University of Adelaide
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Nucleon structure from global QCD analysis of parton distributions*

Wally Melnitchouk

Jefferson Lab

* CTEQ-JLab (CJ) collaboration: http://www.jlab.org/CJ

JLab Angular Momentum (JAM) collaboration: http://www.jlab.org/JAM

Outline

- Introduction to PDFs

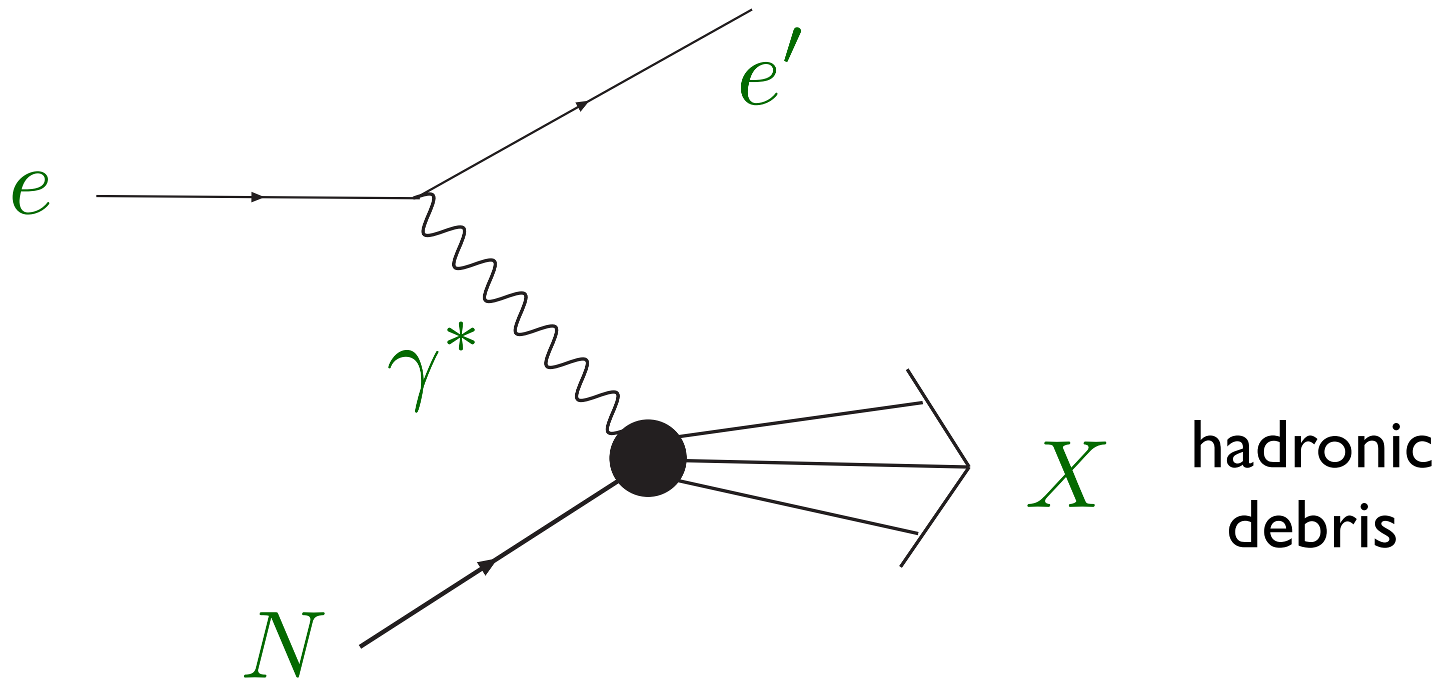
- Unpolarised distributions
  - → new "CJ" global analysis (including high-x, low-Q^2 region)
  - → d/u ratio and nuclear effects (tested in ed QE scattering)
  - → implications of PDF uncertainties for high-energy colliders

- Spin structure of the nucleon
  - → new "JAM" global analysis of polarised PDFs
  - → $x \to 1$ behavior of polarised to unpolarised ratios $\Delta q/q$

- Outlook

Electron-nucleon scattering

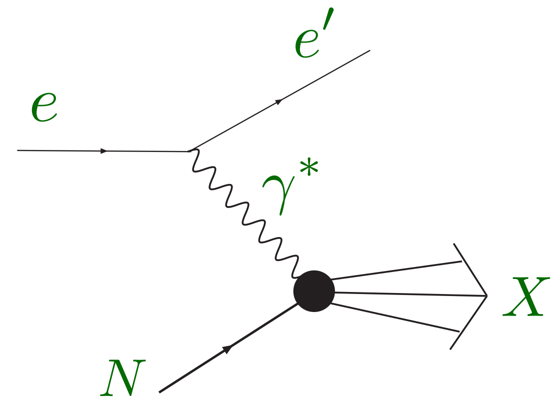
- Inclusive cross section for $eN \to eX$



$\longrightarrow$ one-photon exchange approximation

Electron-nucleon scattering

- Inclusive cross section for $eN \to eX$



$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2\frac{\theta}{2}}{Q^4}\left(2\tan^2\frac{\theta}{2}\frac{F_1}{M} + \frac{F_2}{\nu}\right)$$

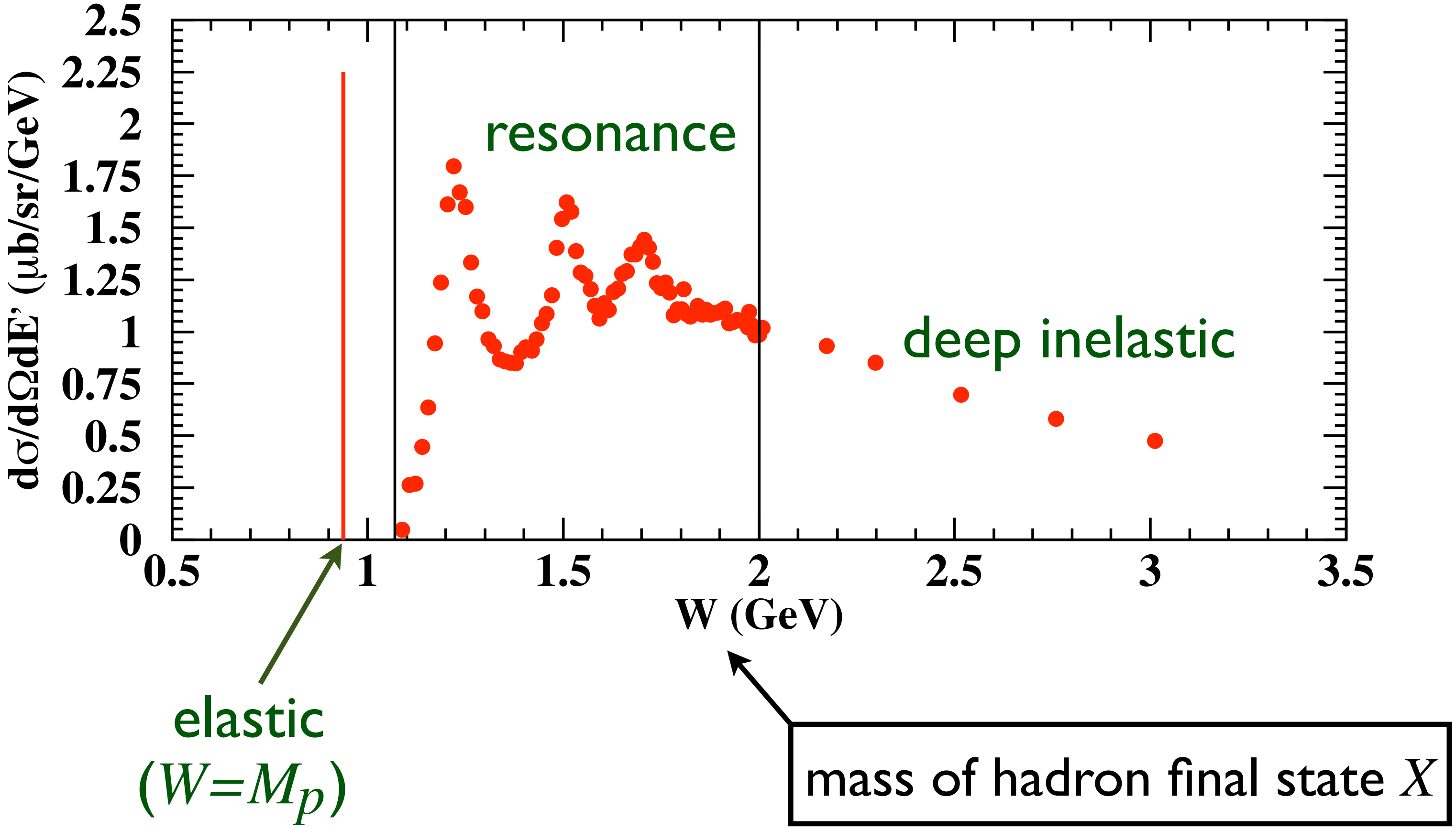
$$\left.\begin{aligned} \nu &= E - E' \\ Q^2 &= \vec{q}^{\,2} - \nu^2 = 4EE'\sin^2\frac{\theta}{2} \end{aligned}\right\} \quad x = \frac{Q^2}{2M\nu}$$

Bjorken scaling variable

- Structure functions F_1, F_2

→ contain all information about structure of nucleon
(δ-functions for point-like particles)

Electron-nucleon scattering

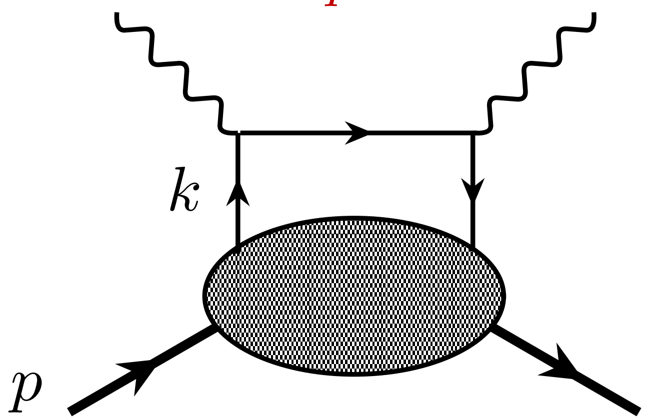


Bjorken variable in terms of Q^2 & W : $x = \dfrac{Q^2}{W^2 - M^2 + Q^2}$

Parton model

→ scatter from individual quarks (*"partons"*) in nucleon

$$F_2(x,Q^2) = x \sum_q e_q^2\, q(x,Q^2) \qquad (q{=}u,d,s\ldots)$$



→ $q\,(x,Q^2)$ = probability to find quark type "q" in nucleon, carrying (light-cone) momentum fraction x

$$x = \frac{k^+}{p^+} = \frac{k^0 + k^z}{p^0 + p^z}$$

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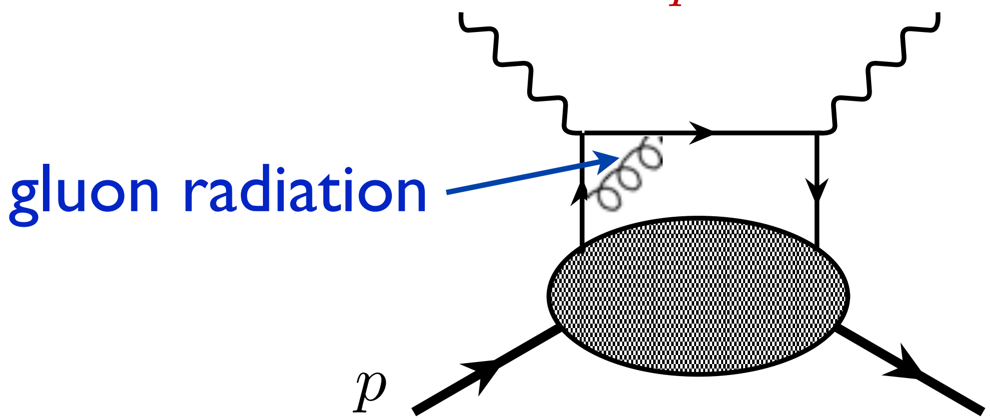
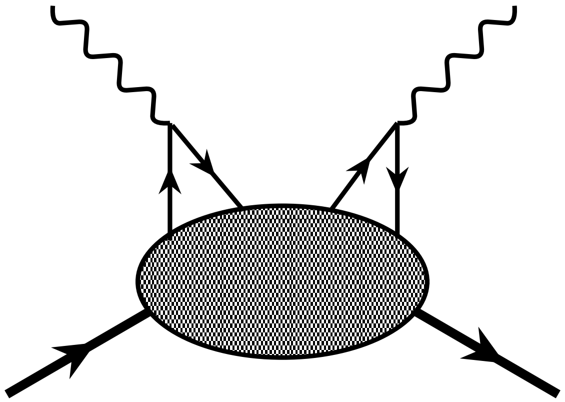


→ at finite energy, Q^2 dependence given by (perturbatively calculable) QCD evolution equations

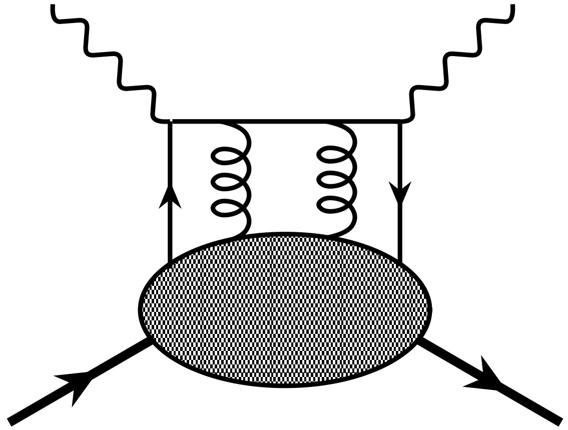
$$F_2 \to F_2(x, \log Q^2)$$

Parton model – higher twist corrections

→ scattering from *different* quarks in nucleon



"cat's ears" diagram



quark-gluon correlations

→ gives rise to $1/Q^2$ corrections

$$F_2(x, Q^2) = F_2^{\rm LT}(x, Q^2) \left(1 + \frac{C(x)}{Q^2}\right)$$

→ important at high x and low Q^2

Parton model – target mass corrections

→ kinematical corrections from derivative operators

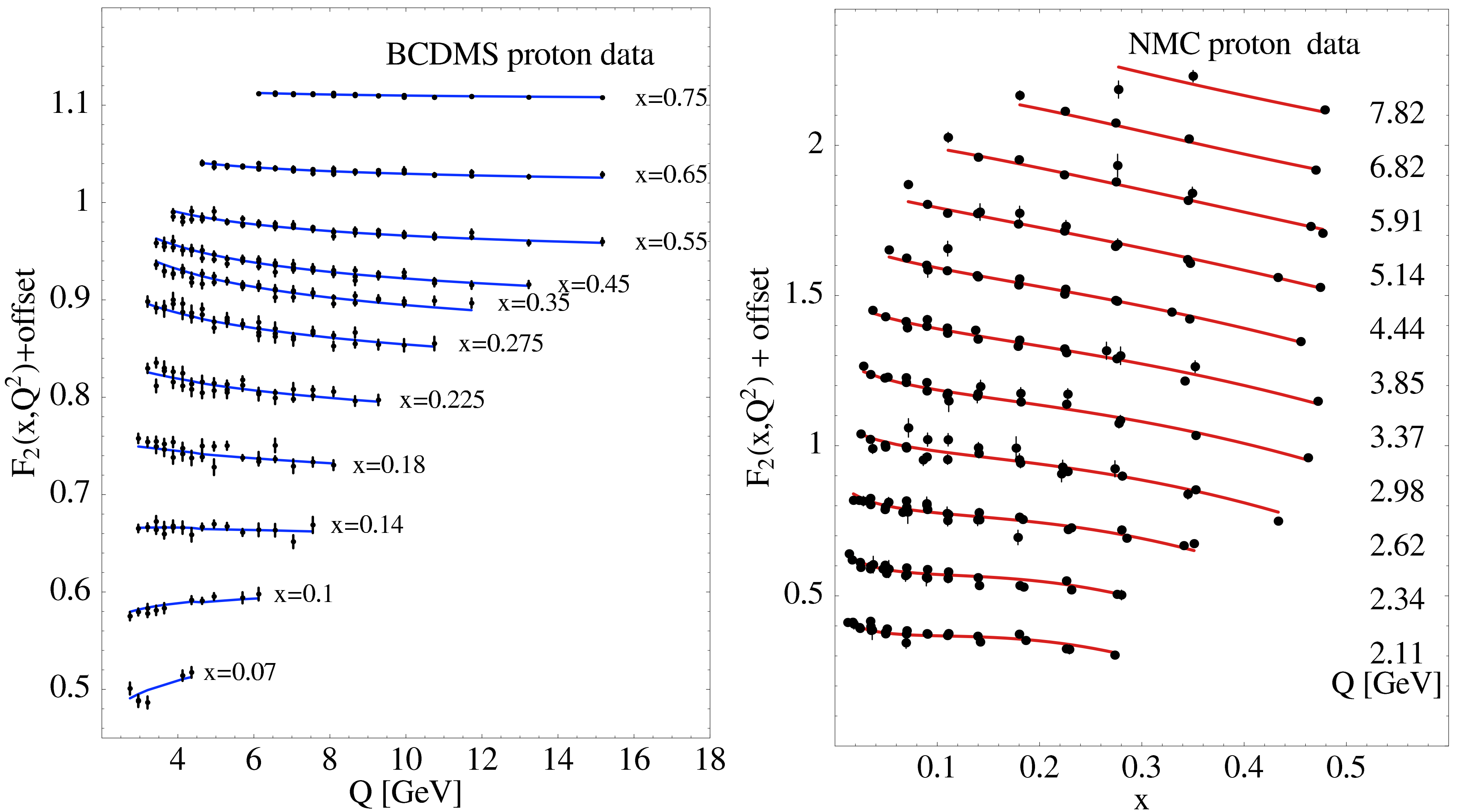
$\sim \; Q^2/\nu^2 = 4M^2x^2/Q^2$ (hence "target mass")

