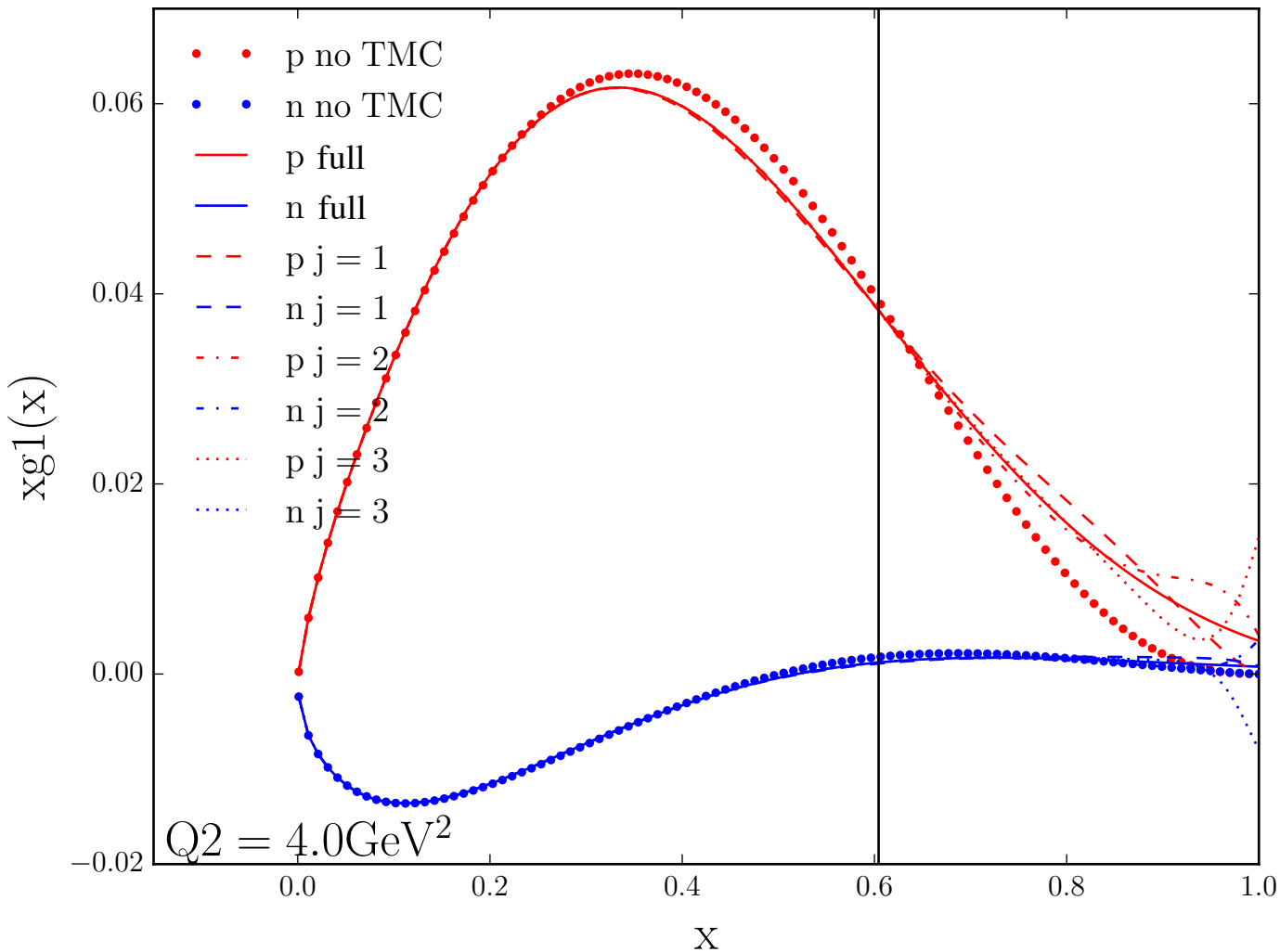
Target mass corrections (twist-2)



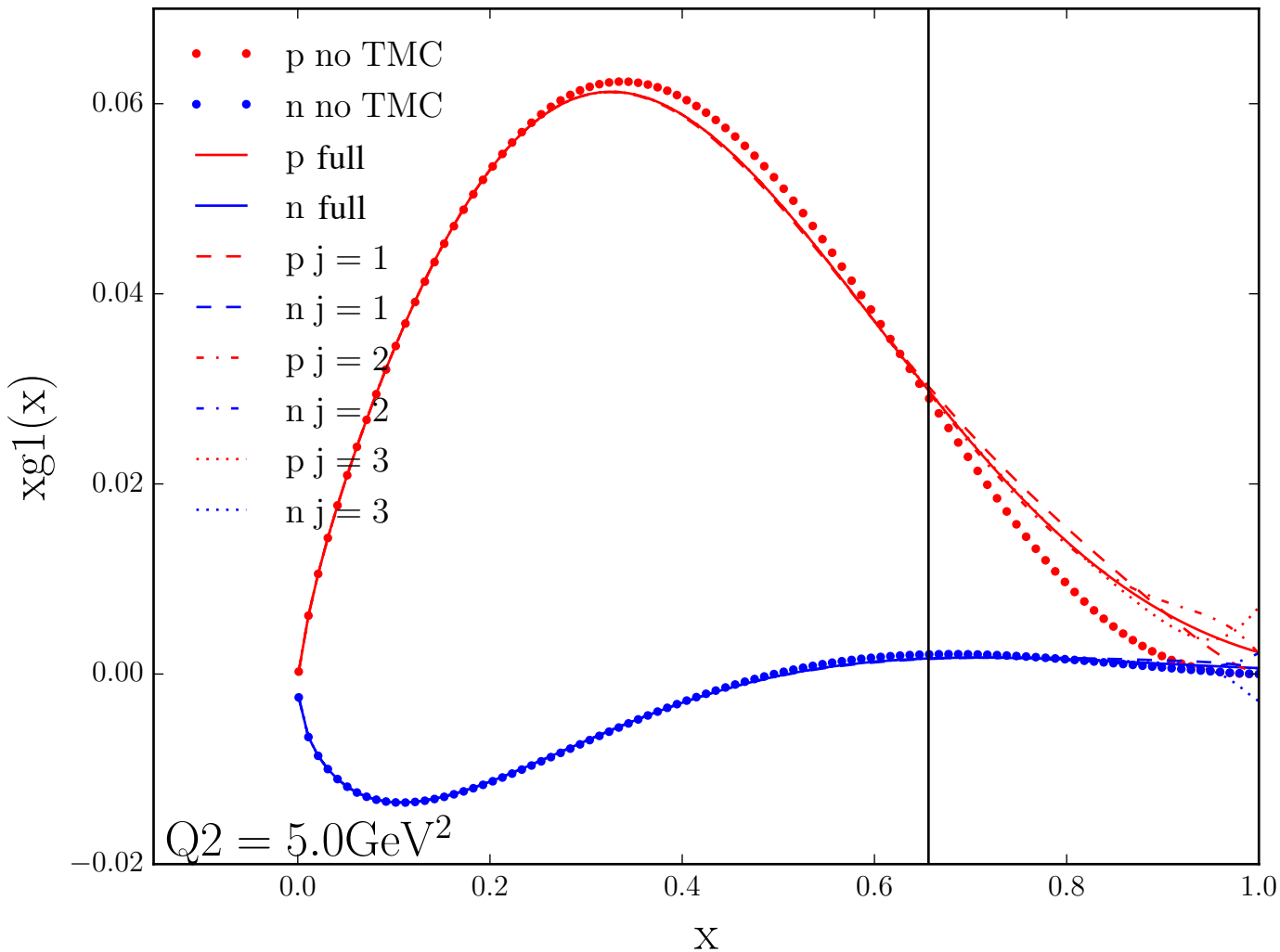
Target mass corrections (twist-2)



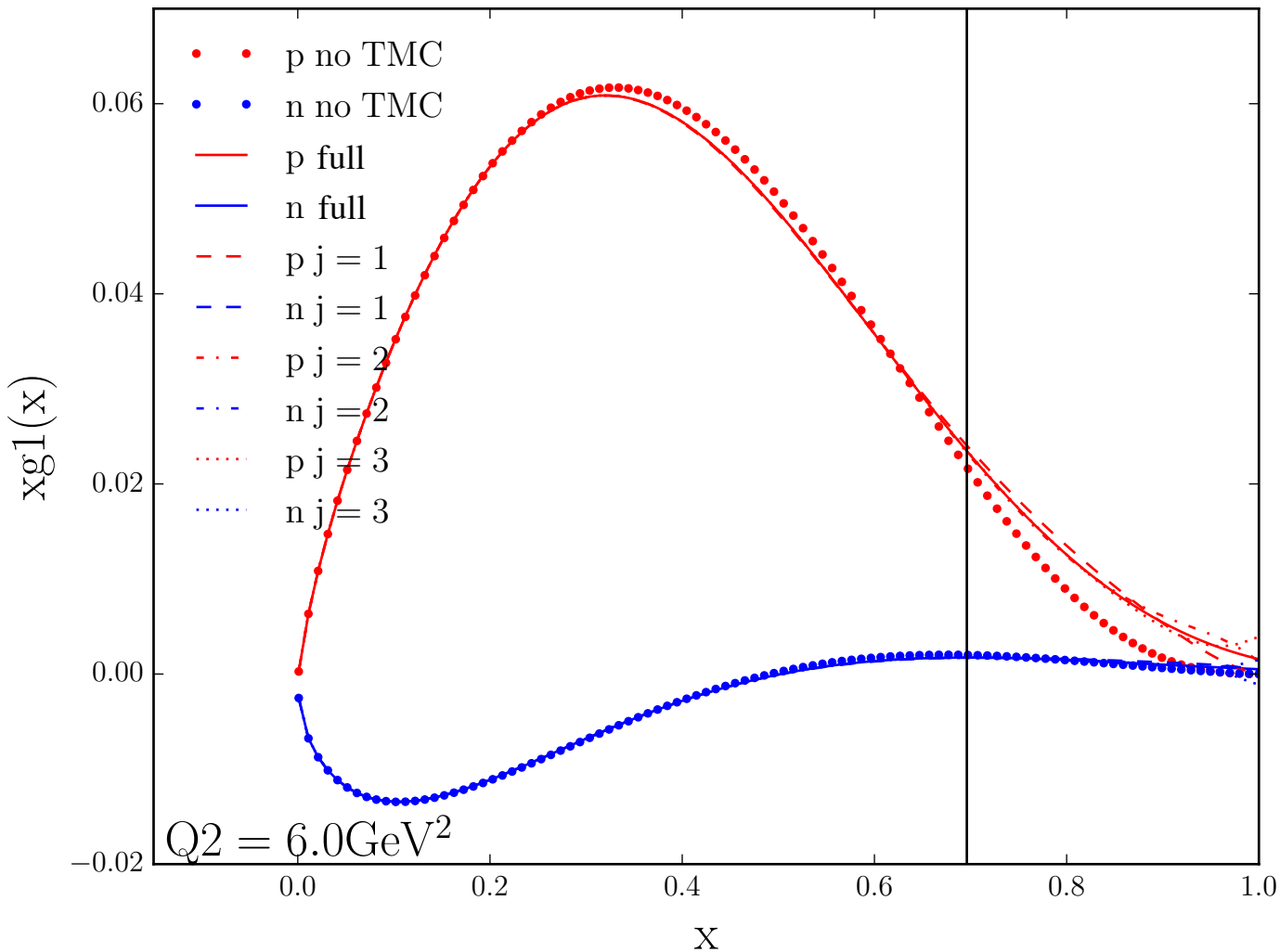
Target mass corrections (twist-2)