→ target mass corrected structure function

$$F_2^{\rm TMC}(x,Q^2) = \frac{x^2}{\xi^2\gamma^3}F_2^{(0)}(\xi,Q^2) + \frac{6M^2x^3}{Q^2\gamma^4}\int_\xi^1 du \frac{F_2^{(0)}(u,Q^2)}{u^2} + \frac{12M^4x^4}{Q^4\gamma^5}\int_\xi^1 dv(v-\xi)\frac{F_2^{(0)}(v,Q^2)}{v^2}$$

- $F_2^{(0)}$ = structure function in massless (Bjorken) limit
- new "Nachtmann" scaling variable $\xi = \dfrac{2x}{1+\sqrt{1+4M^2x^2/Q^2}}$

F_2^p structure function data



*Lai et al., EPJ C**12**, 375 (2000)*

→ describes data over many orders of magnitude in x and Q^2

Parton distribution functions (PDFs)

- PDFs extracted in global QCD analyses (CTEQ, MSTW, ...) of structure function data from e, μ & ν scattering
  (also from lepton-pair & W-boson production in hadronic collisions)

  → determined over large range of x and Q^2

$$x f(x, Q_0^2) = N x^\alpha (1-x)^\beta (1 + \epsilon \sqrt{x} + \eta\, x)$$

- Provide basic information on structure of QCD bound states

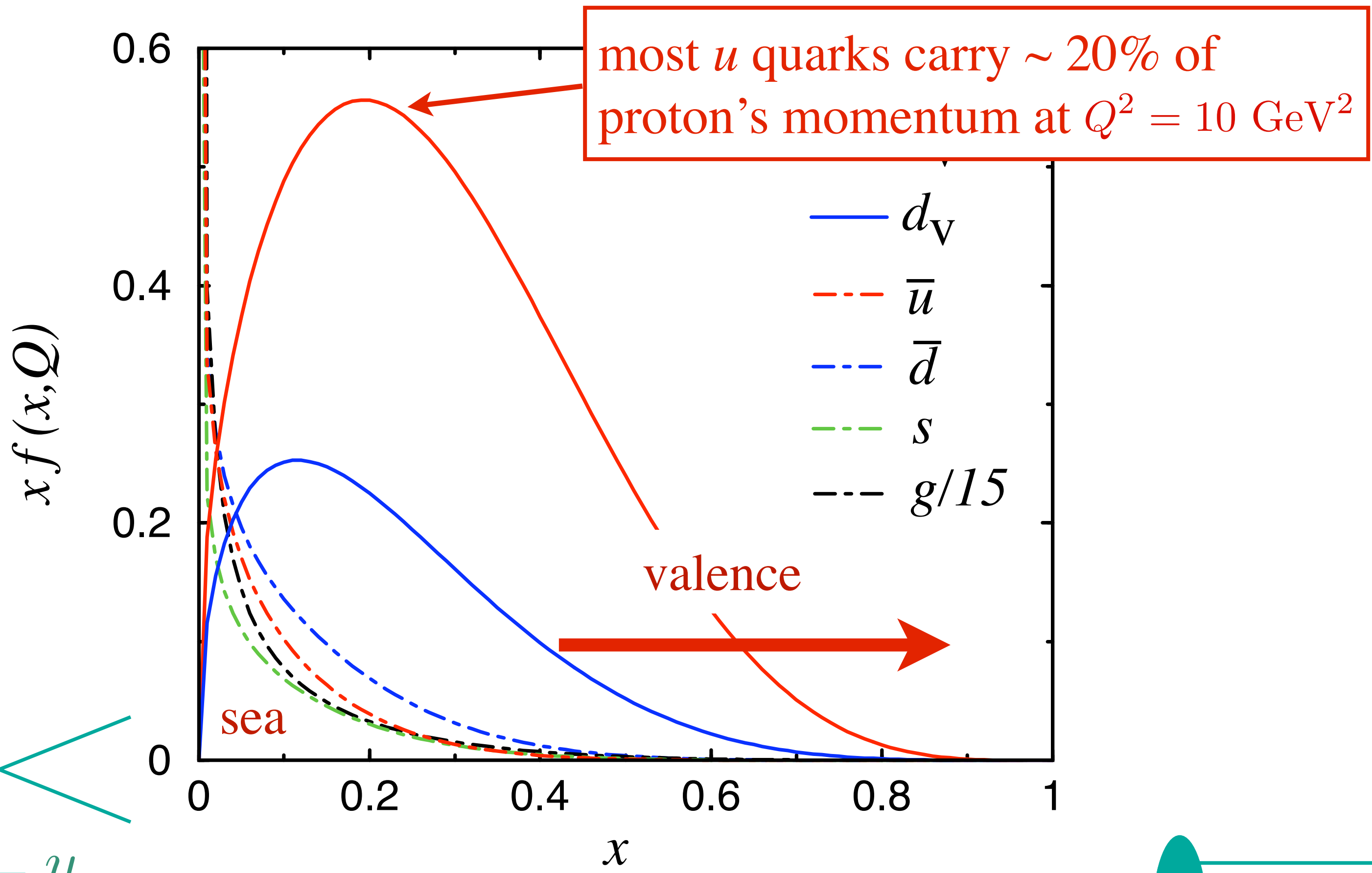
- Needed to understand backgrounds in searches for physics *beyond the Standard Model* in high-energy colliders *e.g.* the LHC

  → Q^2 evolution feeds low x, high Q^2 from high x, low Q^2

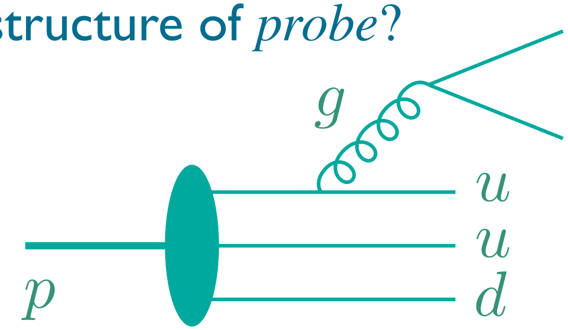
Parton distribution functions (PDFs)

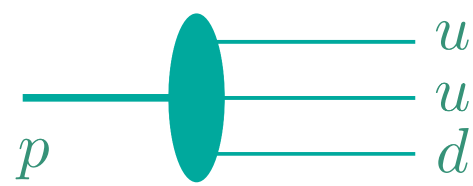
- Most direct connection between quark distributions and models of nucleon structure is via *valence* quarks

  → most cleanly revealed at $x > 0.4$



structure of *hadron*
or structure of *probe*?





PDFs at large x

- At large x, valence u and d distributions extracted from p and n structure functions

$$F_2^p \approx \frac{4}{9} x u_v + \frac{1}{9} x d_v$$

$$F_2^n \approx \frac{4}{9} x d_v + \frac{1}{9} x u_v$$

- u quark distribution well determined from *proton* data
- d quark distribution requires *neutron* structure function

$$\longrightarrow \quad \frac{d}{u} \approx \frac{4 - F_2^n / F_2^p}{4 F_2^n / F_2^p - 1}$$

PDFs at large x

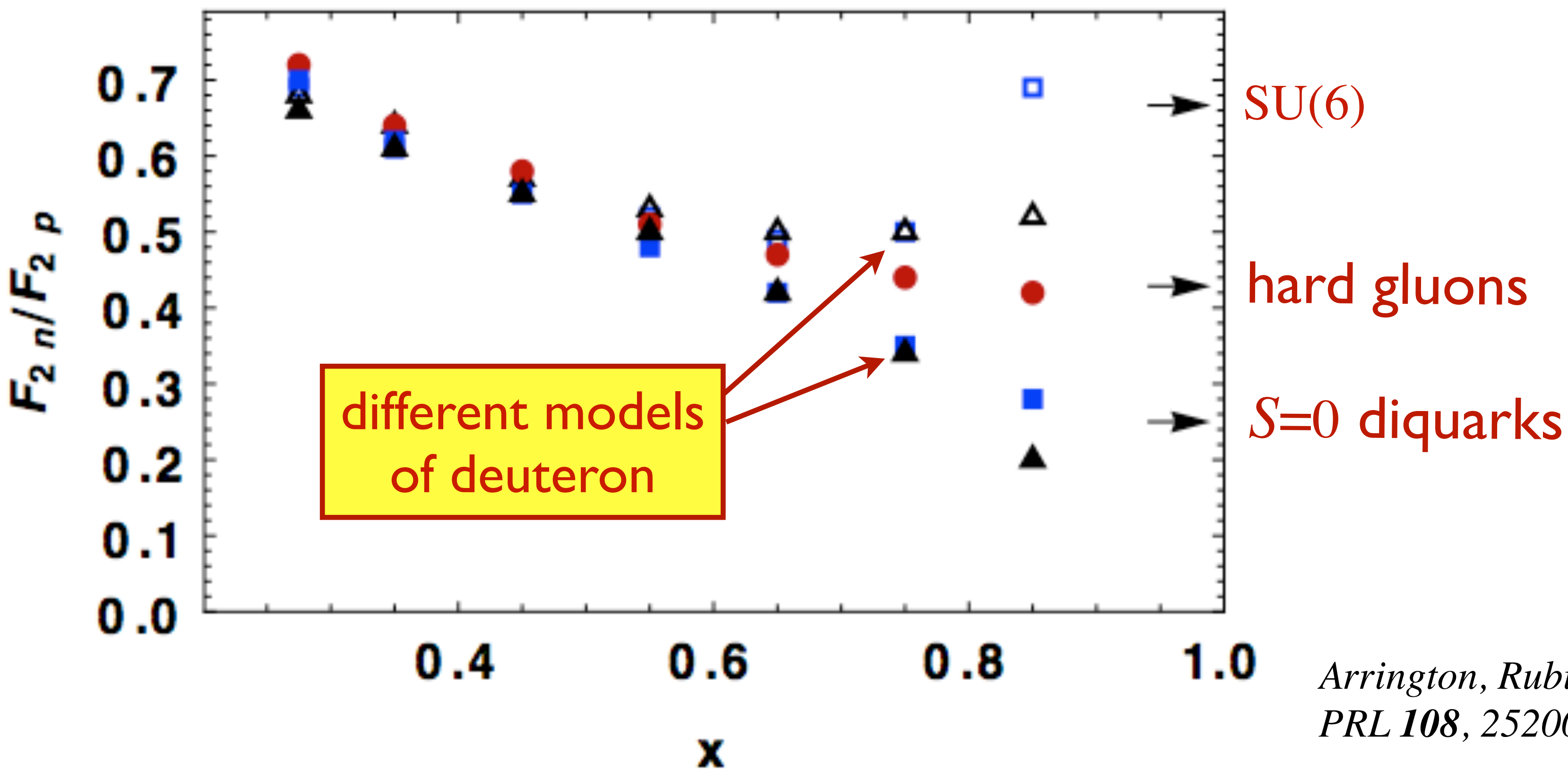
- Ratio of d to u quark distributions particularly sensitive to nonperturbative quark-gluon dynamics in nucleon

  - $d/u \to 1/2$ SU(6) symmetry
  - $d/u \to 0$ $S = 0$ qq dominance
  - $d/u \to 1/5$ $S_z = 0$ qq dominance (pQCD-inspired)
  - $d/u \to \dfrac{4\,\mu_n^2/\mu_p^2 - 1}{4 - \mu_n^2/\mu_p^2} \approx 0.42$ local quark-hadron duality* ($\mu_{p,n}$ magnetic moments)

*structure function at $x \to 1$ given by elastic form factor at $Q^2 \to \infty$

Neutron structure

- Absence of free neutron targets
  → deuterium (weakly bound state of p and n) used instead



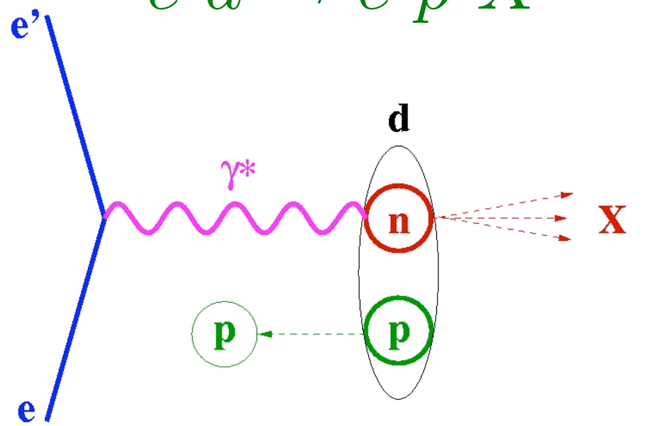
Arrington, Rubin, WM
*PRL **108**, 252001 (2012)*

→ deuteron model dependence obscures free neutron structure information at large x

Neutron structure

- BONuS: slow spectator tagging

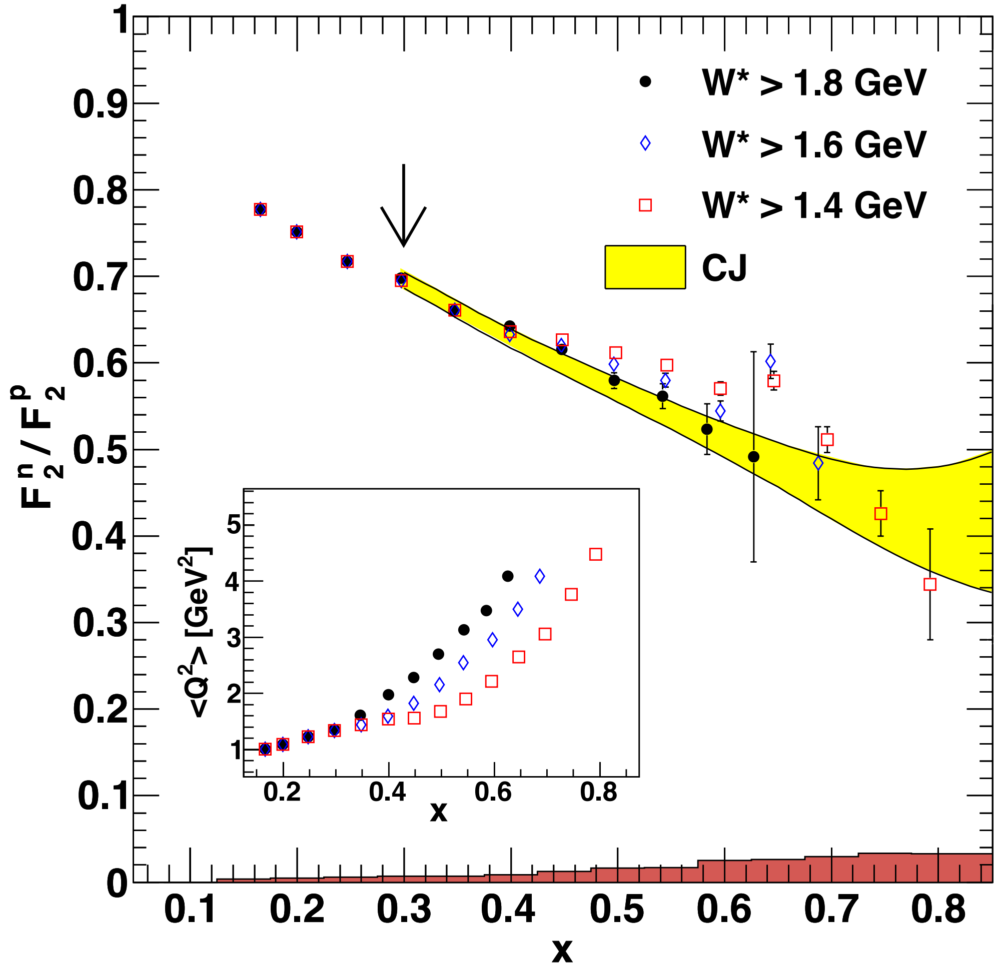
$$e\ d \to e\ p\ X$$



slow backward p

→ neutron nearly on-shell

→ minimize rescattering



Baillie et al., PRL ***108****, 199902 (2012)*

- Need for global analysis to investigate these aspects of PDFs

CJ global analysis of spin-averaged PDFs

A. Accardi, J. Owens, WM
E. Christy, C. Keppel, P. Monaghan

"CJ12" PDFs: *PRD* ***87****, 094012 (2013)*

http://www.jlab.org/CJ

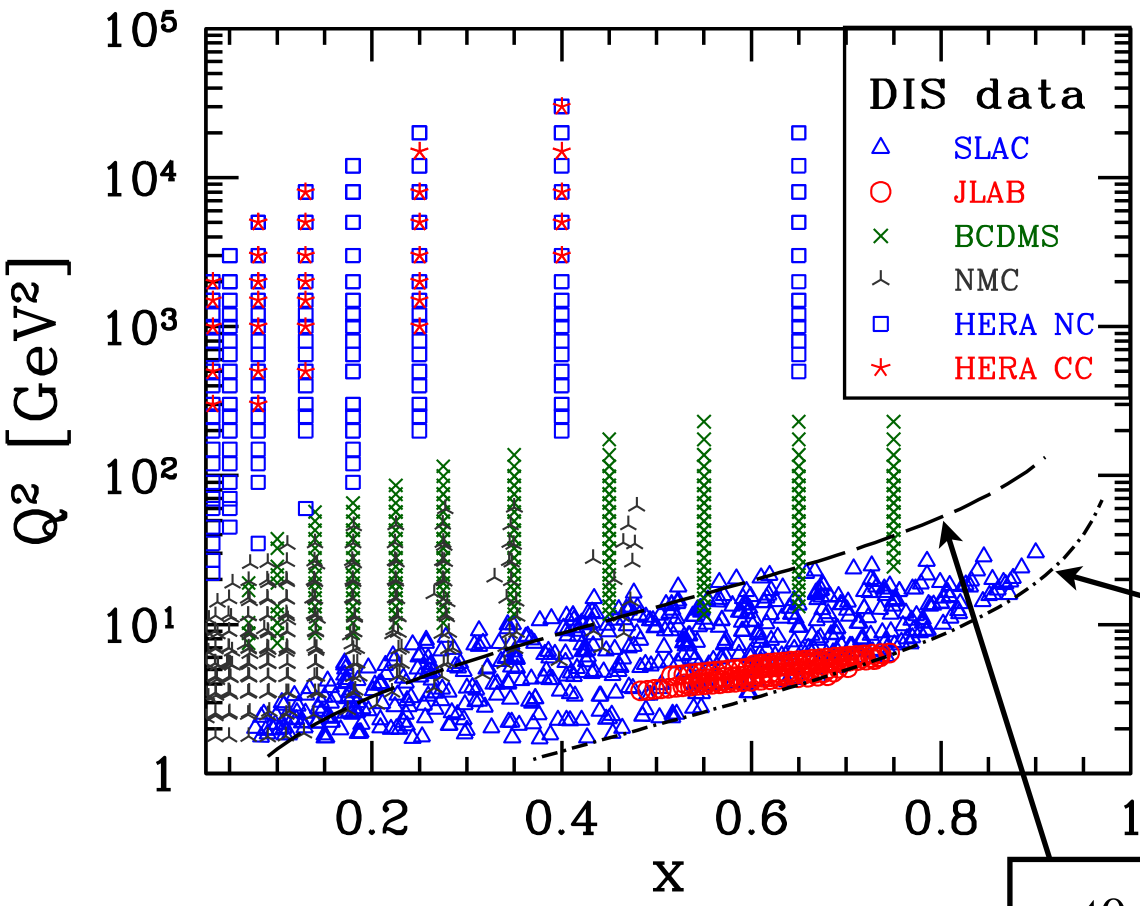
- Next-to-leading order (NLO) analysis of expanded set of *proton* and *deuterium* data (no heavy nuclei)
  - ⟶ include large-x, low-Q^2 region
- Systematically study effects of Q^2 & W cuts
  - ⟶ as low as $Q \sim m_c$ and $W \sim 1.7$ GeV
- Include subleading $1/Q^2$ corrections
  - ⟶ target mass corrections & dynamical higher twists
- Correct for nuclear effects in deuteron (binding + off-shell)
  - ⟶ most global analyses assume *free* nucleons

- CJ database

~ 4,000 data points over large range of x and Q^2

	Experiment	Ref.	# points	χ^2 CJ12min	CJ12mid	CJ12max
DIS F_2	BCDMS (p)	[13]	351	434	436	437
	BCDMS (d)	[13]	254	294	297	302
	NMC (p)	[14]	275	434	432	430
	NMC (d/p)	[15]	189	179	177	182
	SLAC (p)	[16]	565	456	455	456
	SLAC (d)	[16]	582	394	388	396
	JLab (p)	[17]	136	170	169	170
	JLab (d)	[17]	136	124	125	126
DIS σ	HERA (NC e^-)	[18]	145	117	117	118
	HERA (NC e^+)	[18]	384	595	596	596
	HERA (CC e^-)	[18]	34	19	19	19
	HERA (CC e^+)	[18]	34	32	32	32
Drell-Yan	E866 (p)	[19]	184	220	221	221
	E866 (d)	[19]	191	297	307	306
W asymmetry	CDF 1998 (ℓ)	[20]	11	14	16	18
	CDF 2005 (ℓ)	[21]	11	11	11	10
	DØ 2008 (ℓ)	[22]	10	4	4	4
	DØ 2008 (e)	[23]	12	40	36	34
	CDF 2009 (W)	[24]	13	20	25	41
Z rapidity	CDF (Z)	[25]	28	29	27	27
	DØ (Z)	[26]	28	16	16	16
jet	CDF run 1	[27]	33	52	52	52
	CDF run 2	[28]	72	14	14	14
	DØ run 1	[29]	90	21	20	19
	DØ run 2	[30]	90	19	19	20
γ+jet	DØ 1	[31]	16	6	6	6
	DØ 2	[31]	16	13	13	12
	DØ 3	[31]	12	17	17	17
	DØ 4	[31]	12	17	16	17
	TOTAL		3958	4059	4055	4096
	TOTAL + norm			4075	4074	4117

Kinematic cuts



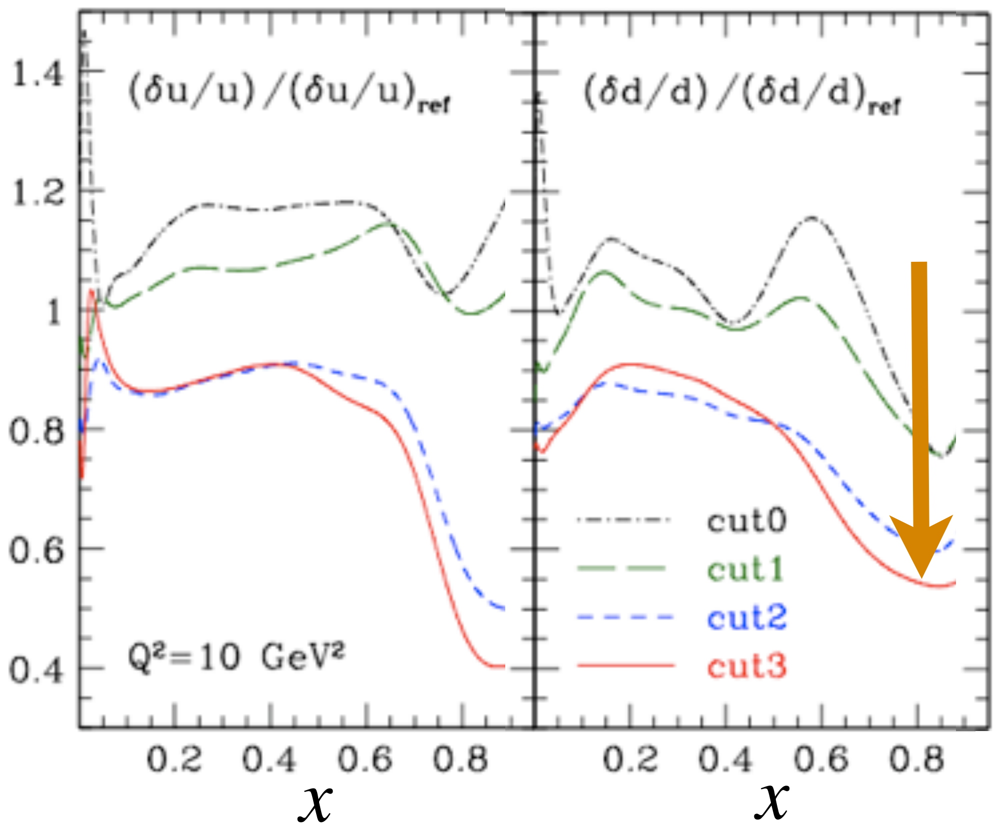
cut3: $Q^2 > m_c^2\ ,\quad W^2 > 3\ \mathrm{GeV}^2$

cut0: $Q^2 > 4\ \mathrm{GeV}^2,\quad W^2 > 12.25\ \mathrm{GeV}^2$

→ factor 2 increase in DIS data from cut0 → cut3 compared to most global analyses

Kinematic cuts

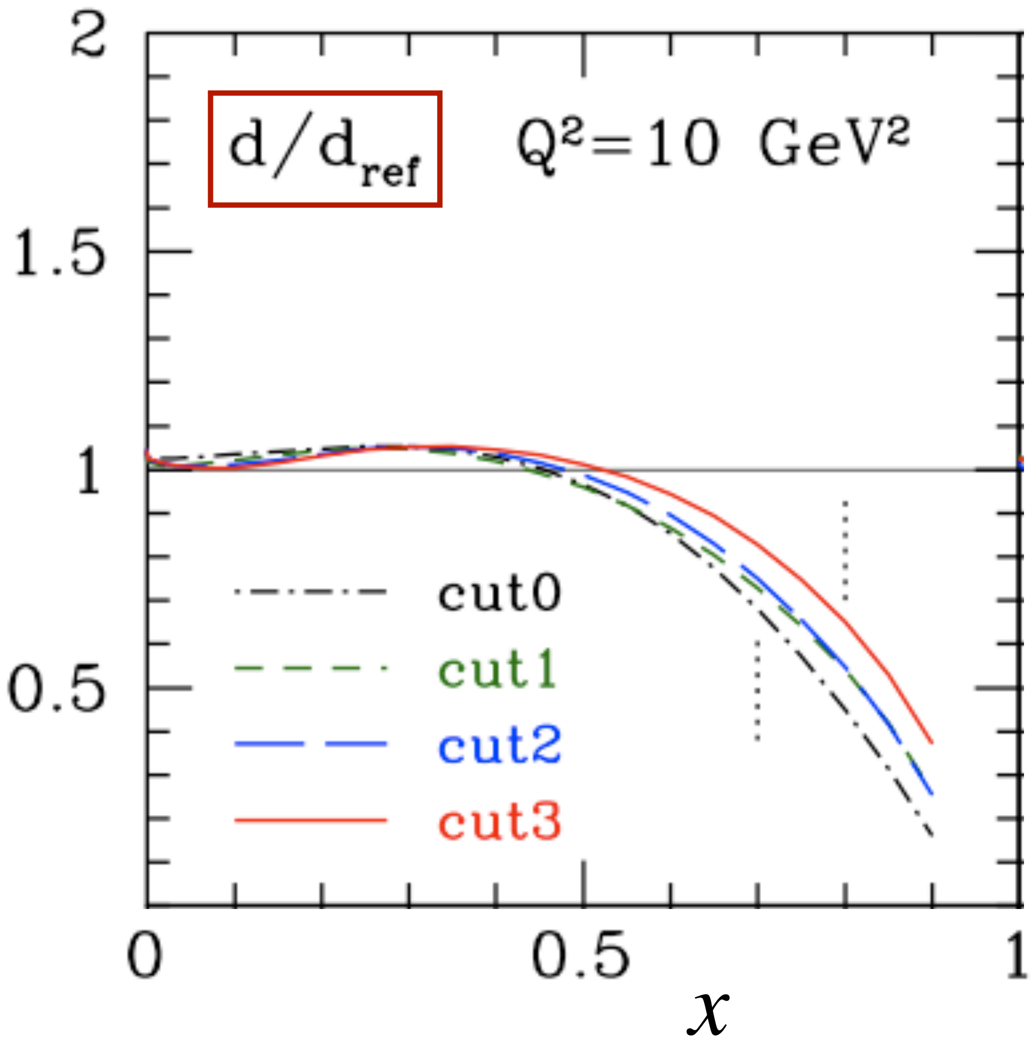
- Larger database with weaker cuts leads to significantly reduced errors, especially at large x



→ up to $40-60\%$ error reduction when cuts extended into resonance region

Kinematic cuts

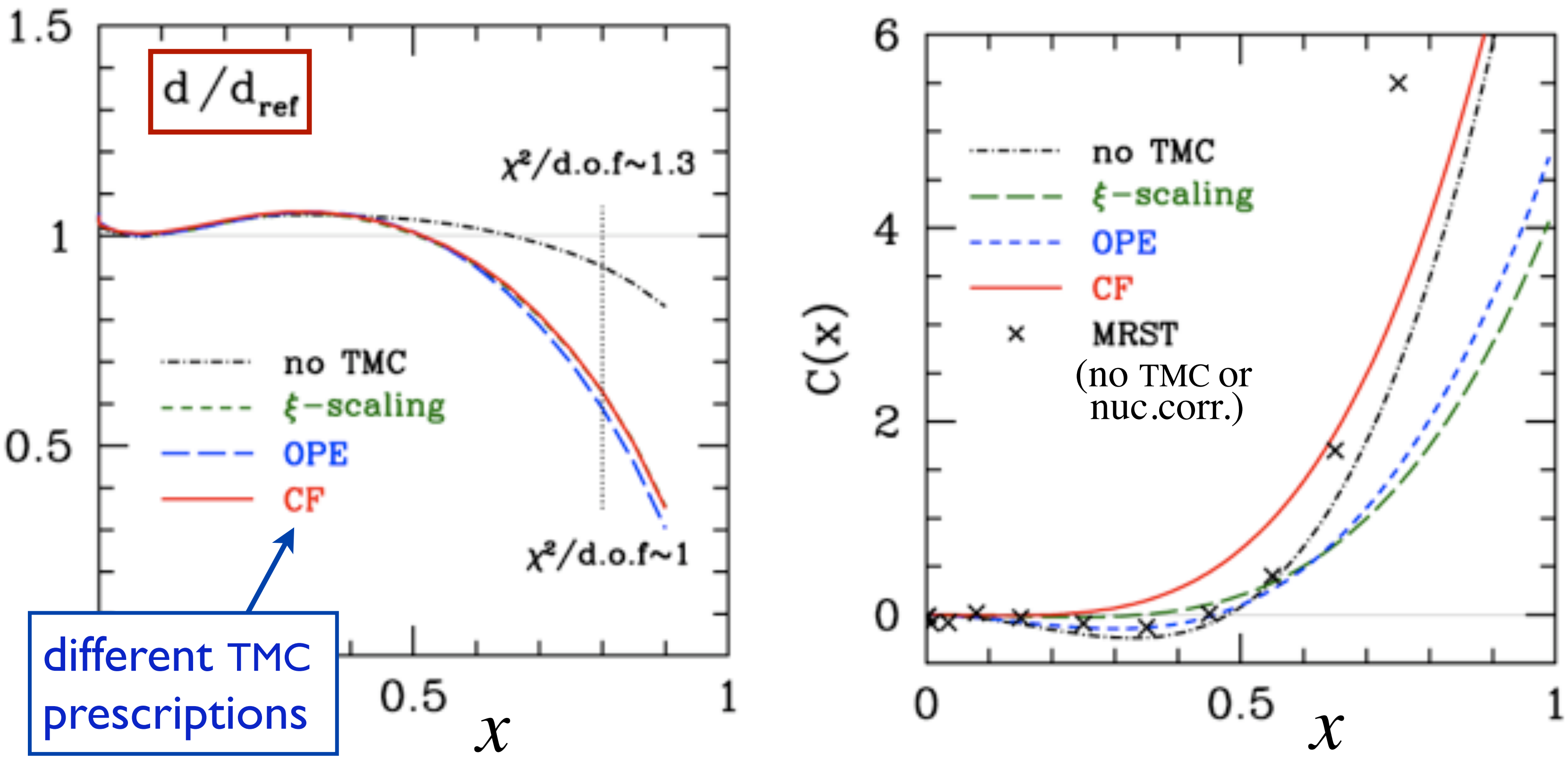
- Fits stable with respect to Q^2 and W cut reduction, as long as subleading $1/Q^2$ corrections included



→ d quark suppressed by $\sim 50\%$ for $x > 0.5$

(driven by nuclear corrections)