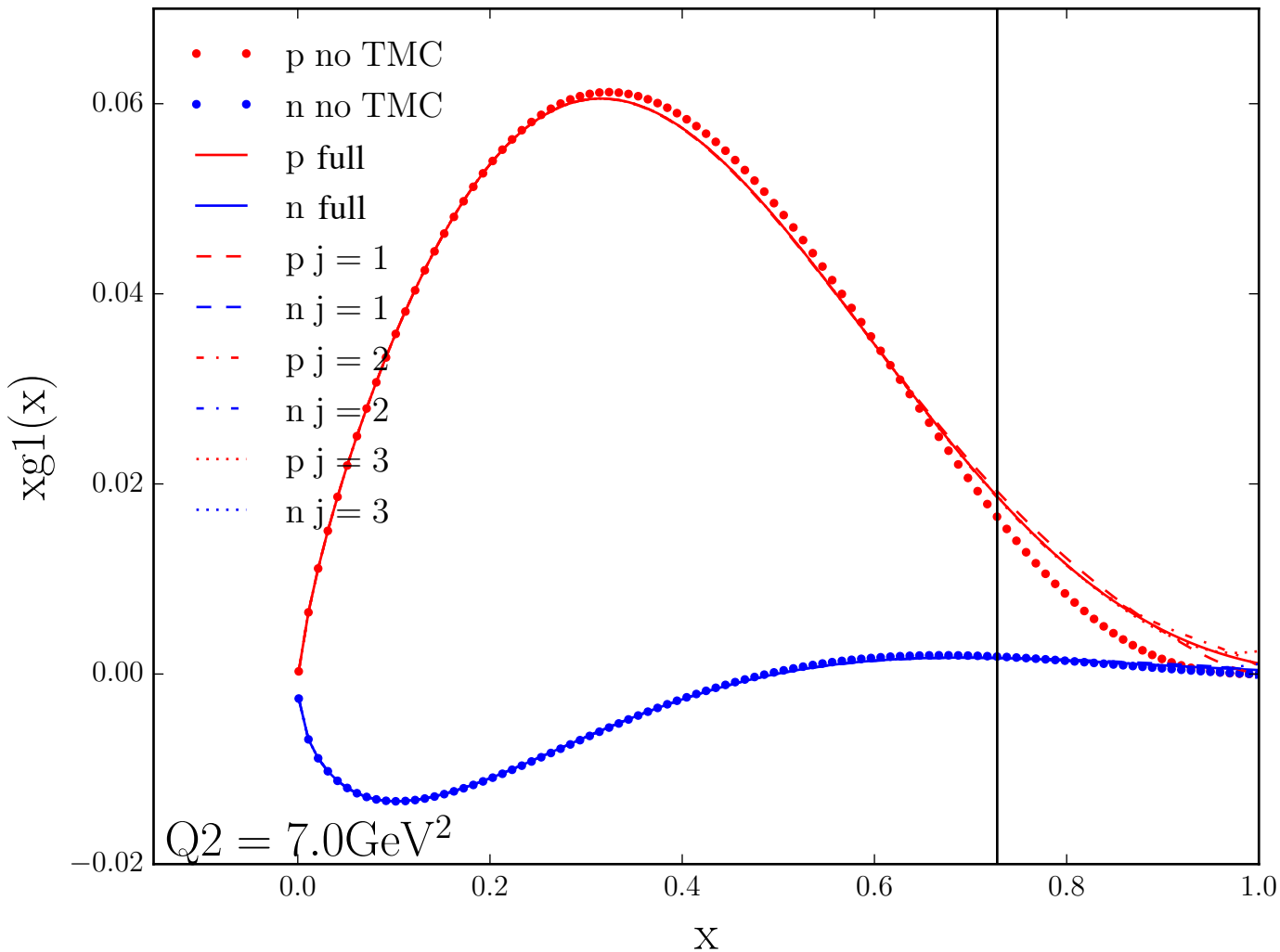
Target mass corrections (twist-2)



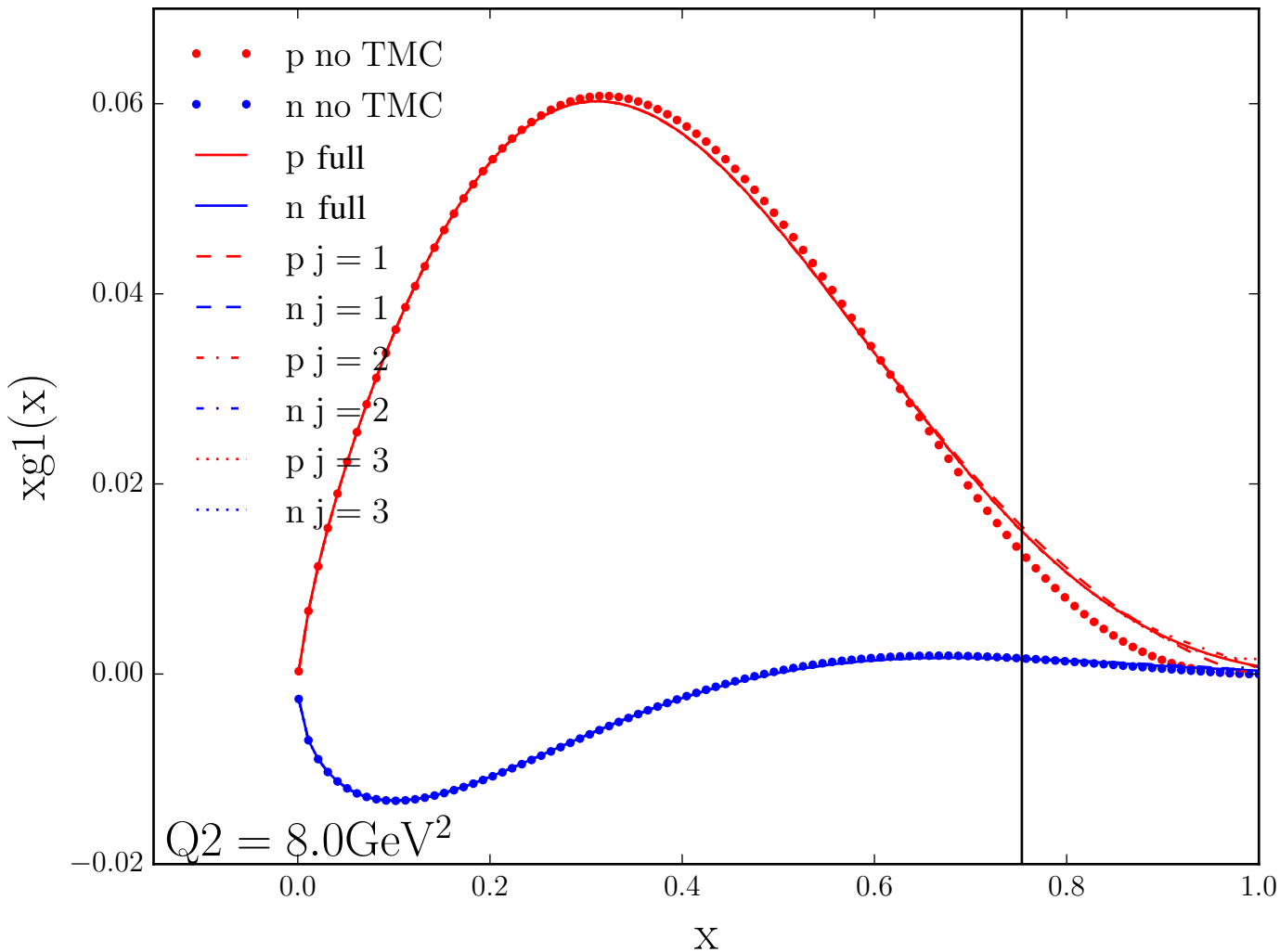
Target mass corrections (twist-2)