Finite-Q^2 corrections



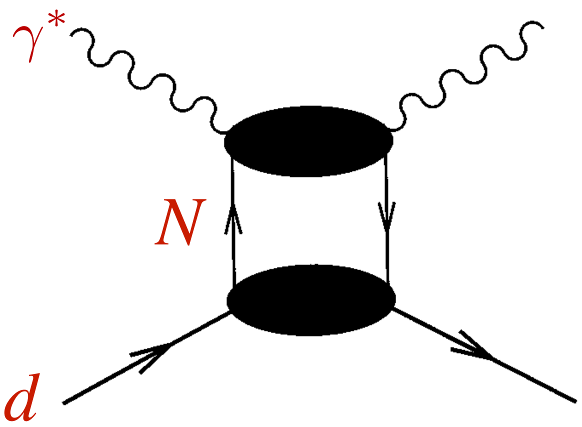
*Accardi et al., PRD **81**, 034016 (2010)*

→ interplay between TMCs and higher twist
– stable LT when both TMCs and HTs included

→ growing importance of HTs as large x

Nuclear corrections

- Nuclear structure function at $x \gg 0$ dominated by incoherent scattering from individual nucleons



$$F_2^d(x, Q^2) = \int_x dy\ f(y, \gamma)\ F_2^N(x/y, Q^2) + \delta^{(\text{off})} F_2^d$$

$N = p + n$

nucleon momentum distribution in d ("smearing function")

off-shell correction

→ y = light-cone momentum fraction of d carried by N

→ at finite Q^2, smearing function depends also on parameter

$$\gamma = |\mathbf{q}|/q_0 = \sqrt{1 + 4M^2x^2/Q^2}$$

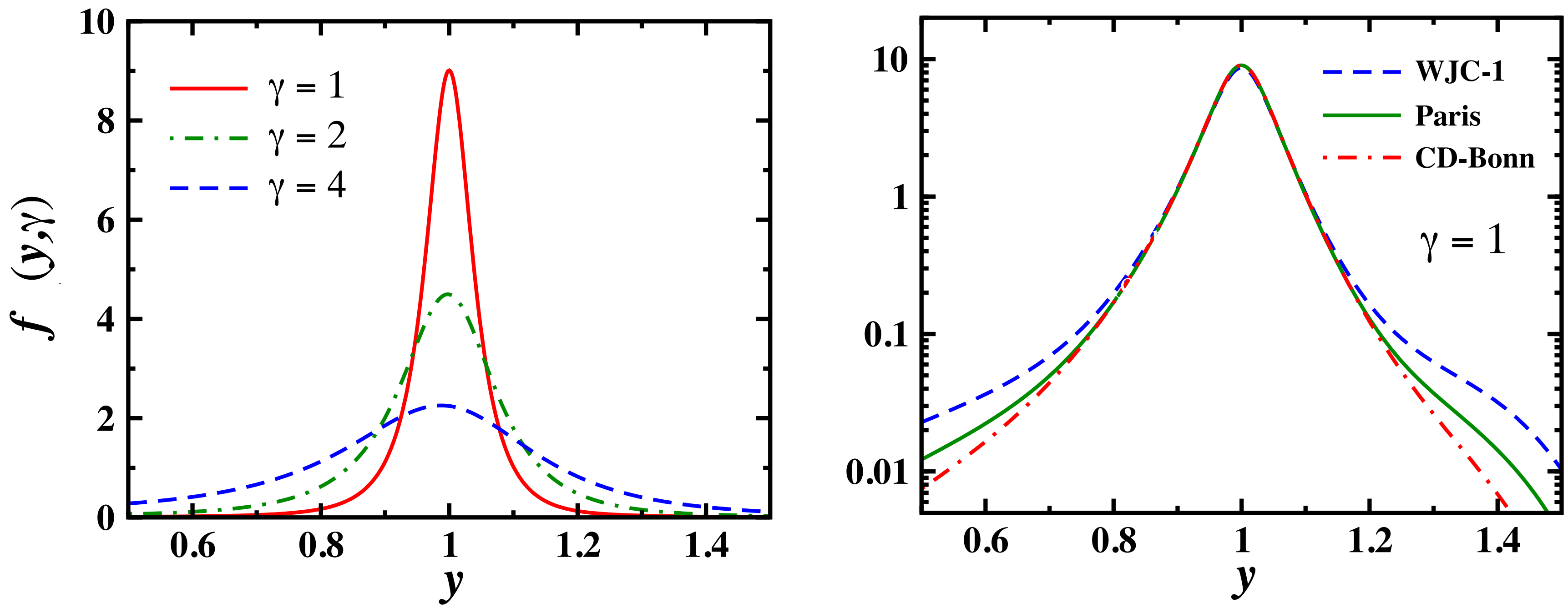
Nuclear corrections

- Smearing function in the deuteron computed in "weak binding approximation" – expand in powers of $\vec{p}^2/M^2$

$$f(y,\gamma) = \int \frac{d^3p}{(2\pi)^3}\, |\psi_d(p)|^2\; \delta\Big(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\Big)$$
$$\times \frac{1}{\gamma^2}\Big[1 + \frac{\gamma^2 - 1}{y^2}\Big(1 + \frac{2\varepsilon}{M} + \frac{\vec{p}^2}{2M^2}(1 - 3\hat{p}_z^2)\Big)\Big]$$

$\psi_d(p)$ = d wave function

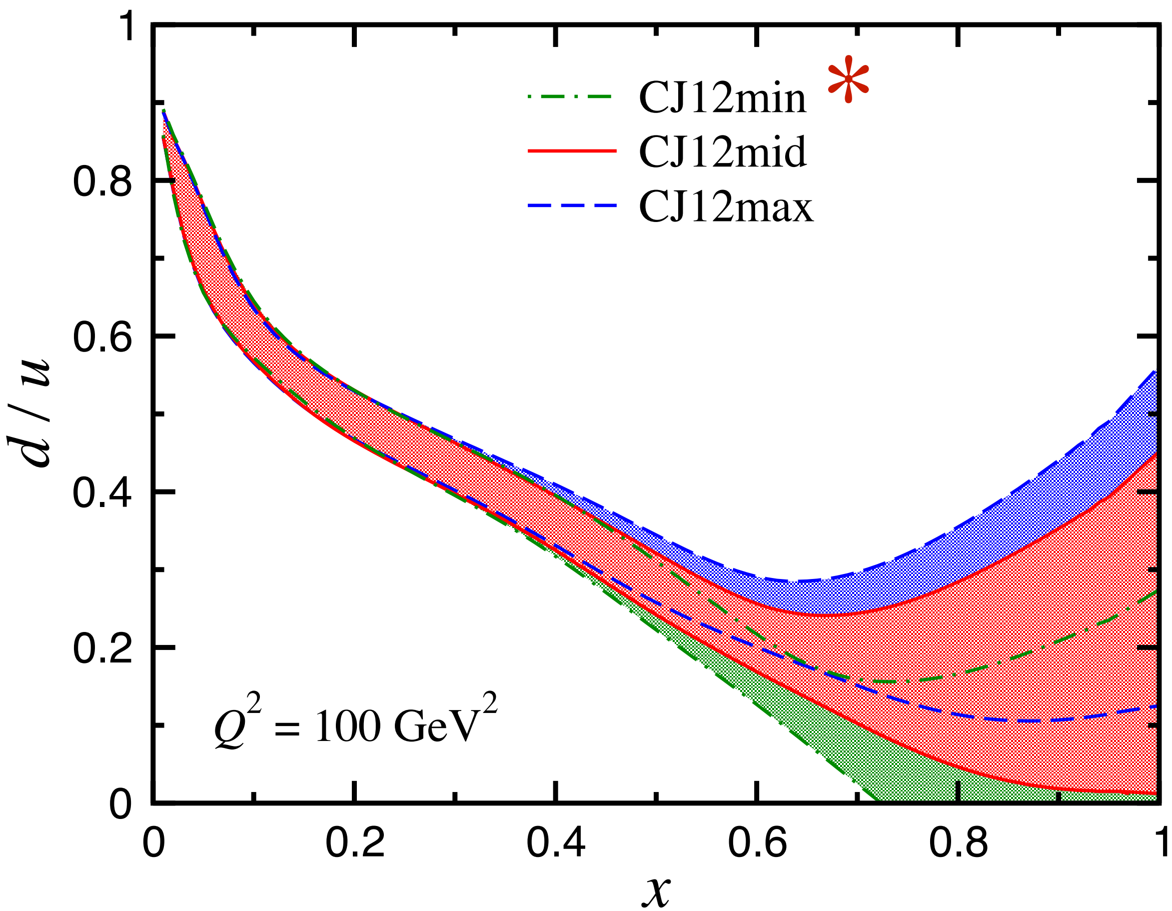
$$\varepsilon = \varepsilon_d - \frac{\vec{p}^2}{2M}$$



→ effectively more smearing for larger x and lower Q^2

→ greater wave function dependence at large y (→ large x)

Nuclear corrections



Owens, Accardi WM
PRD ***87****, 094012 (2013)*

- flexible parametrization for $x \to 1$ behavior

$$d \;\to\; d + a\, x^b\, u$$

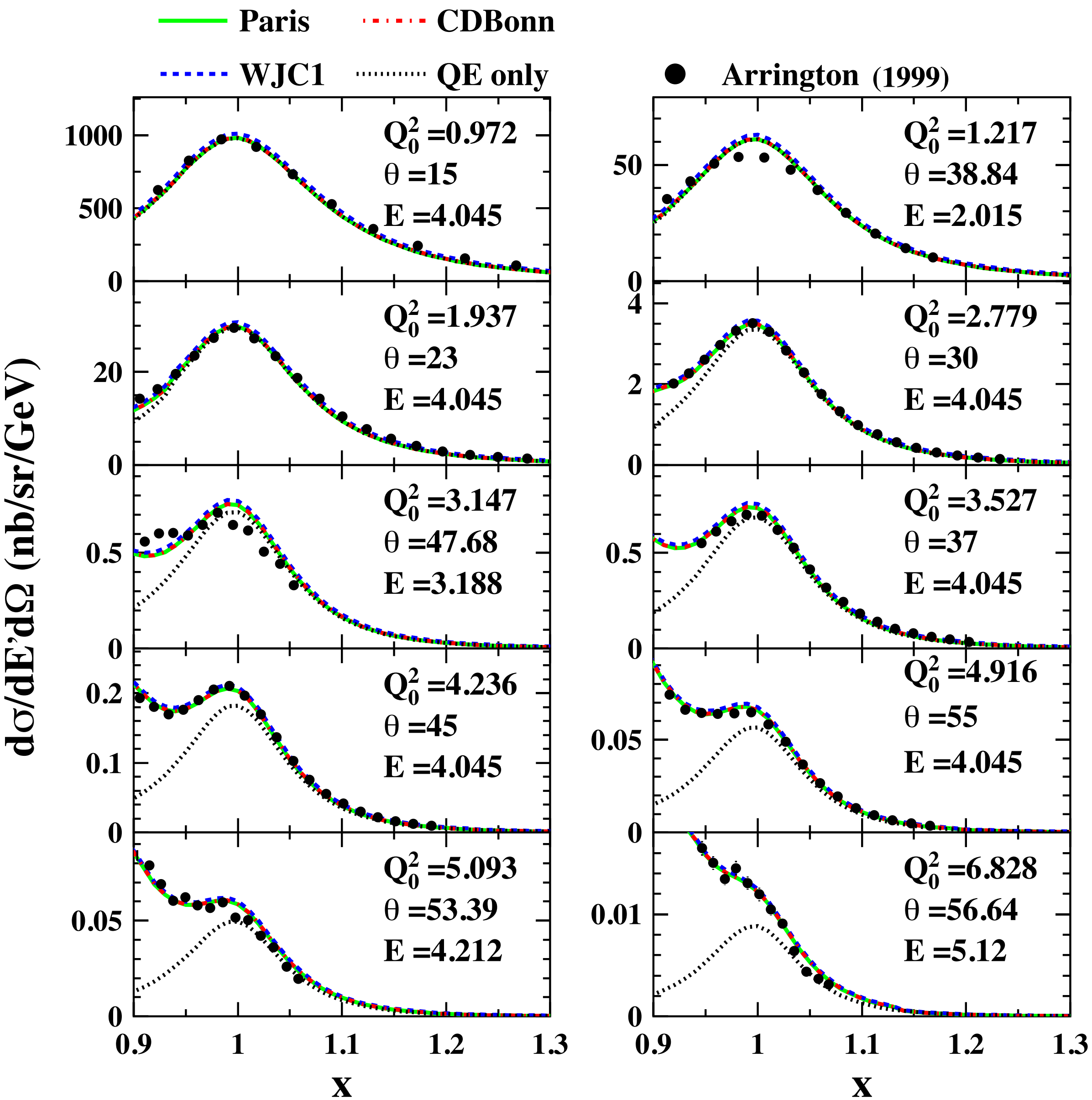
- allows finite, nonzero $x = 1$ limit

$$d/u \;\to\; 0.22 \pm 0.20\,(\mathrm{PDF}) \pm 0.10\,(\mathrm{nucl})$$

* CJ12min: WJC-1 + mild off-shell (0.3% nucleon swelling)
CJ12mid: AV18 + medium off-shell (1.2% swelling)
CJ12max: CD-Bonn + large off-shell (2.1% swelling)

Quasi-elastic *ed* scattering

- Smearing functions can be tested in quasi-elastic (QE) electron−deuteron scattering



$$\sigma_{(\mathrm{QE})} \sim f_{N/d}(y,\gamma) \times G_N(Q^2)$$

elastic eN form factors

Ethier, Doshi, Malace, WM
arXiv:1402.3910

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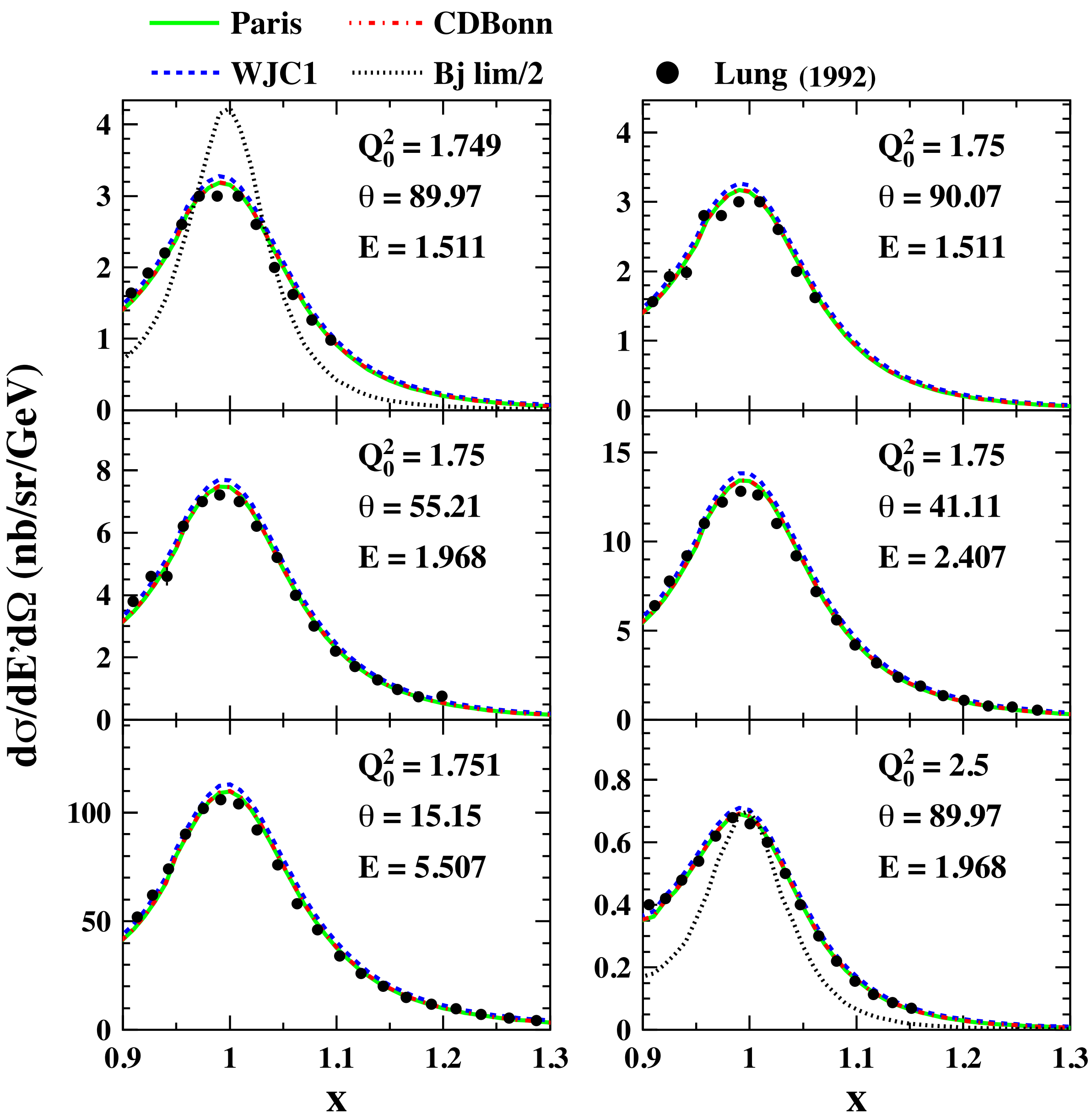

→ importance of correct Q^2 dependence in $f(y,\gamma)$

Ethier, Doshi, Malace, WM
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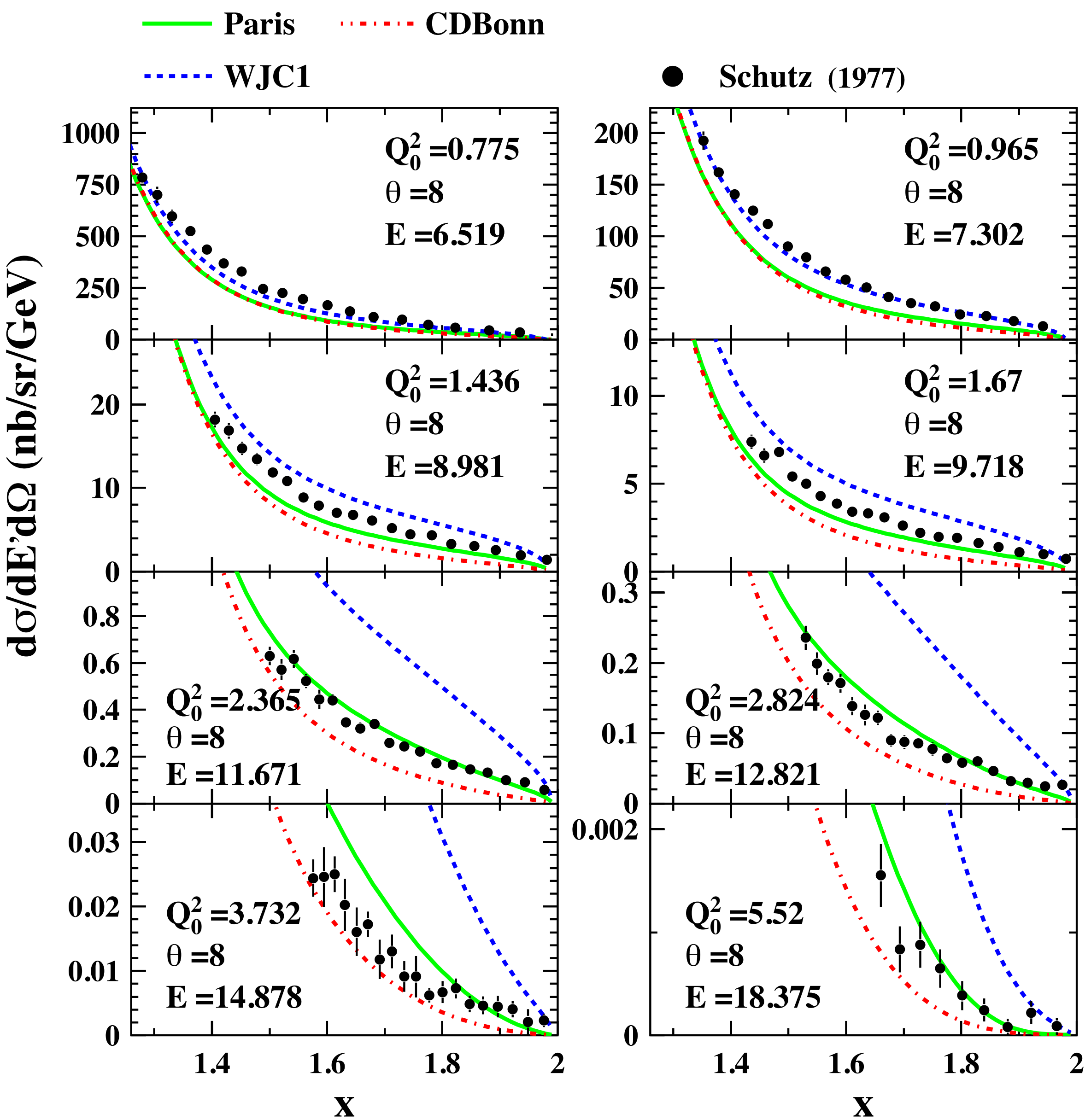

→ importance of correct Q^2 dependence in $f(y,\gamma)$

→ strong sensitivity to d wfn. at $x \gg 1$

Ethier, Doshi, Malace, WM
arXiv:1402.3910

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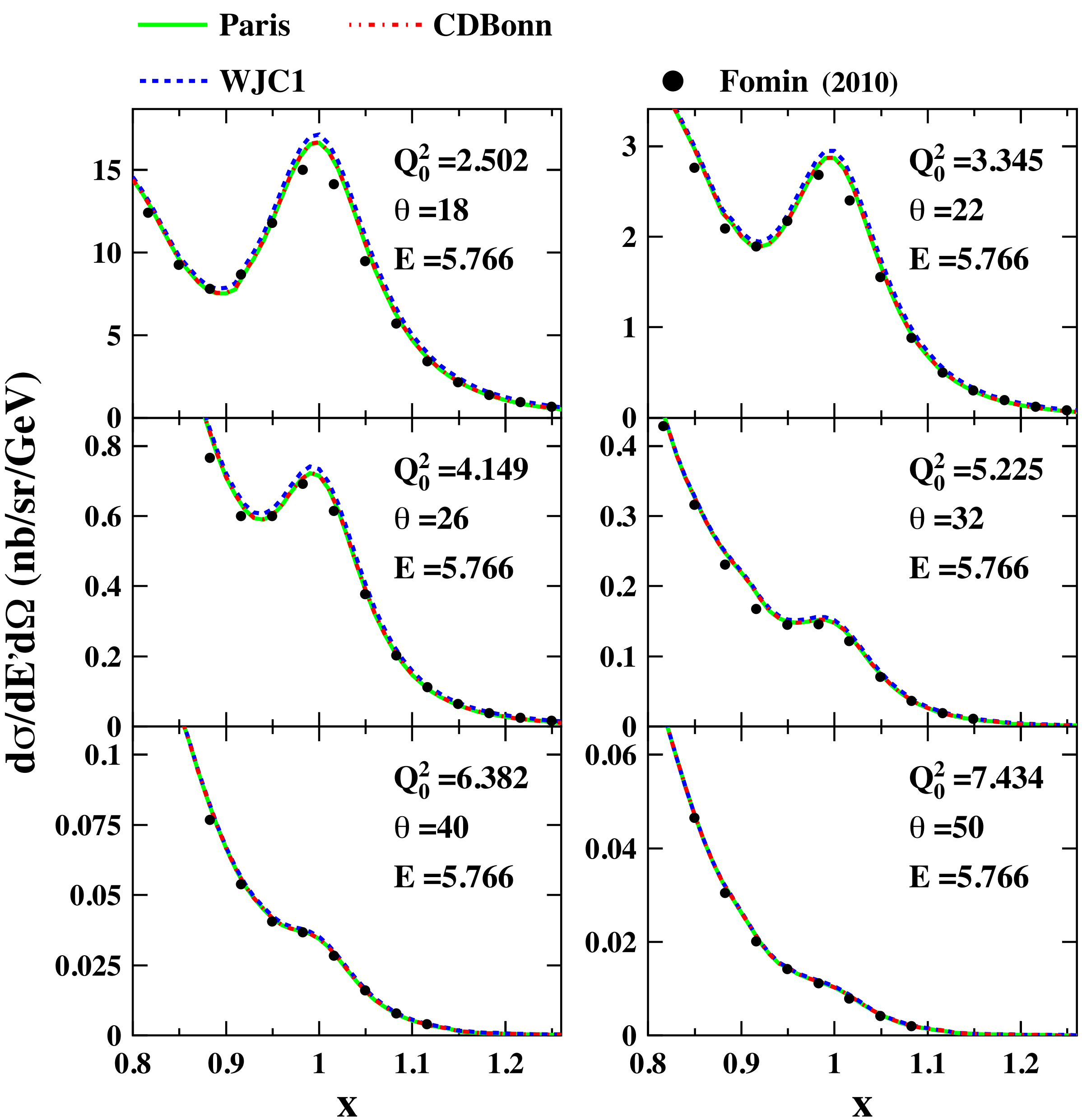


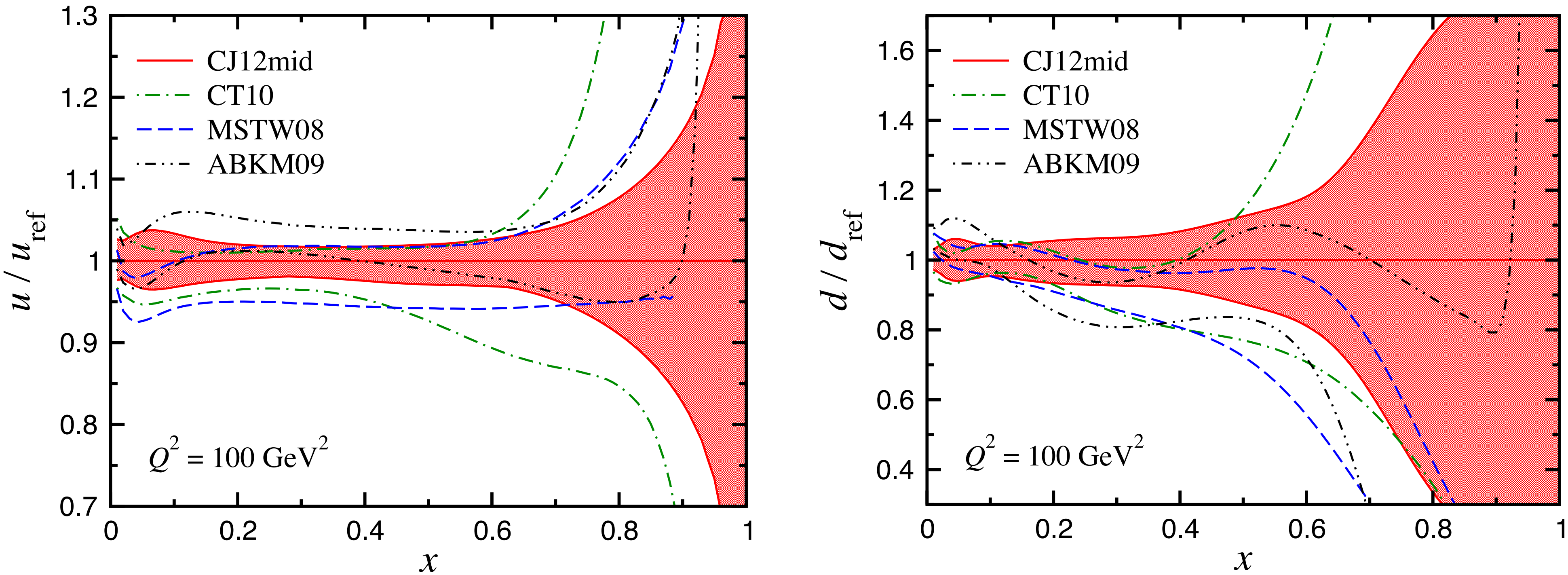
→ importance of correct Q^2 dependence in $f(y,\gamma)$

→ strong sensitivity to d wfn. at $x \gg 1$

→ excellent agreement with data near QE peak ($\sim 2{,}000$ data points)

Ethier, Doshi, Malace, WM
arXiv:1402.3910

Comparison with other PDFs fits

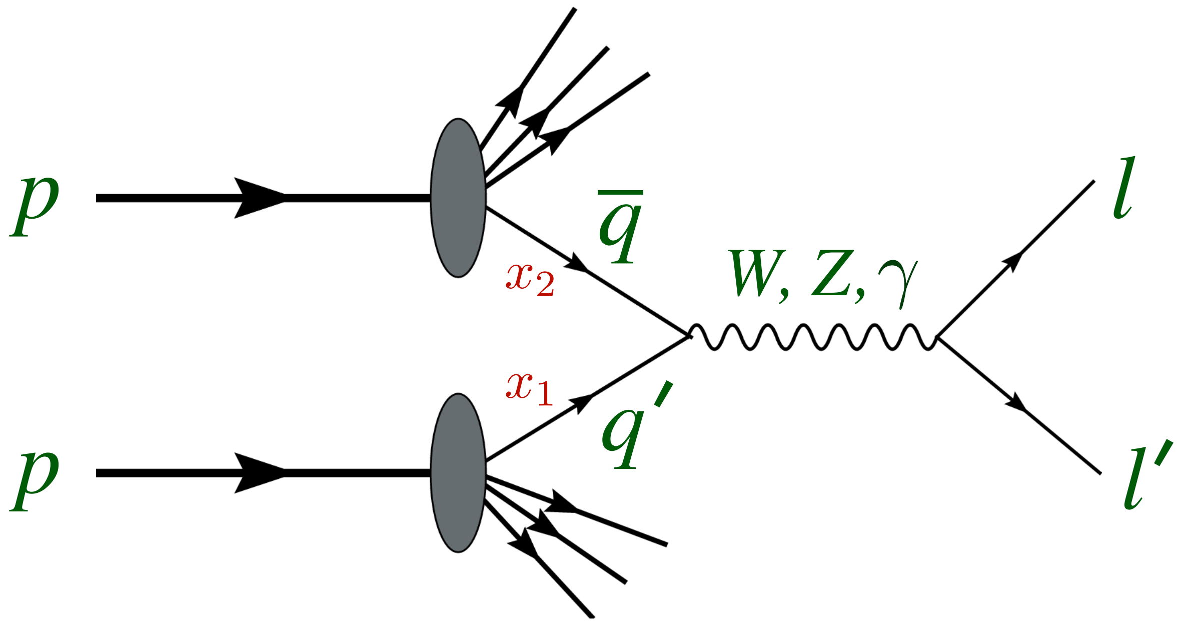


→ *increase* in PDF error from more realistic treatment of nuclear corrections

→ *reduction* of error from larger database

Implications for colliders

lepton pair production in pp collisions



Implications for colliders

- Large-x PDF uncertainties affect observables at large *rapidity* y, with

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) \quad \rightarrow \quad \boxed{x_{1,2} = \frac{M}{\sqrt{s}}\, e^{\pm y}}$$

$e.g.$ $W^{\pm}$ asymmetry

$$A_W(y) = \frac{\sigma_{W^+} - \sigma_{W^-}}{\sigma_{W^+} + \sigma_{W^-}}$$

$$\approx \frac{d(x_2)/u(x_2) - d(x_1)/u(x_1)}{d(x_2)/u(x_2) + d(x_1)/u(x_1)} \qquad [x_1 \gg x_2]$$

where

$$\sigma_{W^+} \equiv \frac{d\sigma}{dy}(pp \rightarrow W^+ X) = \frac{2\pi G_F}{3\sqrt{2}} x_1 x_2 \left(u(x_1)\bar{d}(x_2) + \cdots \right)$$

Implications for colliders

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$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) \rightarrow x_{1,2} = \frac{M}{\sqrt{s}}\,e^{\pm y}$$

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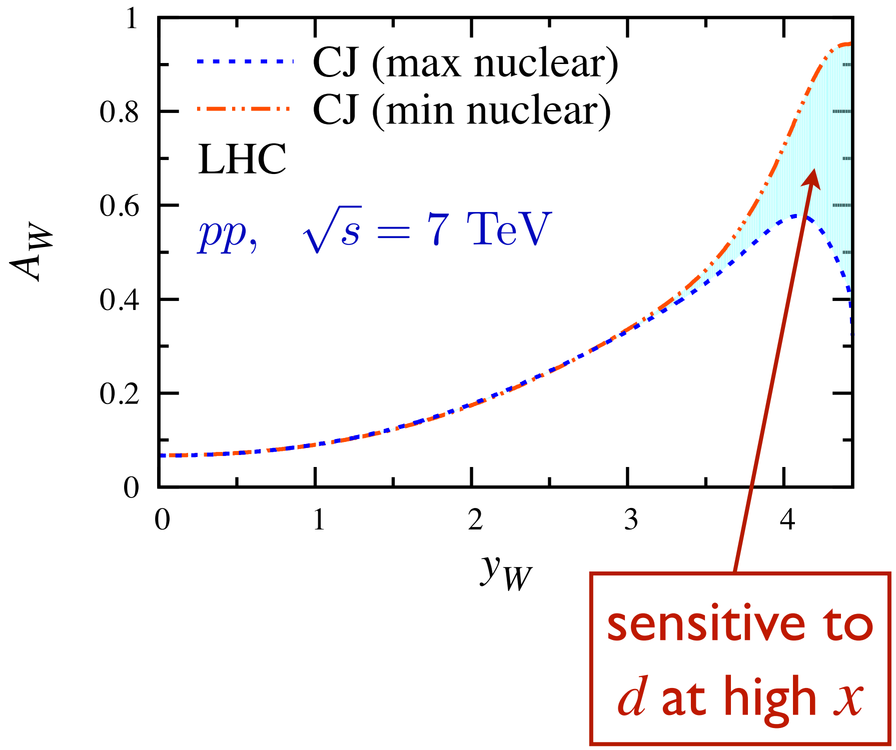
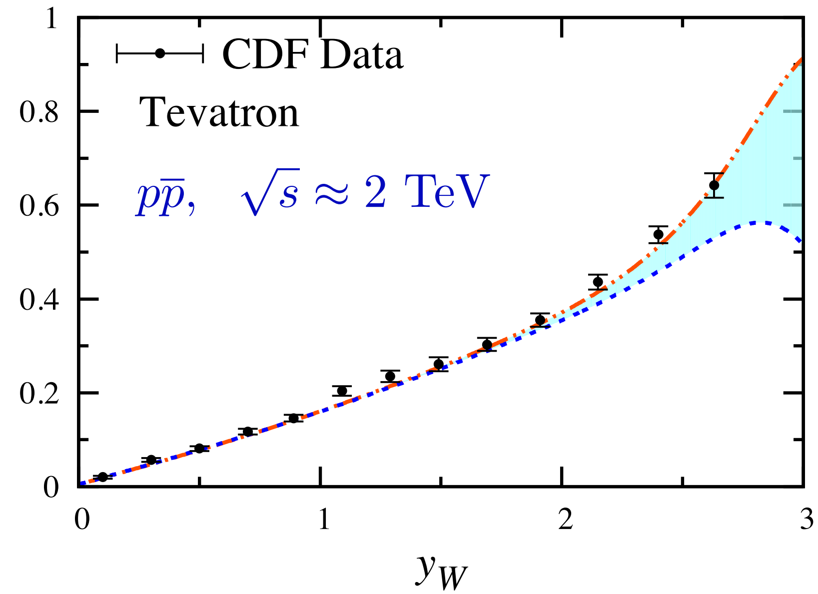