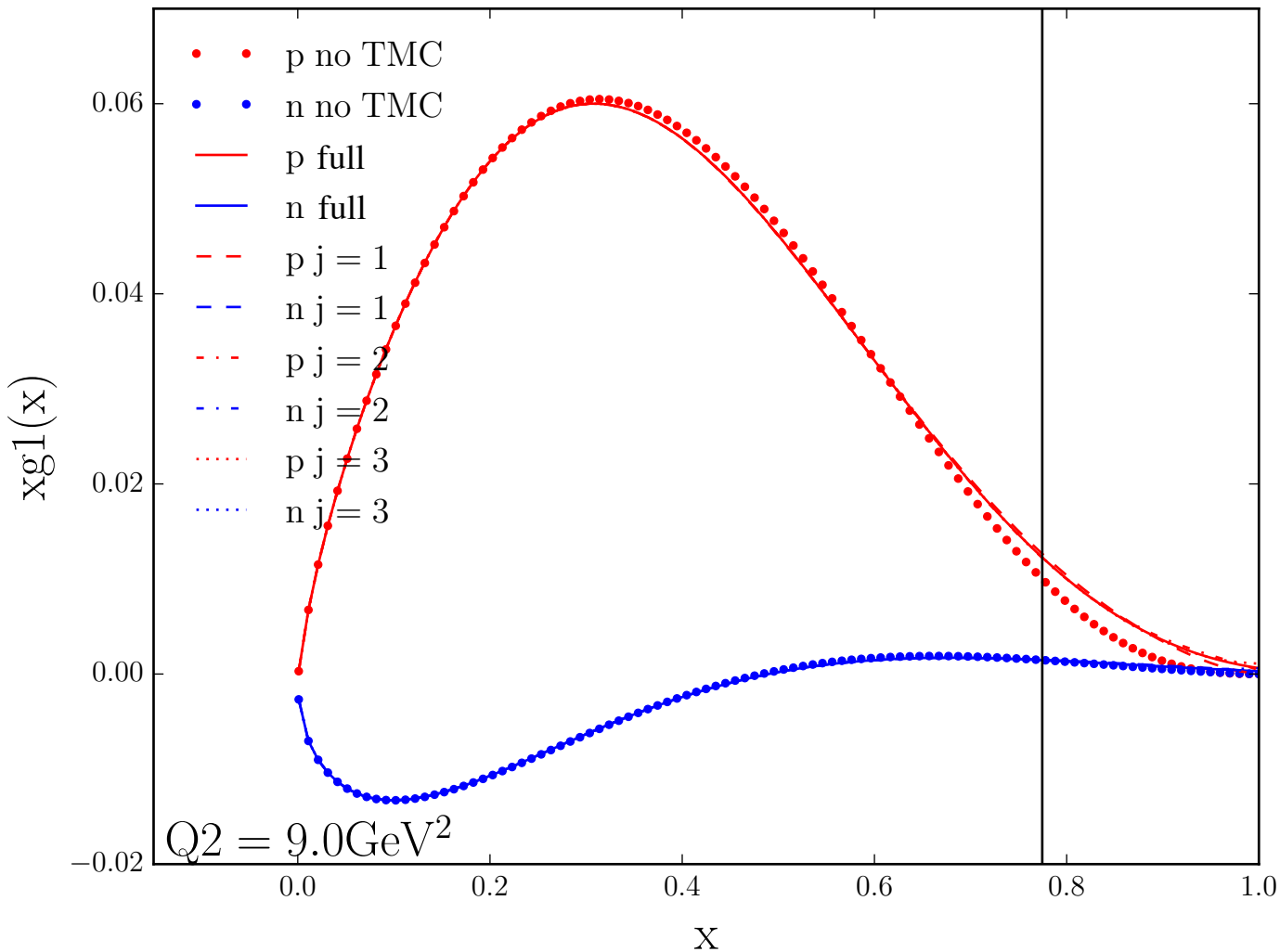
Target mass corrections (twist-2)



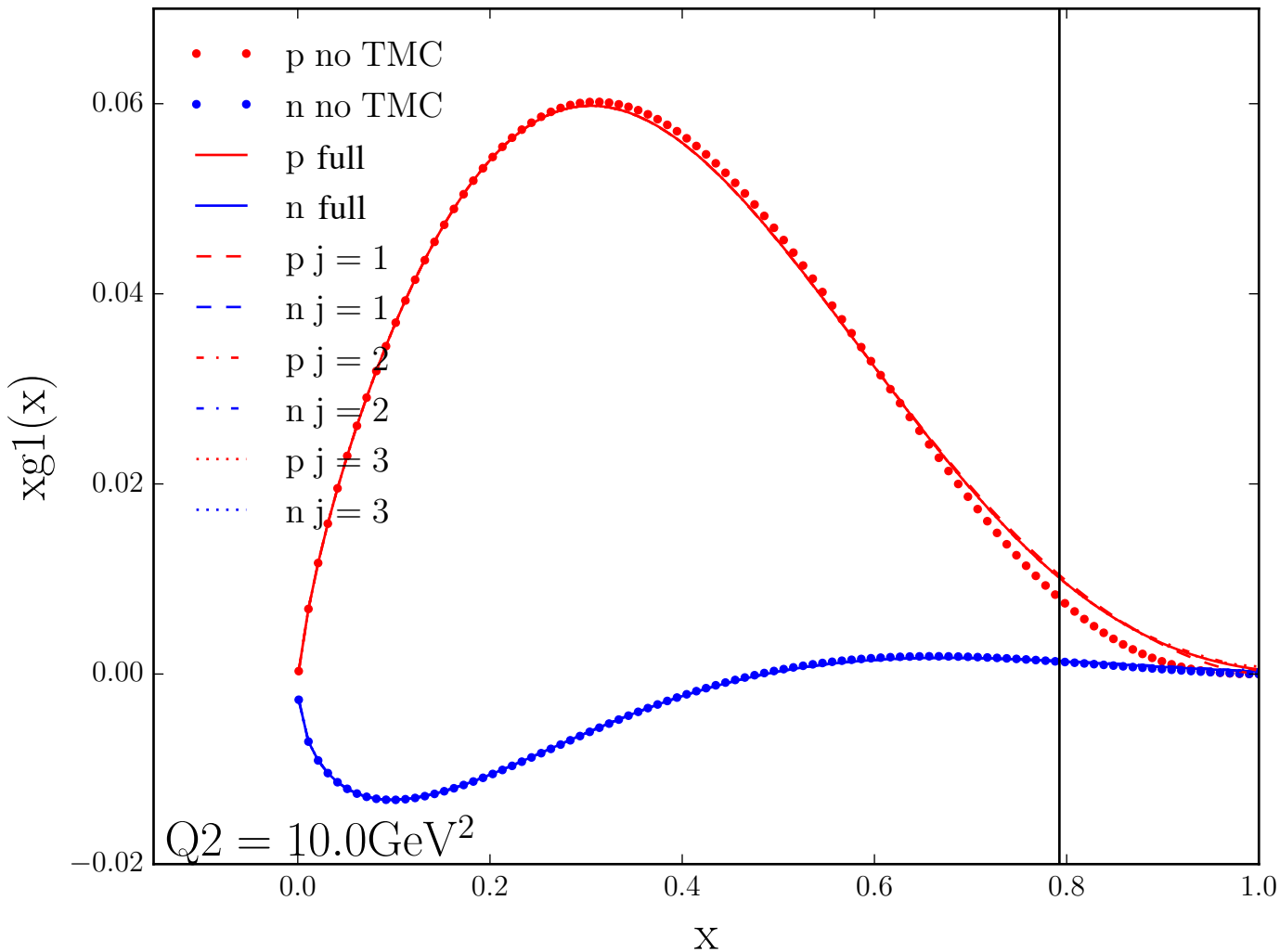
Target mass corrections (twist-2)



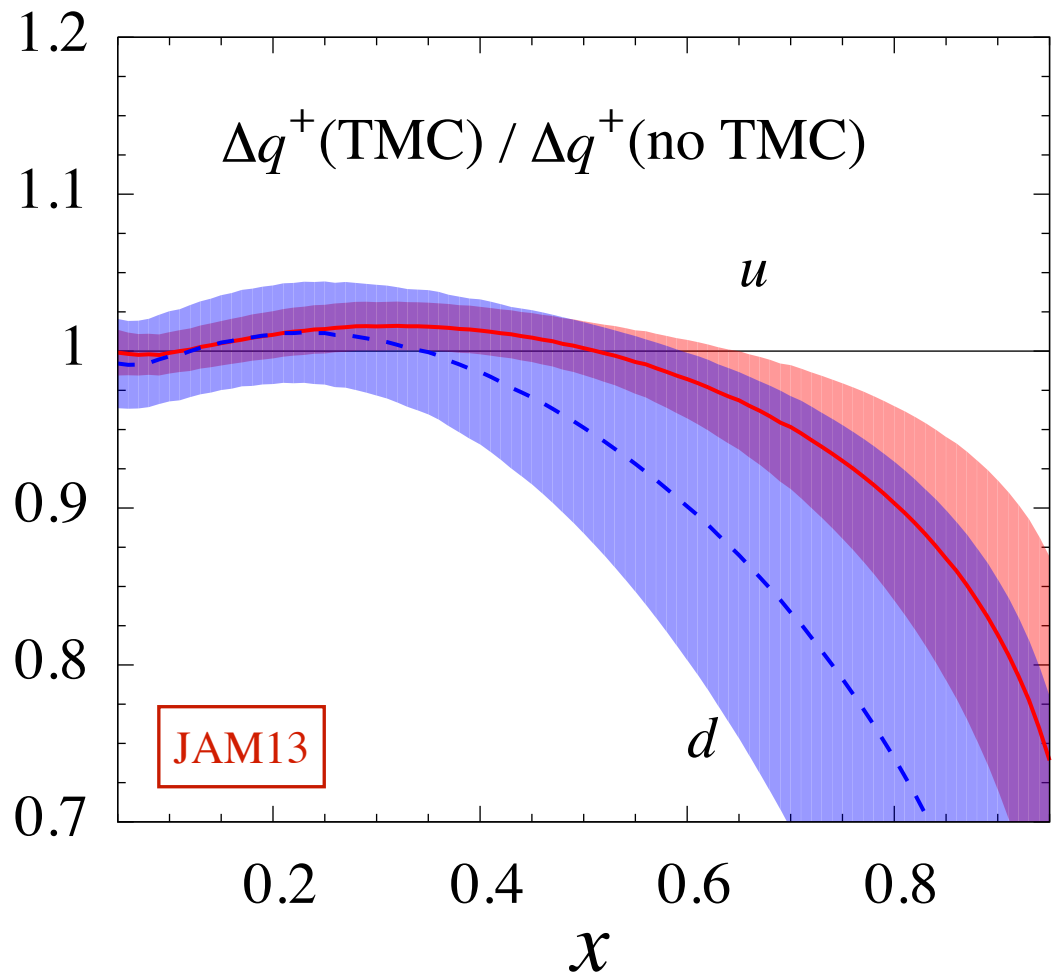
Target mass corrections (twist-2)



Target mass corrections (twist-2)



Target mass corrections (twist-2)



*Jimenez-Delgado et al., PRD **89**, 034025 (2014)*

→ differences between TMC and no-TMC results

→ immaterial whether use "full" or series approximation

Higher twist corrections

→ twist-3 part of g_1 related to twist-3 part of g_2

$$g_1^{\tau 3} = (\rho^2 - 1)\left[g_2^{\tau 3} - 2\int_x^1 \frac{dy}{y}\, g_2^{\tau 3}\right]$$

Bluemlein, Tkabladze
NPB ***553****, 427 (1999)*

→ twist-3 part of g_2 inspired by LCWF model

JAM13

$$g_2^{\tau 3} = t_0\left[\log x + (1-x) + \frac{1}{2}(1-x)^2\right] + \sum_{i=1}^{4} t_i (1-x)^{i-1}$$

Braun et al.,
PRD ***83****, 094023 (2011)*

NOT Q^2 SUPPRESSED!