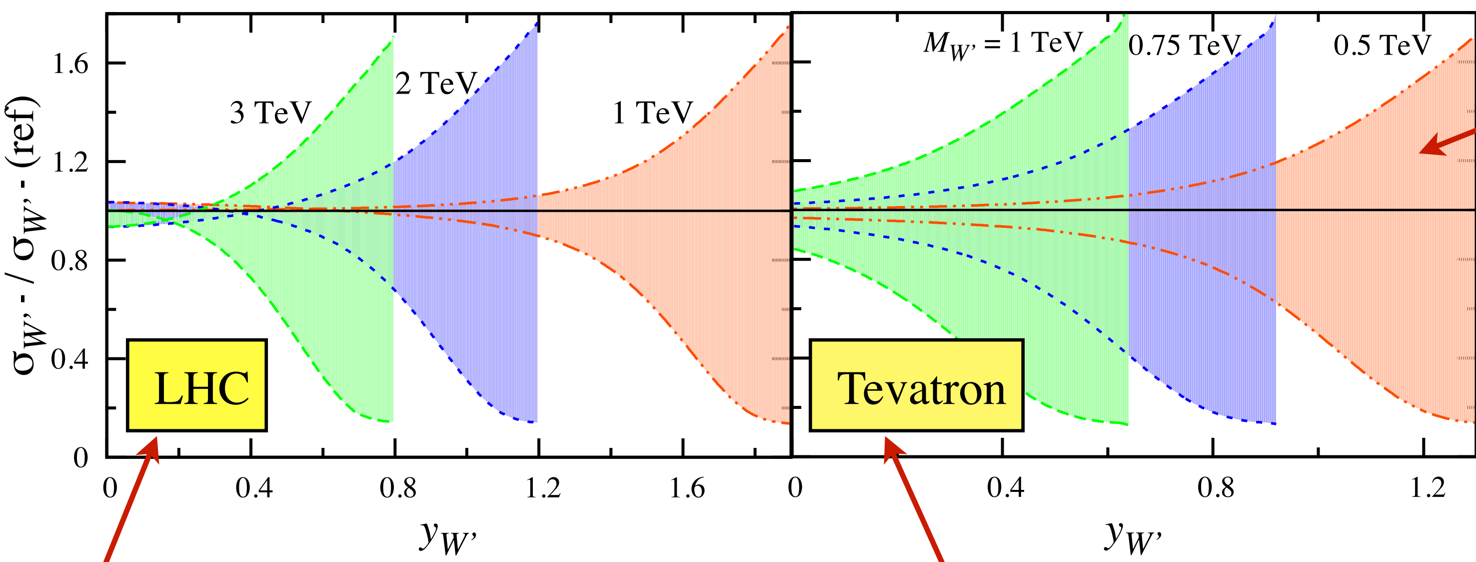


Brady, Accardi, WM, Owens
JHEP ***1206****, 019 (2012)*

Implications for colliders

- Uncertainty in d-quark feeds into larger uncertainty in *gluon* at high x (relevant for LHC physics)

heavy W'^- production



> 100% uncertainty at large y !

Brady et al. *JHEP* ***1206***, *019 (2012)*

dominated by $d * \bar{u}$

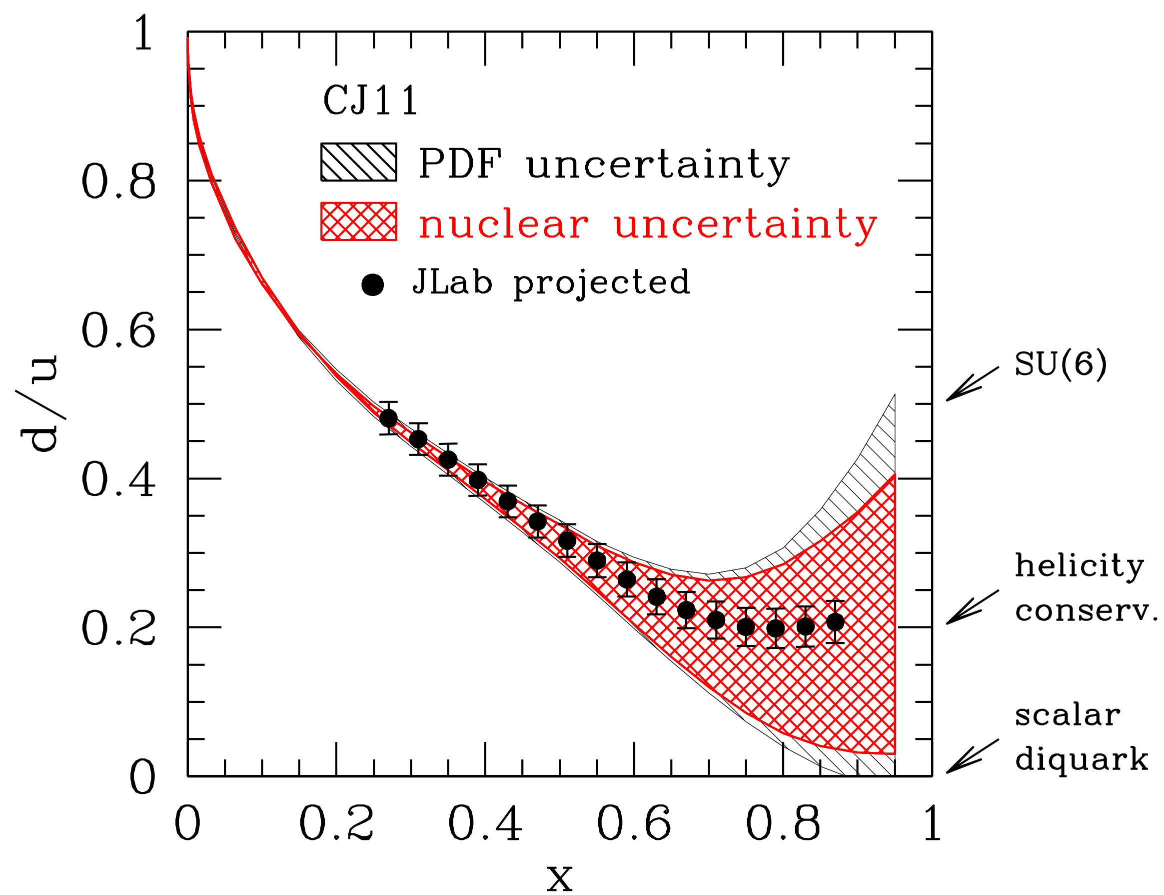
dominated by $d * u + u * d$

$\longrightarrow$ observation of new physics signals requires accurate determination of QCD backgrounds $\rightarrow$ depend on PDFs!

JLab 12 GeV plans

- Several planned experiments at JLab with 12 GeV will measure d/u to $x \sim 0.85$ with minimal nuclear corrections

  → SIDIS from D with slow backward proton ("BoNuS"); inclusive ^3He / ^3H ratio; and PVDIS from proton



*Accardi et al., PRD **84**, 014008 (2011)*

Spin-dependent PDFs

P. Jimenez-Delgado, A. Accardi, WM
H. Avakian, B. Sawatzky, ...

"JAM" PDFs: *arXiv:1310.3734, to appear PRD (2014)*
http://www.jlab.org/JAM

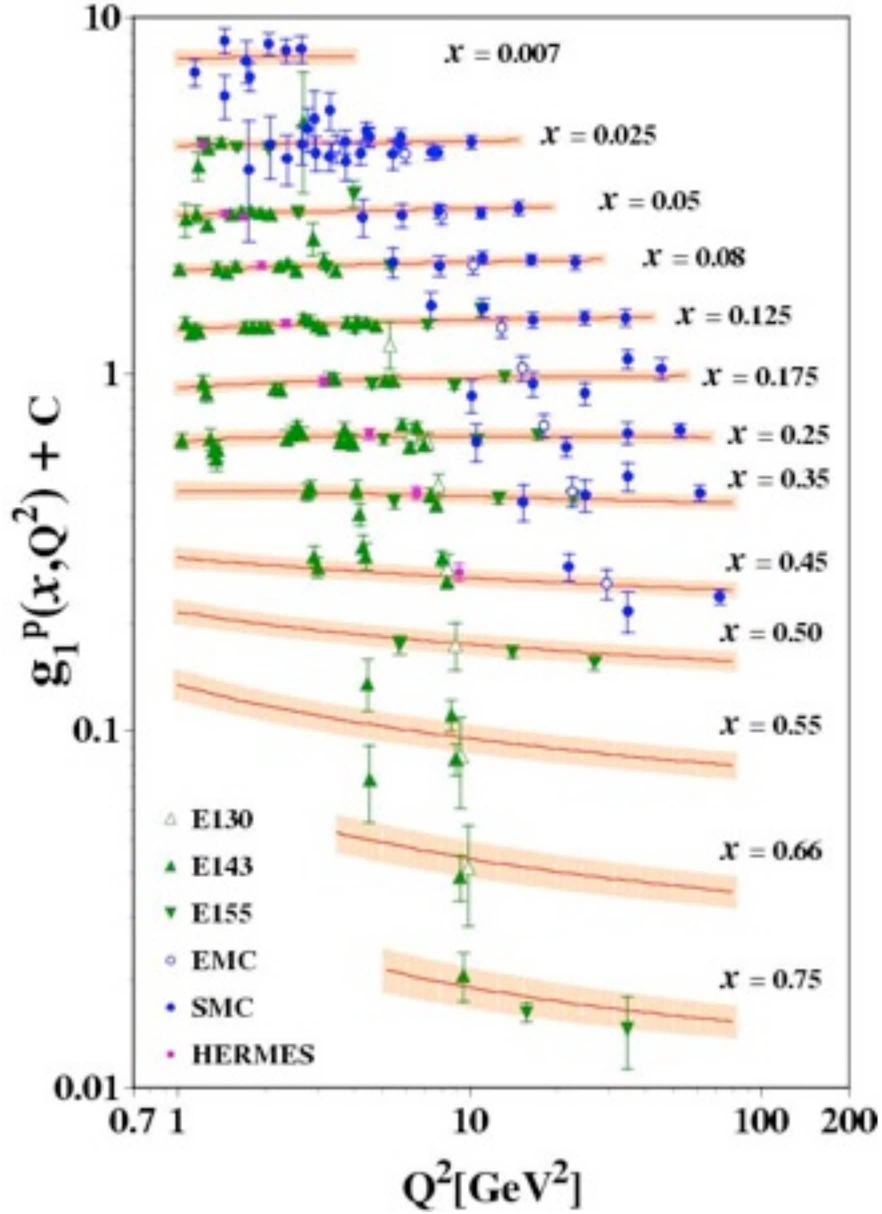
Nucleon spin structure

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

$\Delta\Sigma \sim 0.25$ (DIS)

$\Delta G \ll 1$ (DIS + pp)

$L_{q,g} = ?$ (GPDs)

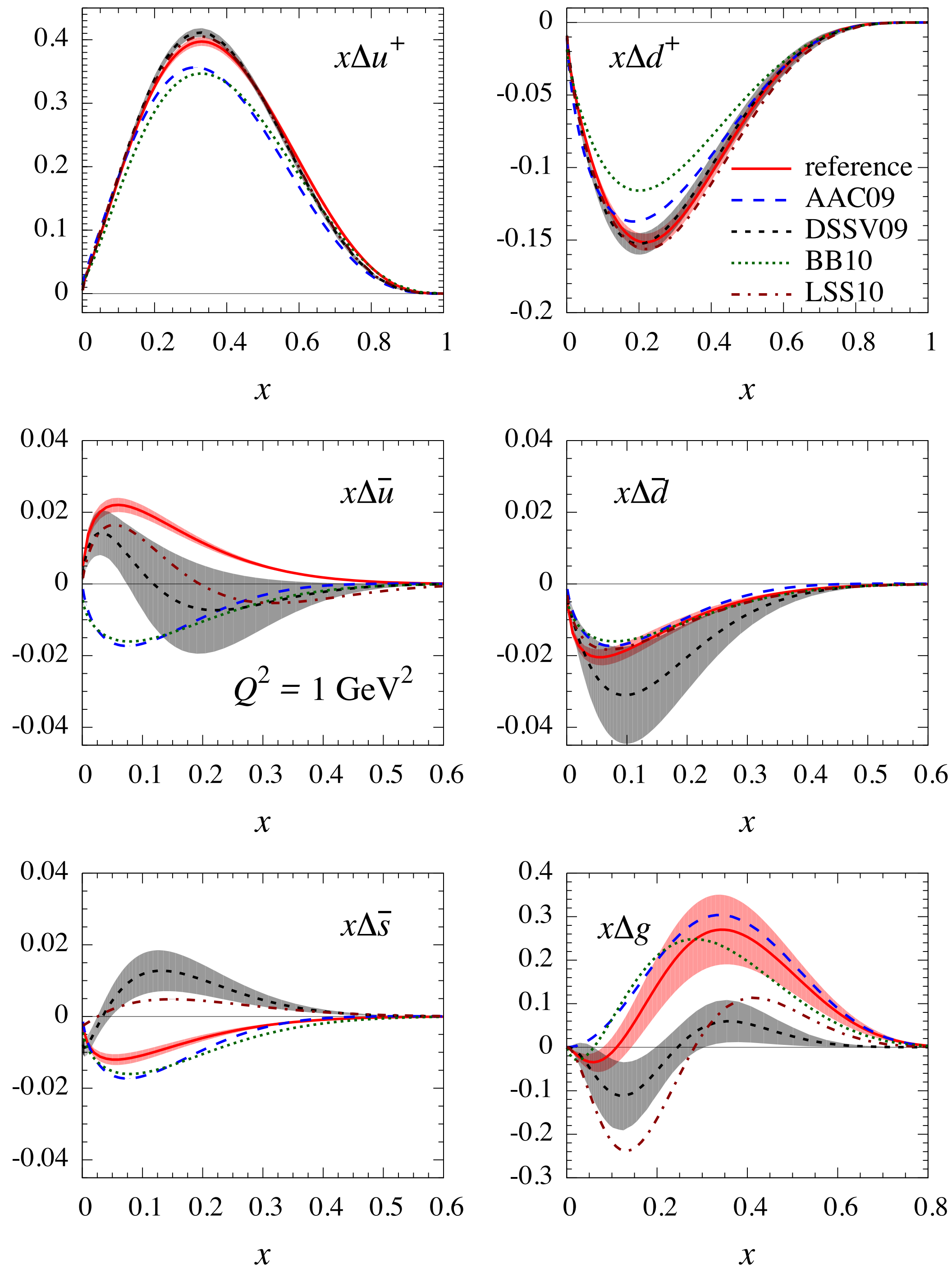


→ fewer data *cf*. unpolarised

Nucleon spin structure

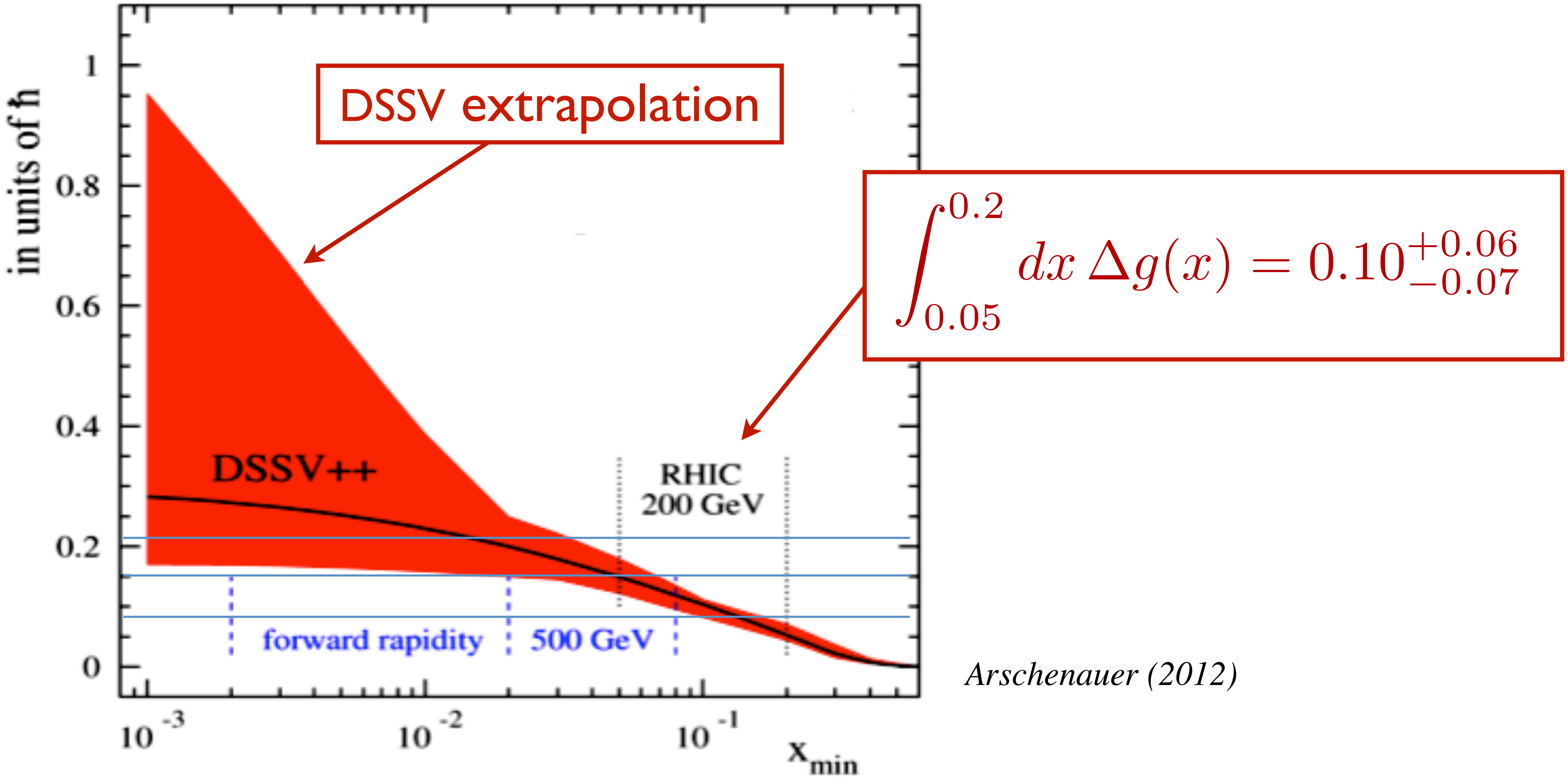
- Global PDF analyses performed by several groups
  - → focus on small-x region (sum rules)
- Data from many experiments at JLab recently collected at low Q^2 and W
  - → need for synthesis of results (current & future) from Halls A, B & C, including finite-Q^2 & nuclear corrections
  - → JAM global analysis

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



Nucleon spin structure

- Recent RHIC *pp* data claimed to imply large gluon polarisation



Arschenauer (2012)

→ important to confirm claim through independent global analysis

JAM database

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

  $$Q^2 > 1\ \mathrm{GeV}^2, \quad W^2 > 3.5\ \mathrm{GeV}^2$$

- Fit experimental asymmetries (longitudinal & transverse) rather than derived g_1 and g_2 structure functions

  $$g_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2\, \Delta q(x, Q^2)$$

experiment	reference	observable	target	$N_{\rm data}$	$\chi^2(\mathrm{LT})/N_{\rm dat}$	$\chi^2(\mathrm{JAM})/N_{\rm dat}$
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	—	—

several high-statistics experiments still being analysed →

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- Fit experimental asymmetries (longitudinal & transverse) rather than derived g_1 and g_2 structure functions

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

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

$$A_1 = \frac{(g_1 - \gamma^2 g_2)}{F_1}, \qquad A_2 = \gamma\,\frac{(g_1 + g_2)}{F_1}$$

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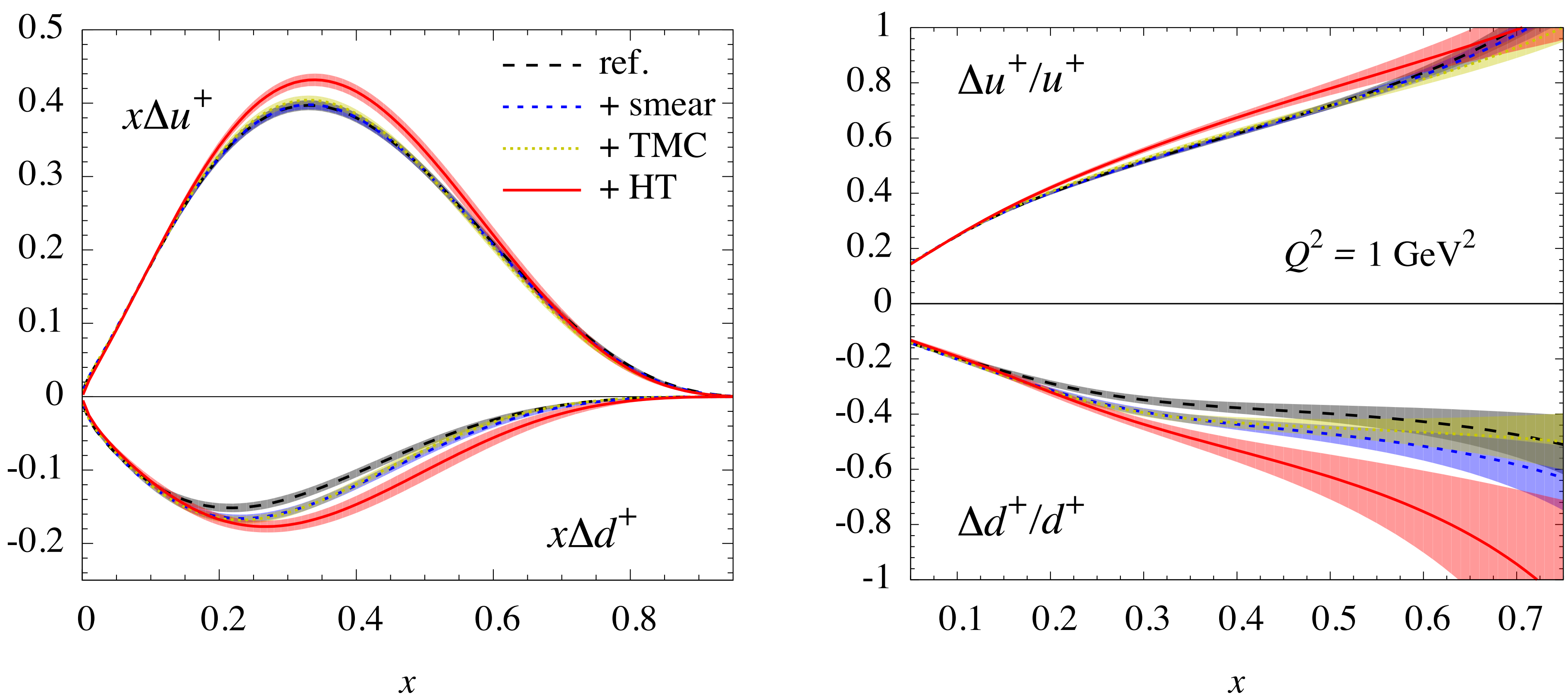
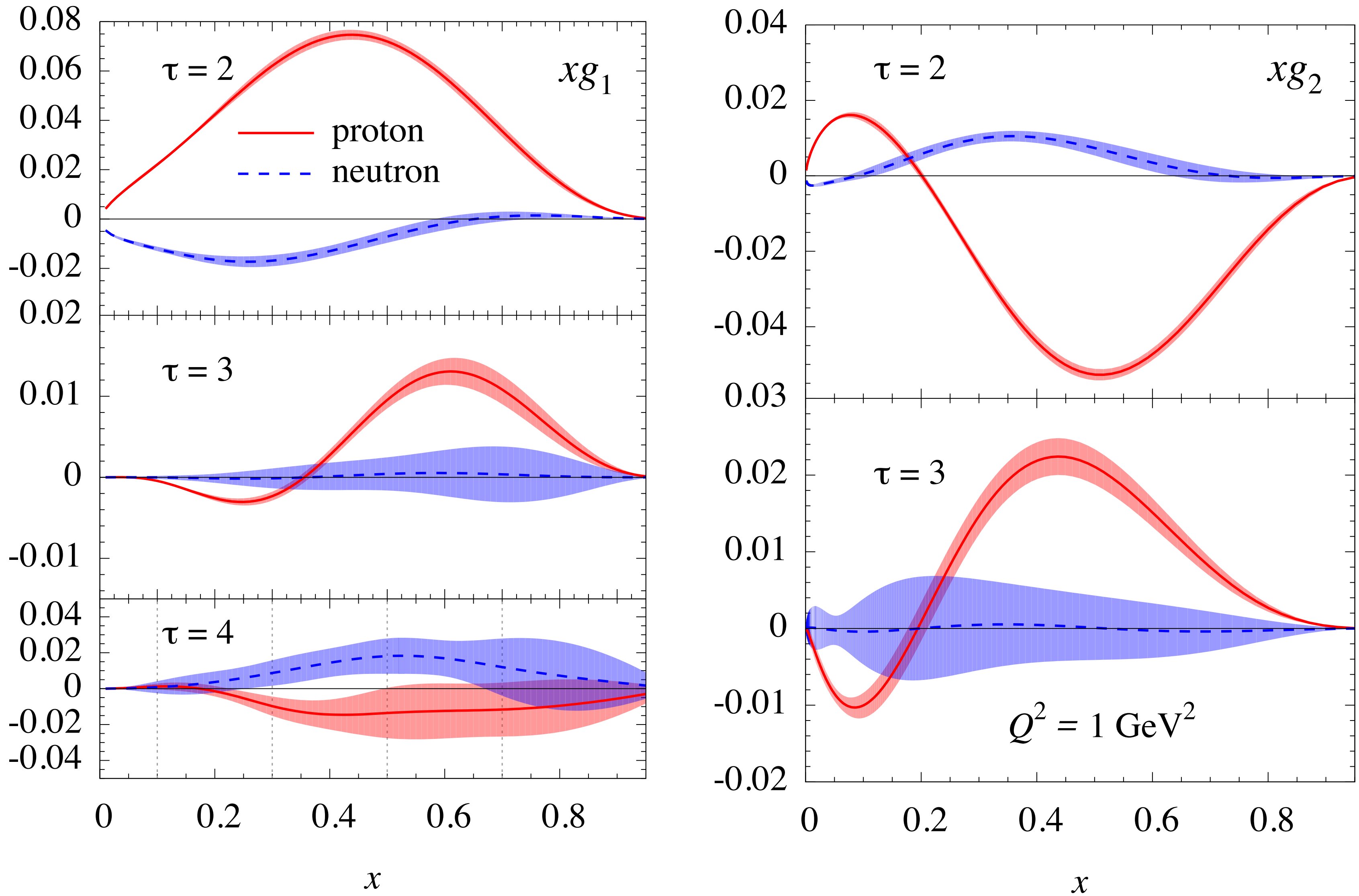
JAM PDFs



→ significantly larger Δd at $x \gtrsim 0.3$

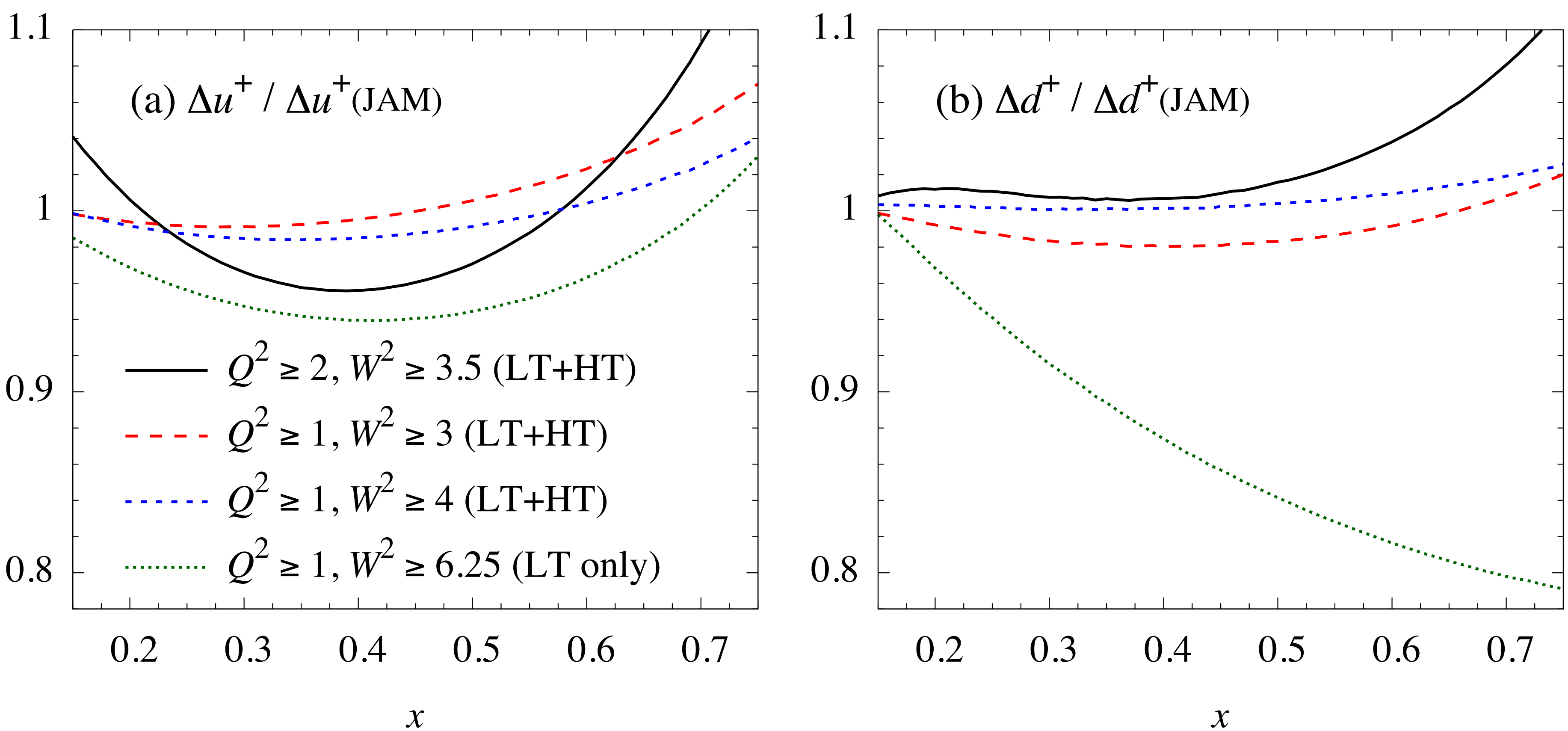
→ greatest effect on polarised PDFs from higher twist corrections

JAM PDFs



→ important $\tau = 3$ contributions to proton g_1, g_2 and $\tau = 4$ contributions to neutron g_1

JAM PDFs



→ PDFs relatively stable w.r.t. cuts in Q^2 and W
(50% of all data points in $Q^2 < 2$ GeV^2 region)

→ significant reduction in Δd with strong W cut
(to avoid HT corrections) – *cf.* "NNPDF" analysis

PDFs at large x

- Ratio of polarised to unpolarised PDFs even more sensitive to nonperturbative quark-gluon dynamics in nucleon