→ splines approximation for twist-4 part

JAM13

$$g_1^{\tau 4} = \frac{h(x)}{Q^2}$$

Higher twist corrections

→ twist-3 part of g_1 related to twist-3 part of g_2

$$g_1^{\tau 3} = (\rho^2 - 1)\left[g_2^{\tau 3} - 2\int_x^1 \frac{dy}{y}\, g_2^{\tau 3}\right]$$

Bluemlein, Tkabladze
NPB ***553****, 427 (1999)*

→ twist-3 part of g_2 parametrized via twist-3 PDFs

JAM15

$$D^{\tau 3}(x) = N x^a (1-x)^b (1 + c\, x)$$

– at parton level

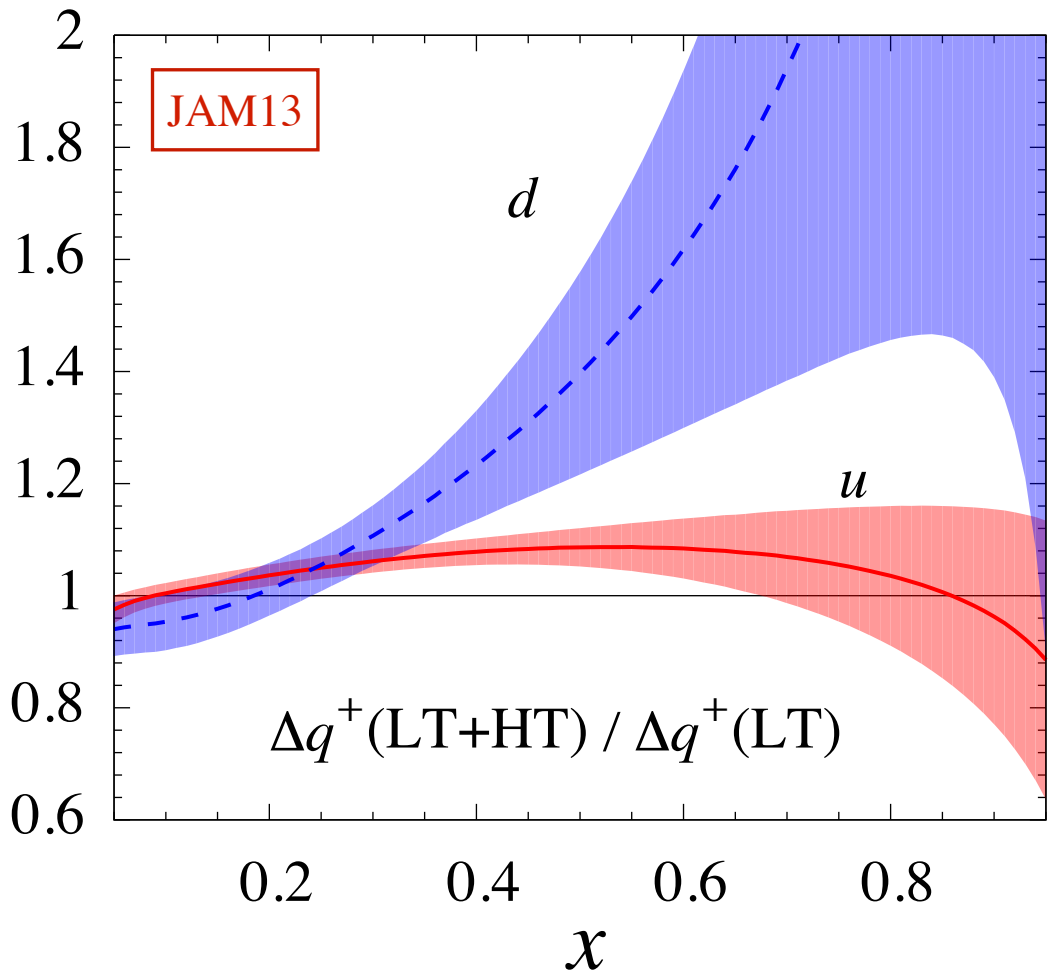
→ similar functional form also for twist-4 part

JAM15

$$g_1^{\tau 4} = N' x^{a'} (1-x)^{b'} (1 + \gamma'\, x)\, \frac{1}{Q^2}$$

– at hadron level

Higher twist corrections



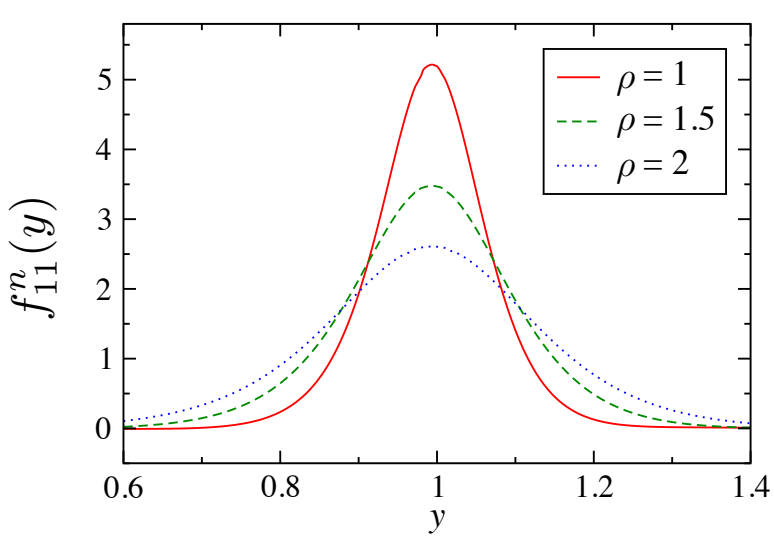
*Jimenez-Delgado et al., PRD **89**, 034025 (2014)*

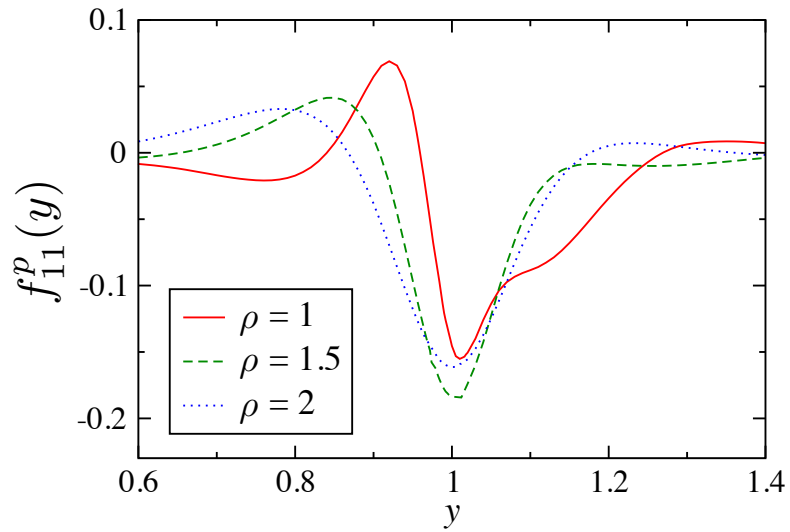
→ large enhancement of $|\Delta d|$ in presence of HTs found in JAM13 analysis

Nuclear corrections

→ nuclear binding and Fermi motion described by (spin-dependent) smearing functions

$$g_i^A(x) = \int \frac{dy}{y}\, f_{ij}^N(y)\, g_j^N(x/y)$$

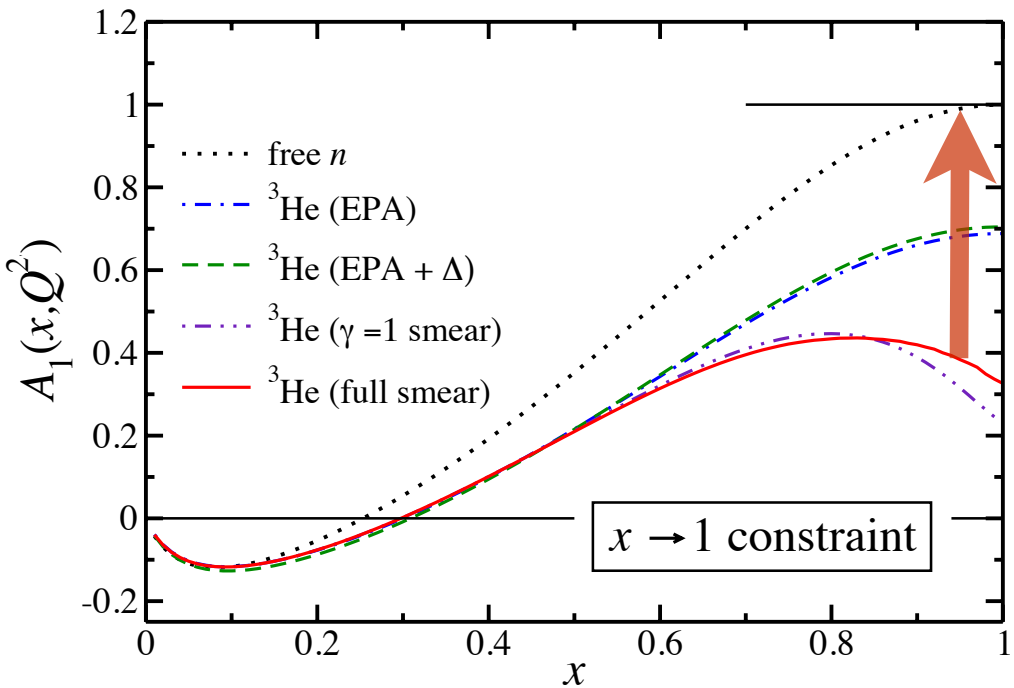




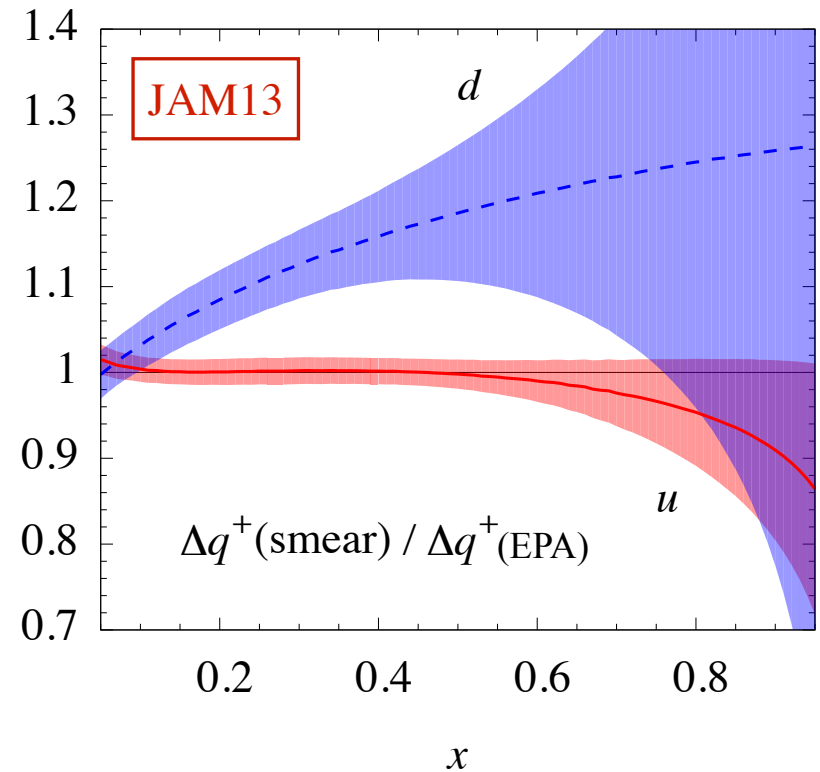
→ effective polarization approximation (EPA)

$$f^N(y) \;\to\; \langle \sigma_z \rangle^N \; \delta(y-1)$$

Nuclear corrections



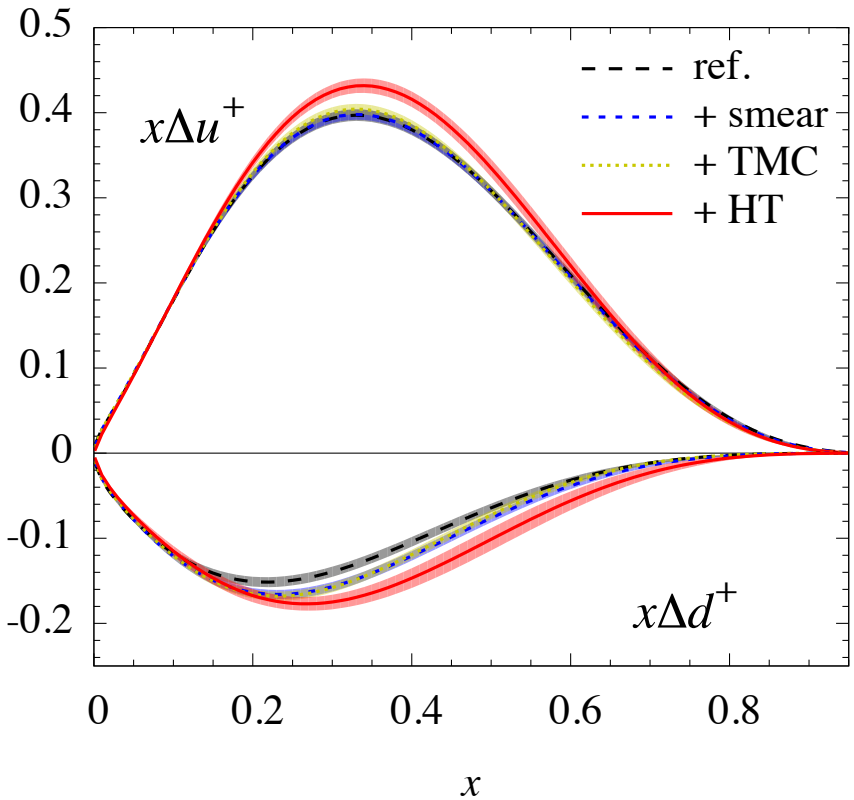
Ethier, WM, PRC ***88****, 5 (2013)*

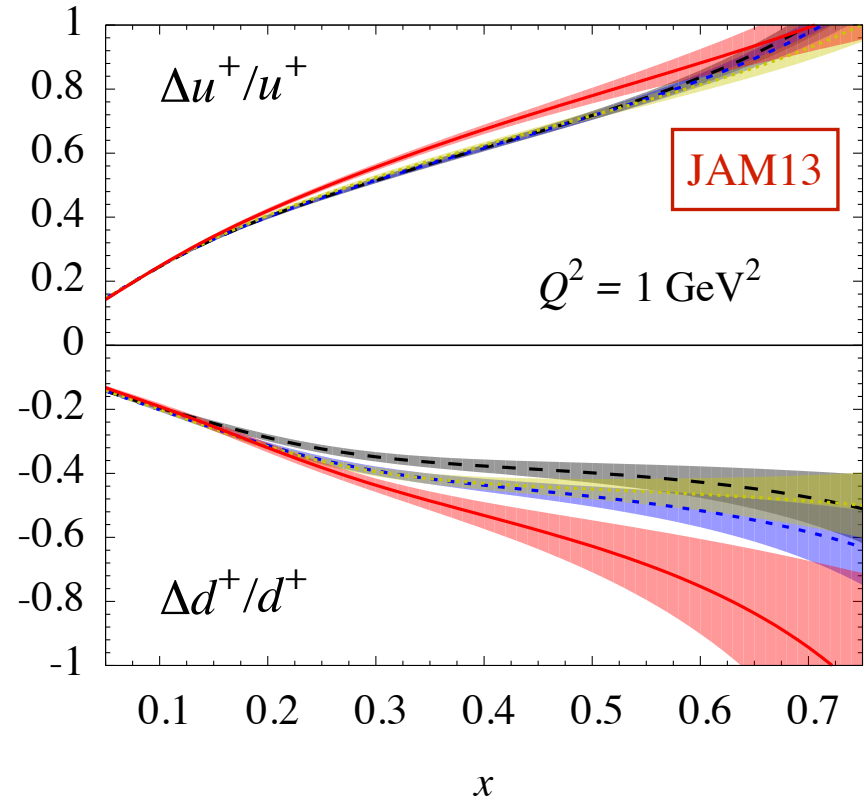


→ significant effect (esp. on d-quark) from nuclear smearing
cf. effective polarization approximation (EPA)

→ neutron asymmetry at $x \to 1$ obfuscated by smearing in ^{3}He nucleus

JAM13 distributions





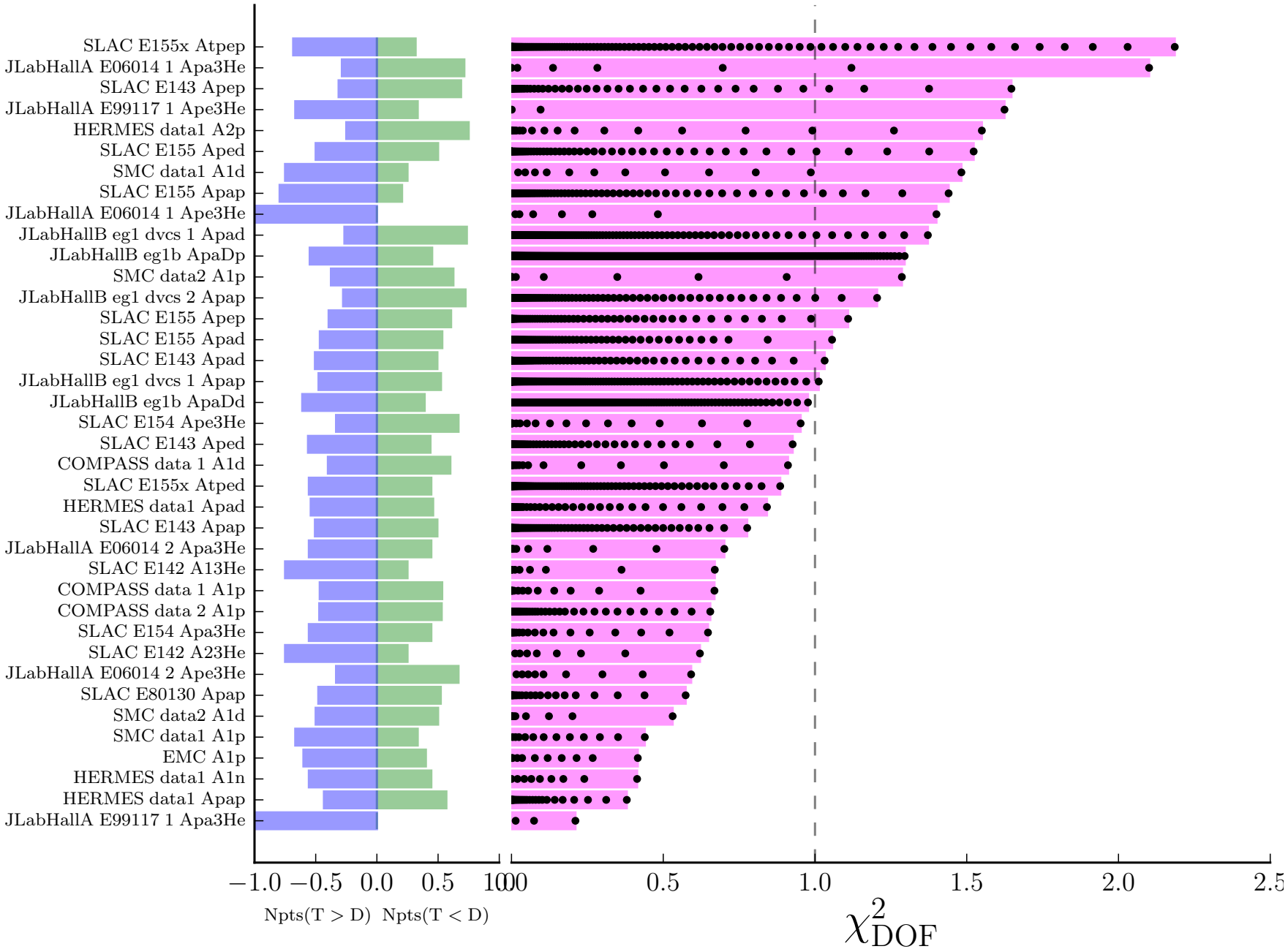
*Jimenez-Delgado et al., PRD **89**, 034025 (2014)*

→ significantly larger $|\Delta d|$ at $x \gtrsim 0.3$

→ greatest effect on polarized PDFs from HT corrections

New JAM15 analysis

- Including all data, total $\chi^2 = 3420$ for 2887 points, or $\chi^2_{\rm dof} = 1.18$



New JAM15 analysis

- Error analysis uses Hessian method to propagate parameter uncertainties

→ χ^2 for parameters $\vec{p}$

$$\chi^2(\vec{p}) = \sum_i \frac{(\mathrm{data}_i - \mathrm{thy}_i(\vec{p}))^2}{\sigma^2_{\mathrm{uncor},i} + \sigma^2_{\mathrm{cor},i}}$$

Hessian matrix

$$H_{ij} = \frac{1}{2} \left. \frac{\partial \chi^2(\vec{p})}{\partial p_i \partial p_j} \right|_{\vec{p}=\mathrm{best}}$$

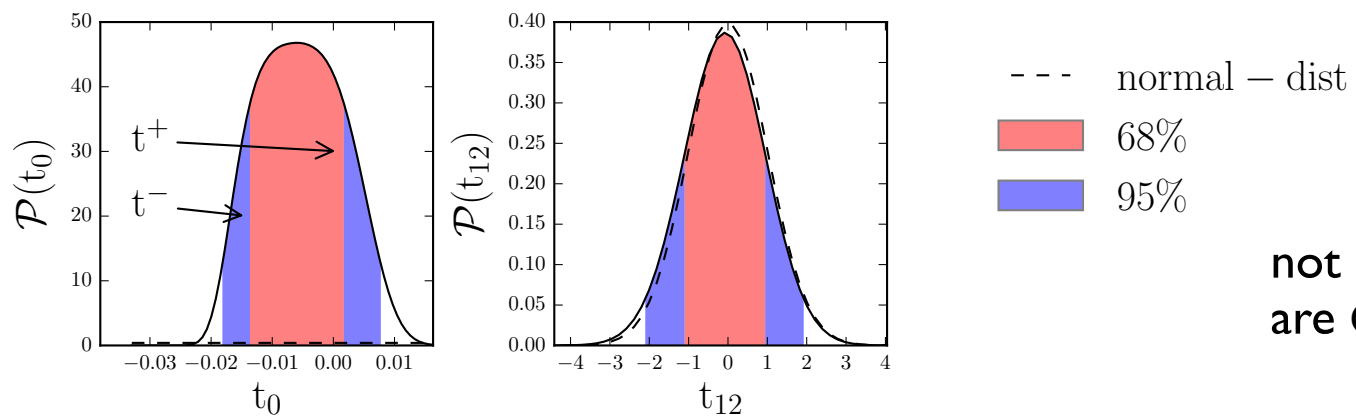
→ deviations of parameters from their best values parametrized by scale factors $\{t_i\}$ in eigenbasis $\{\hat{e}_i\}$ of covariance matrix $C = H^{-1}$

$$\Delta\vec{p} = \sum_i t_i \, \hat{e}_i$$

New JAM15 analysis

→ probability distribution assumed to factorize in $\{\hat{e}_i\}$

$$\mathcal{P}(\Delta\vec{p}) \approx \prod_i \mathcal{P}_i(t_i) \propto \prod_i \exp\left[-\frac{1}{2}\chi^2(t_i)\right]$$



not all distributions are Gaussian!

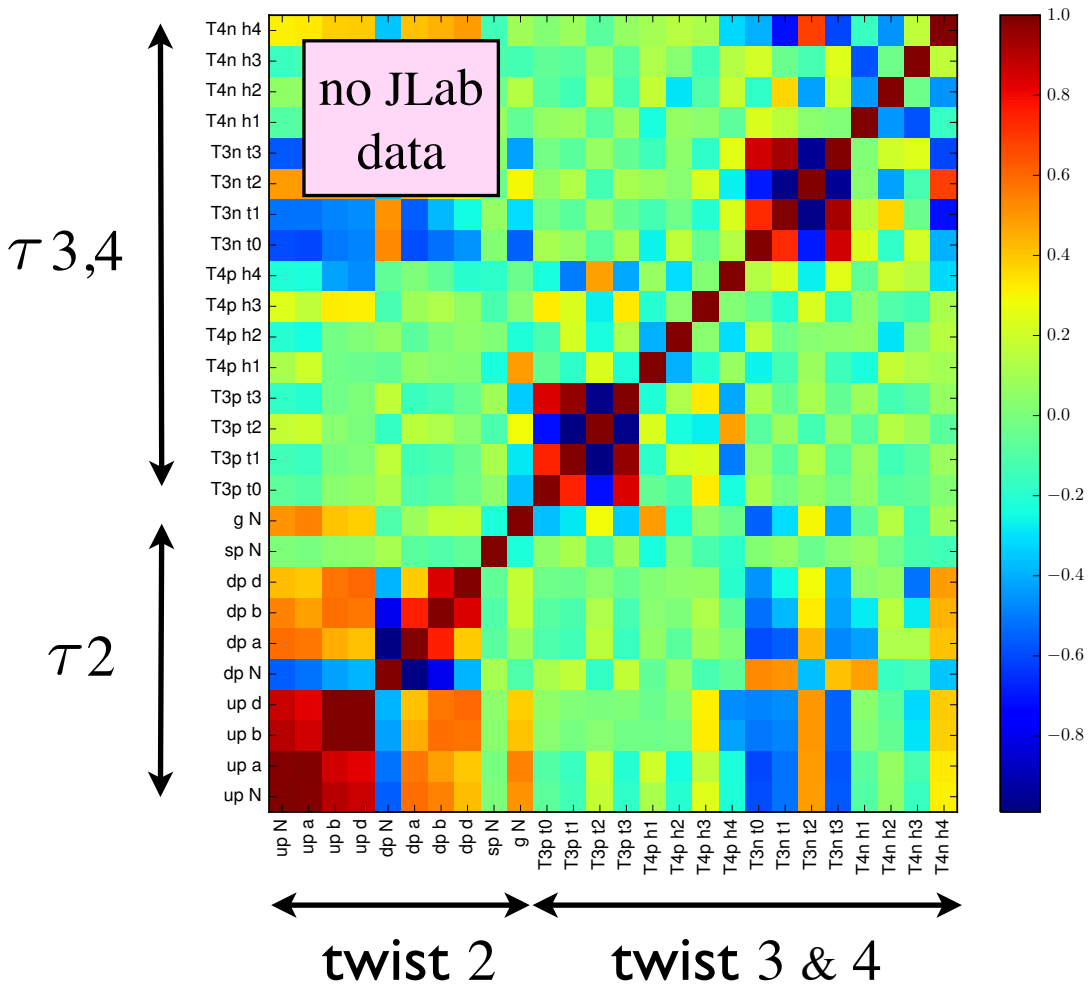
→ errors on observable $\mathcal{O}$ defined in terms of edges $t_i^{\pm}$ of confidence regions

$$\delta\mathcal{O}_+^2 \approx \sum_i \max\left[\mathcal{O}(t_i^+) - \mathcal{O}^{(0)}, \mathcal{O}(t_i^-) - \mathcal{O}^{(0)}, 0\right]^2$$

$$\delta\mathcal{O}_-^2 \approx \sum_i \max\left[\mathcal{O}^{(0)} - \mathcal{O}(t_i^+), \mathcal{O}^{(0)} - \mathcal{O}(t_i^-), 0\right]^2$$

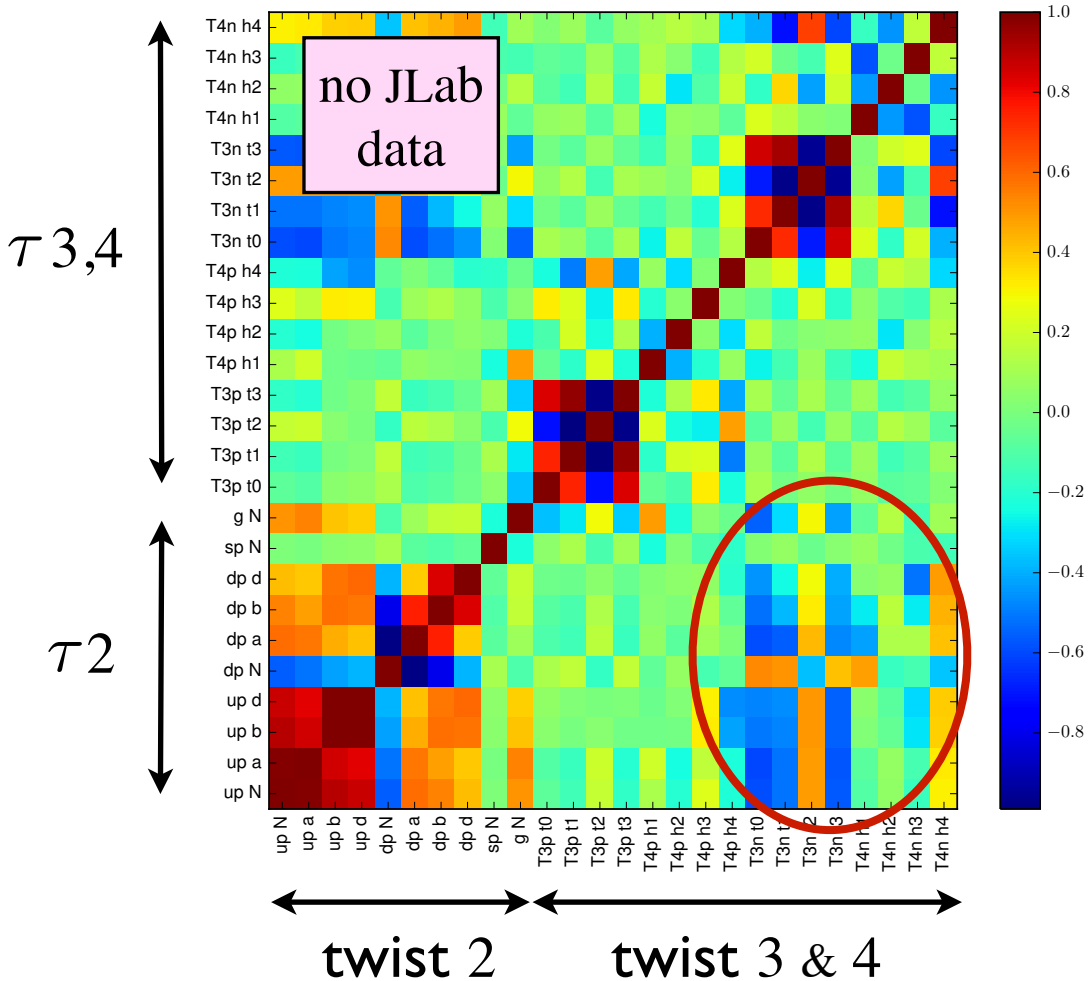
New JAM15 analysis

- Correlations between fit parameters



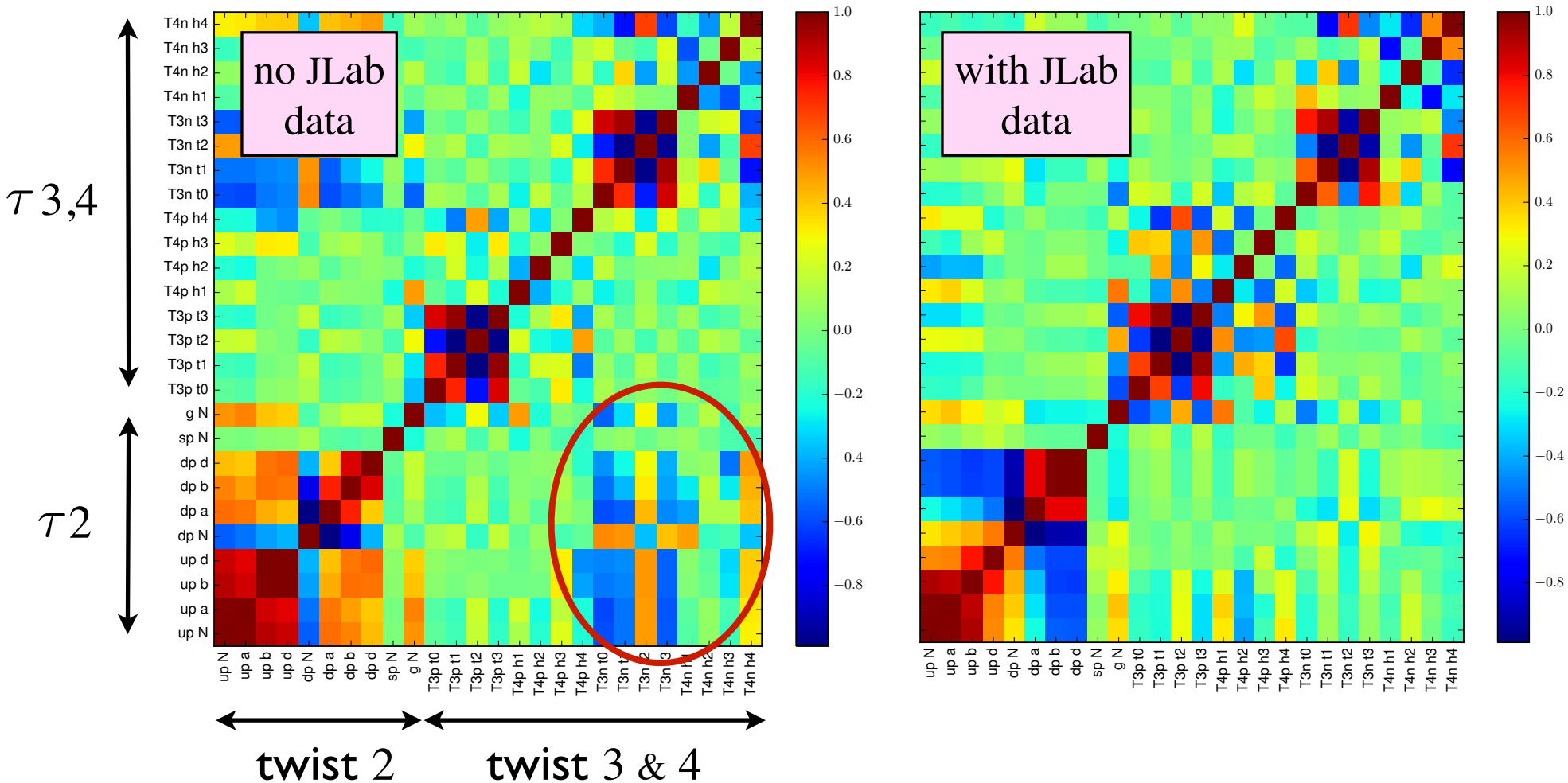
New JAM15 analysis

- Correlations between fit parameters



New JAM15 analysis

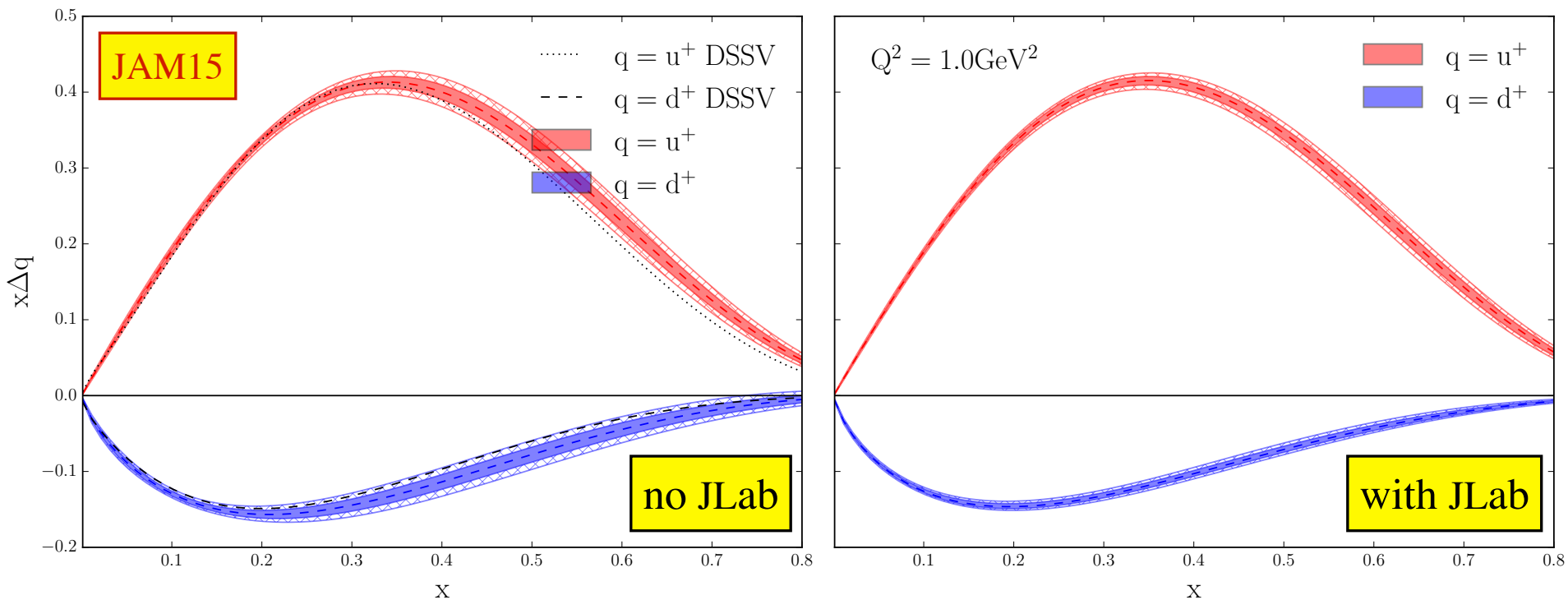
- Correlations between fit parameters



→ less correlation between LT and HT parameters with inclusion of JLab data

New JAM15 analysis

- Δu^+ & Δd^+ distributions

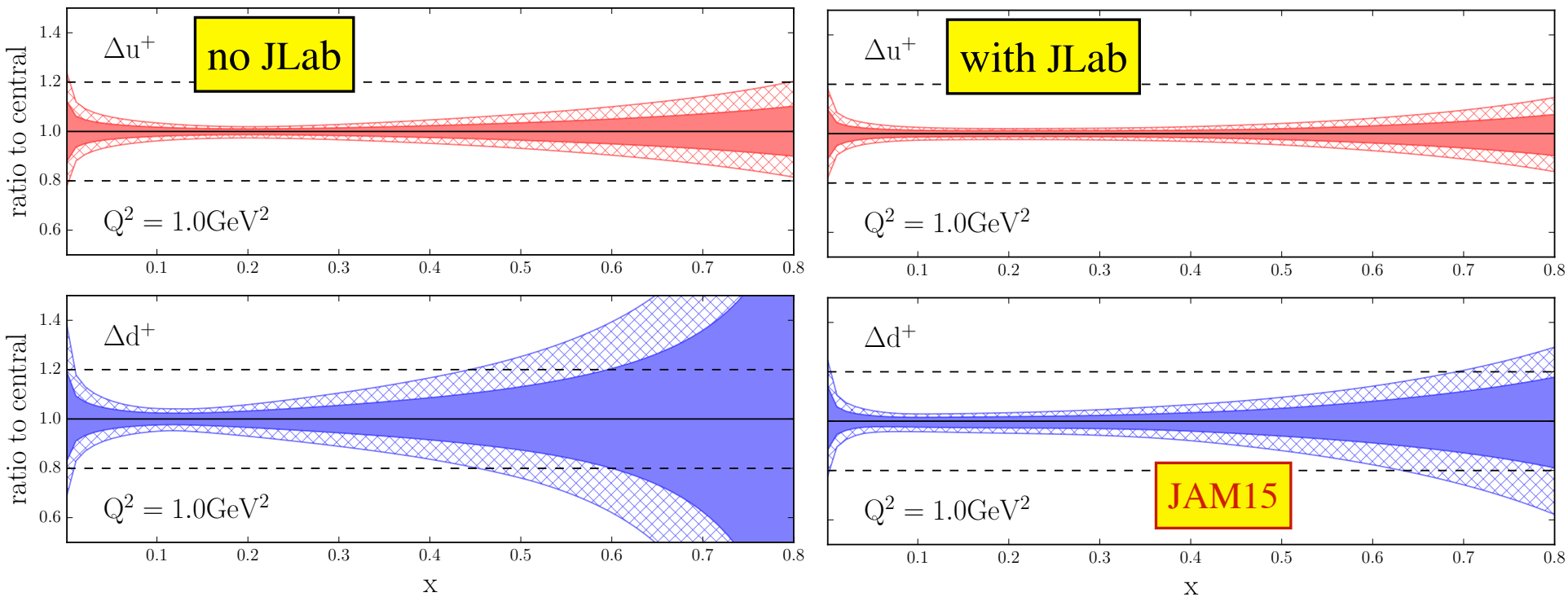


→ JAM15 PDFs consistent with DSSV, within errors

→ reduced uncertainties with inclusion of JLab data

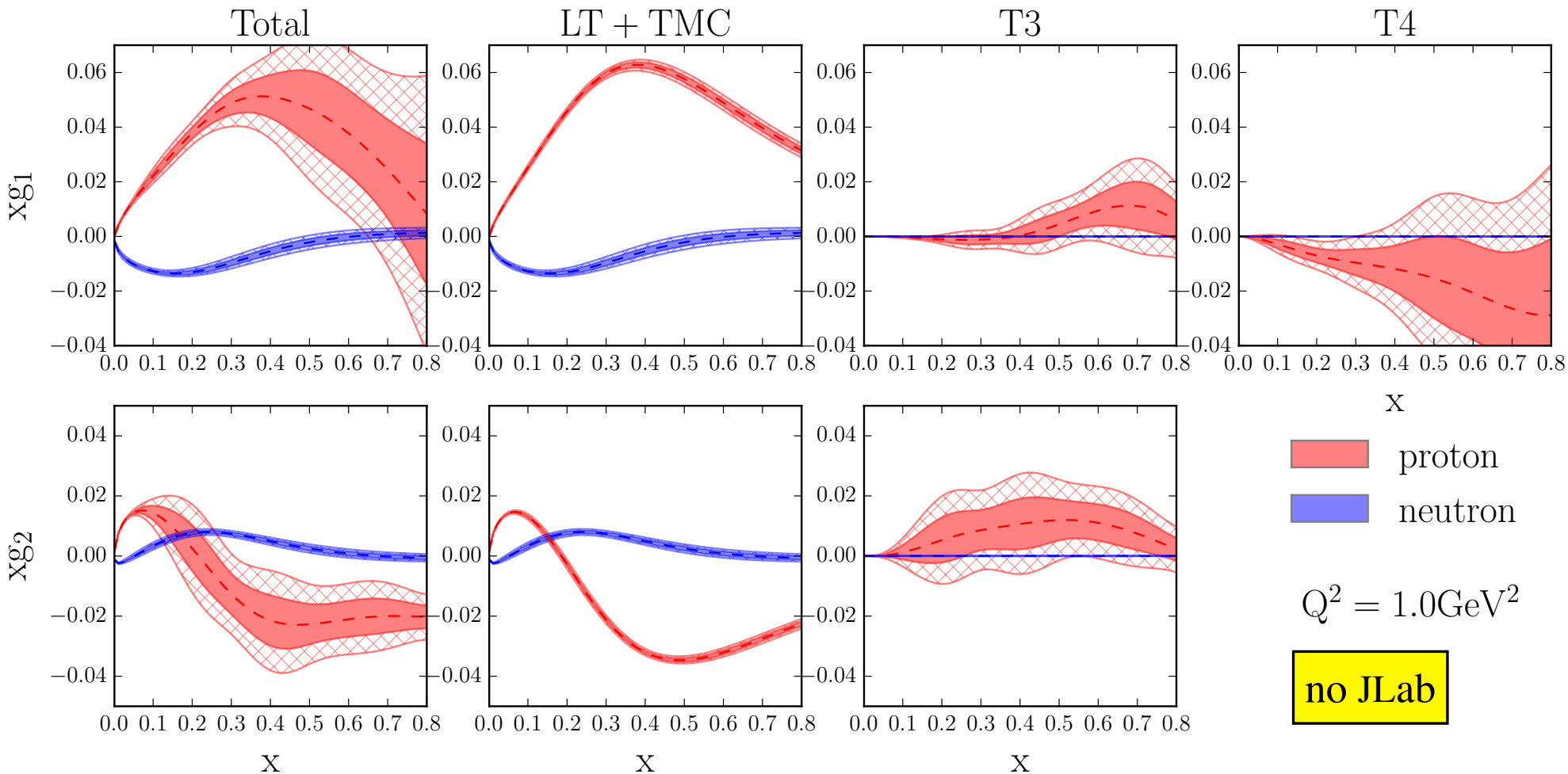
New JAM15 analysis

- Δu^+ & Δd^+ distributions

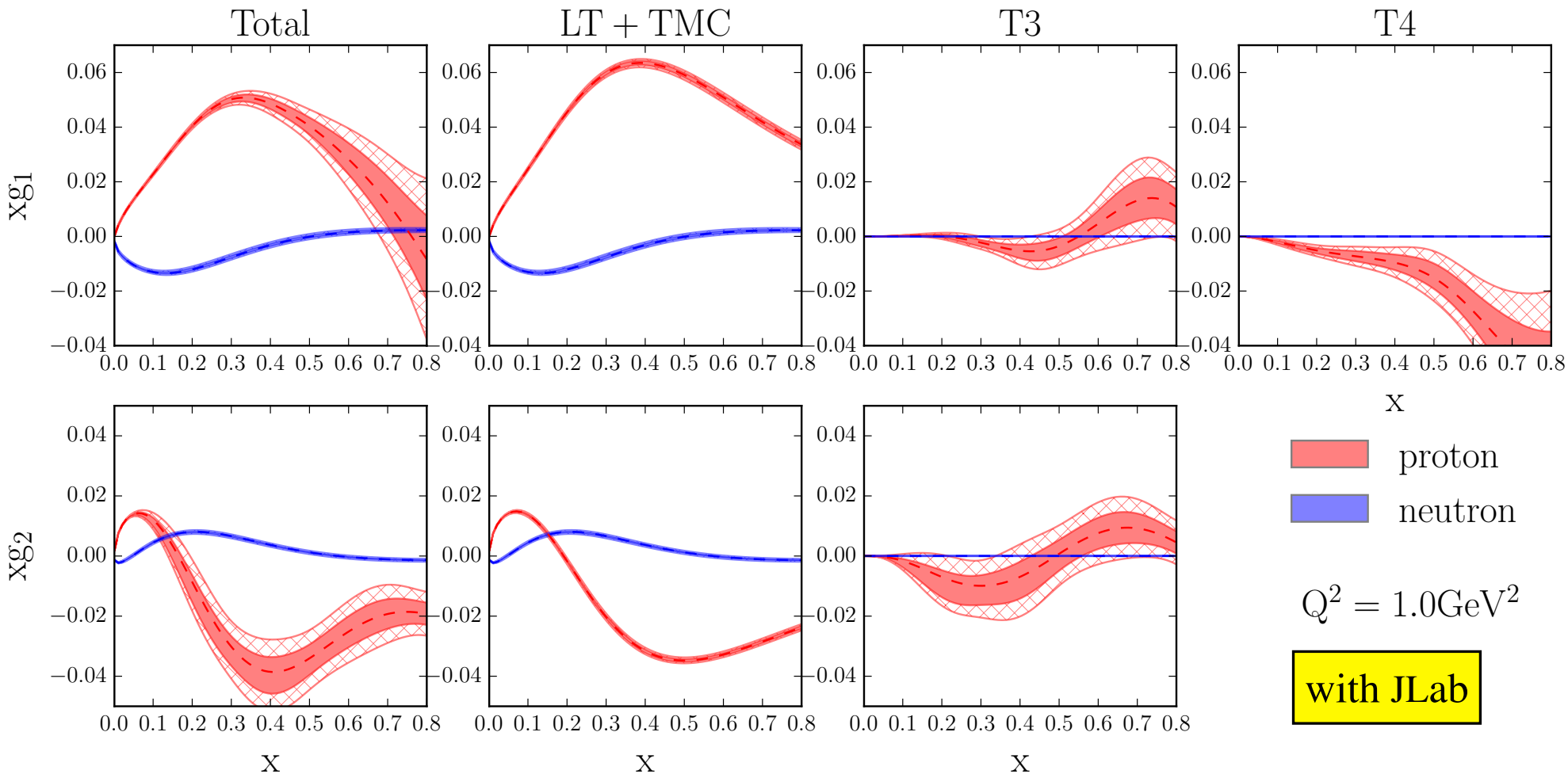


→ error reduction most dramatic for Δd^+ at large x

New JAM15 analysis



New JAM15 analysis



→ error reduction also on HT contributions

→ no reliable constraint on neutron HT (set to zero)

Outlook

- Ongoing JAM15 analysis studying impact of JLab 6 GeV inclusive DIS data at low W, high x

- Future analysis to study polarization of sea quarks & gluons
  - → semi-inclusive DIS for flavor separation
  - → polarized pp cross sections (inclusive jet & π production) for Δg
  - → maximally utilize data over all available kinematics (JLab 6 GeV, 12 GeV, RHIC-spin, EIC ...)

- Longer term goal – extend analysis to transverse spin (transversity) and momentum (TMDs)

http://www.jlab.org/JAM