  - $\Delta u/u \to 2/3$, $\Delta d/d \to -1/3$ — SU(6) symmetry

  - $\Delta u/u \to 1$, $\Delta d/d \to -1/3$ — $S = 0$ qq dominance

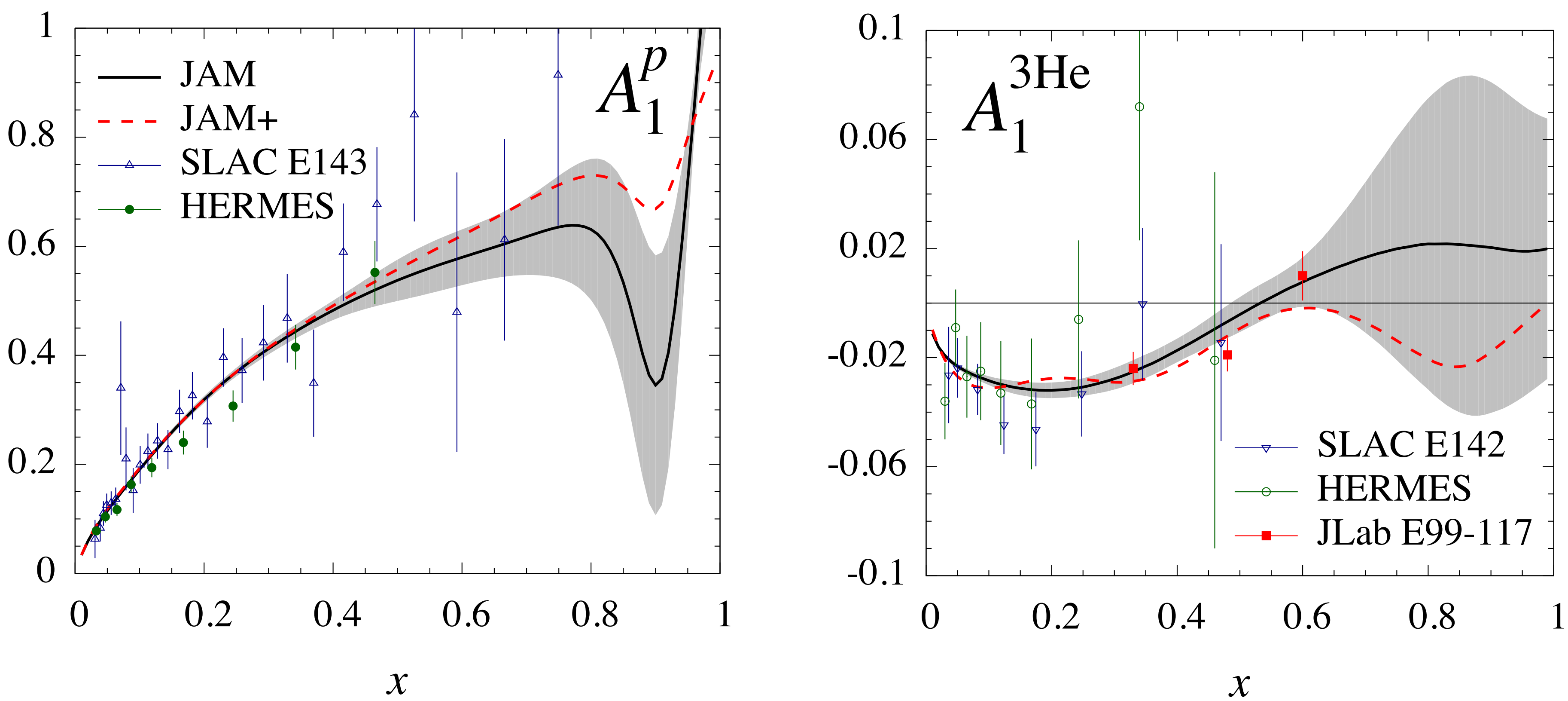
  - $\Delta u/u \to 1$, $\Delta d/d \to 1$ — $S_z = 0$ qq dominance (pQCD) *or* local duality

PDFs at large x

- Current data cannot discriminate between different $x \to 1$ behaviours

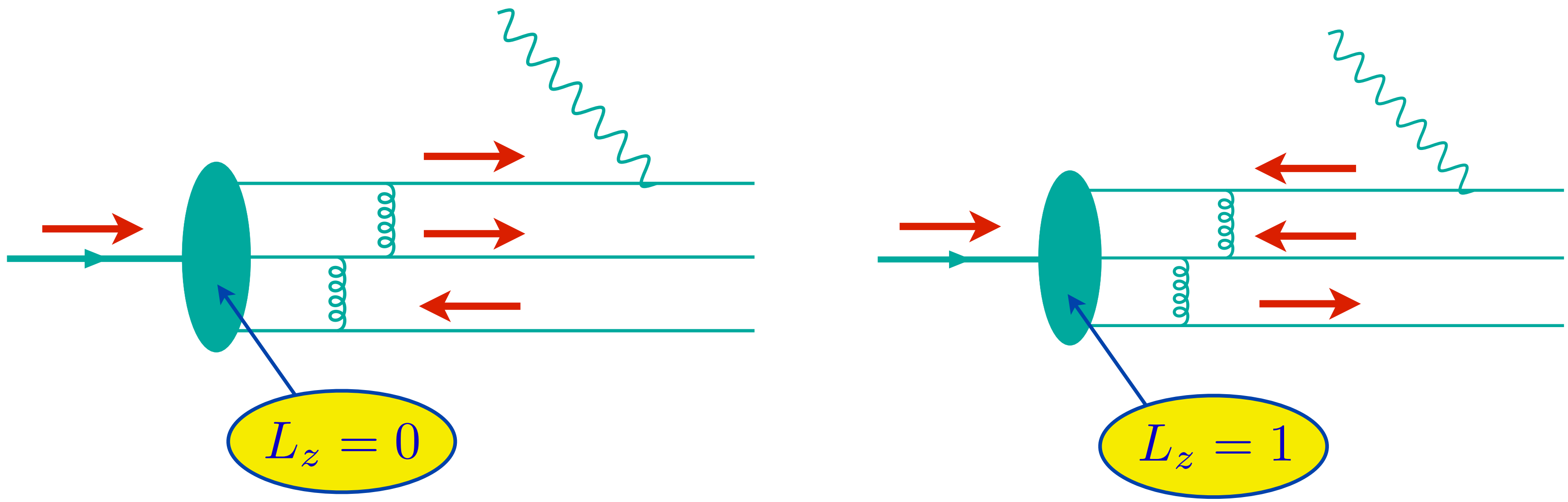
- Impose $x \to 1$ pQCD constraint on PDFs "by hand"

  ⟶ "JAM+" fit



Orbital angular momentum

- Earlier analysis suggested need for additional nonzero OAM ($L_z = 1$) component in nucleon wave function



→ leading $(1-x)^3$ behaviour from $L_z = 0$ component

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

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

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

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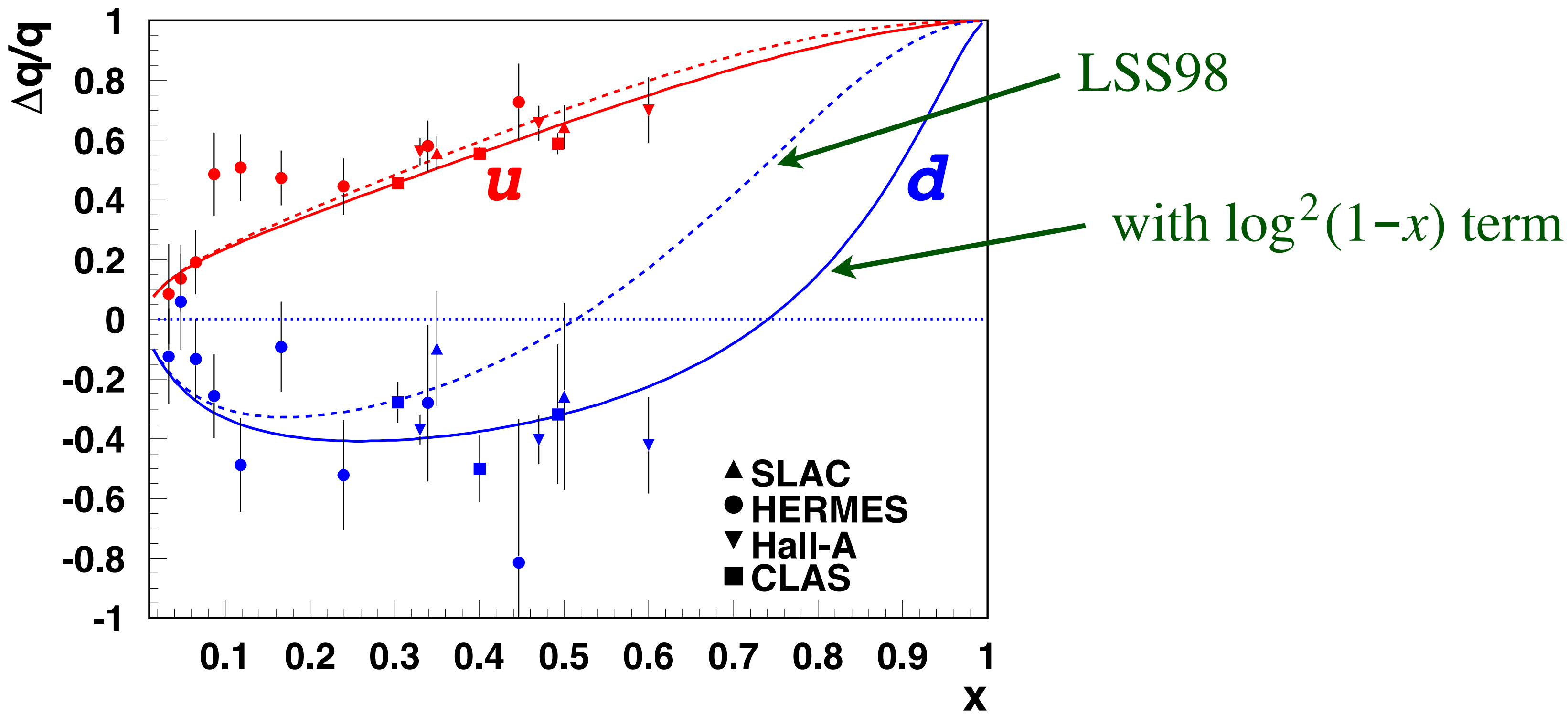

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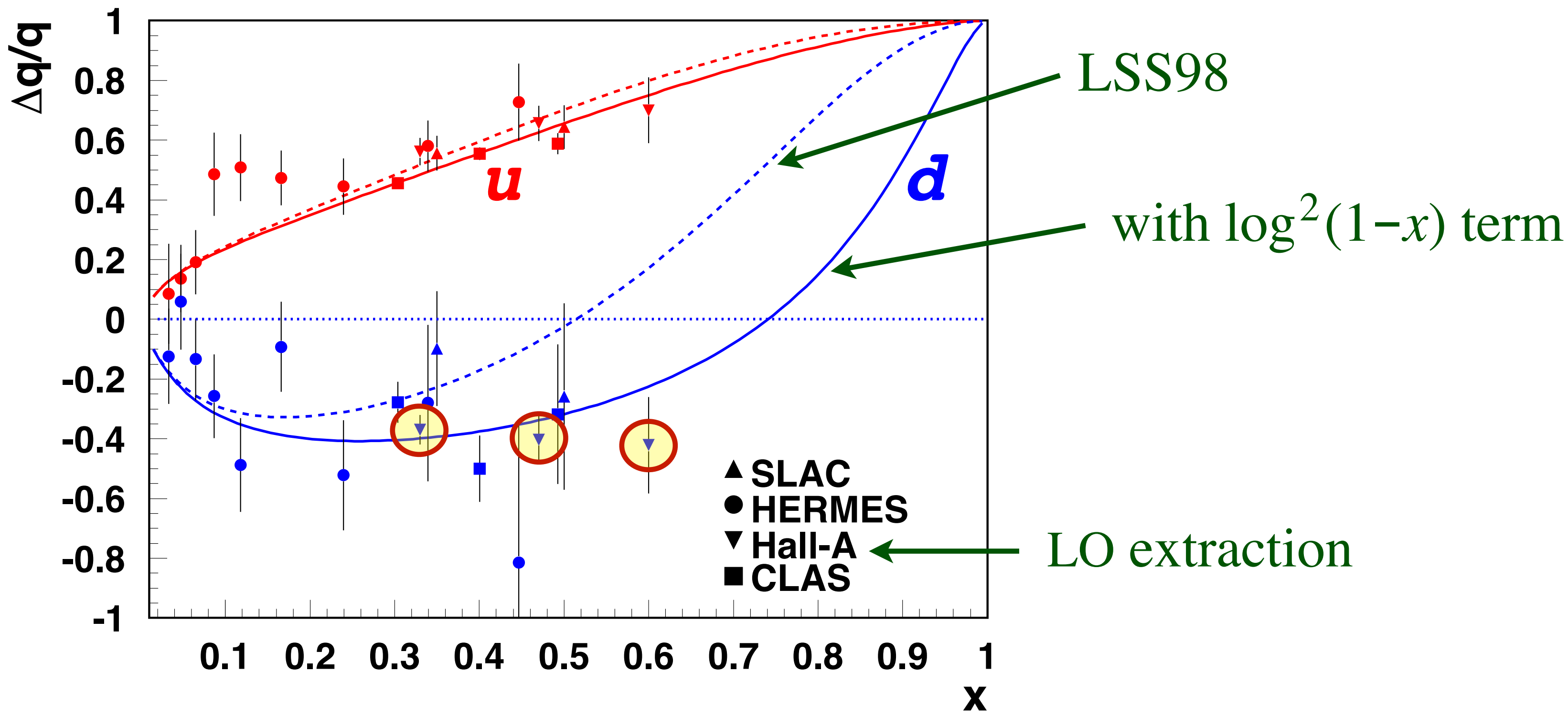
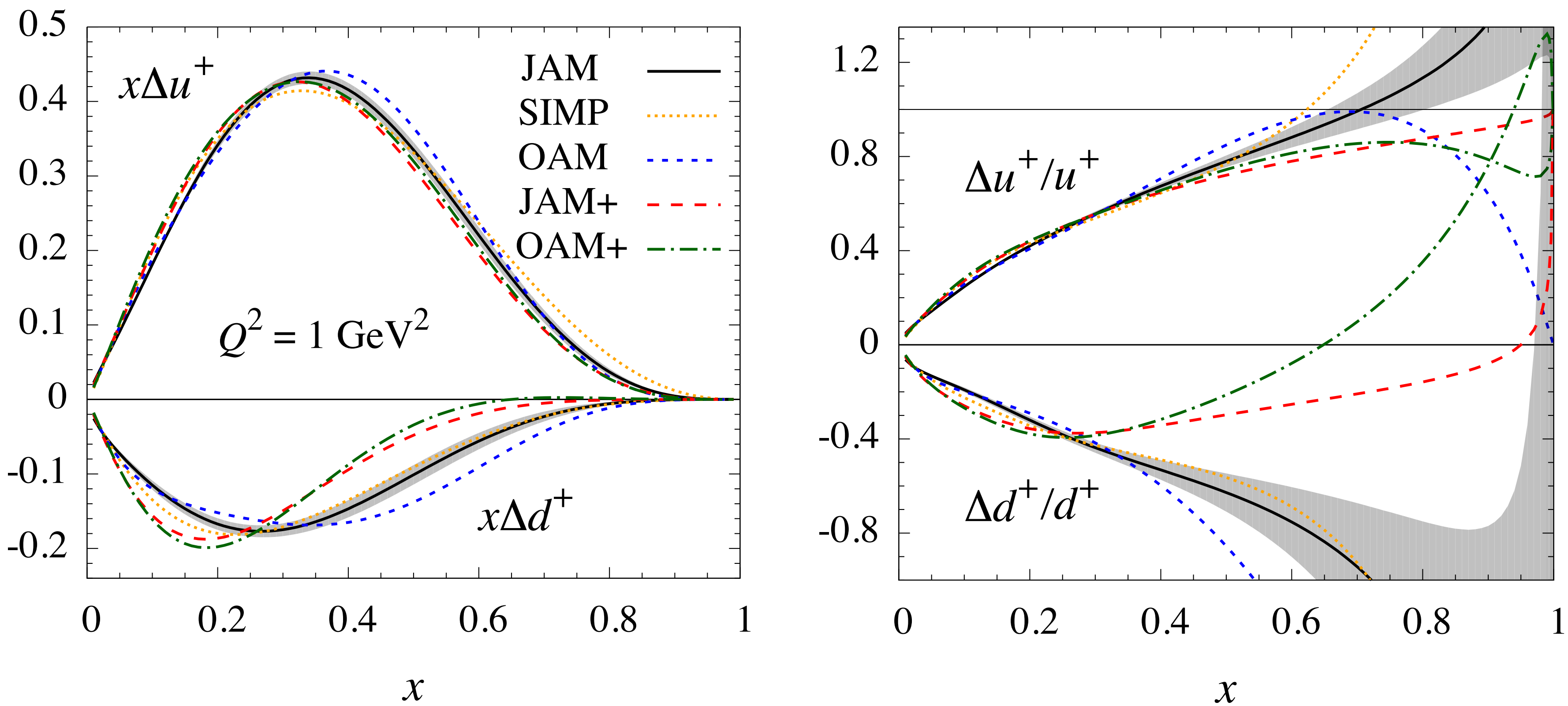


→ $L_z = 1$ term needed to delay Δd turnover until larger x

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

Orbital angular momentum

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



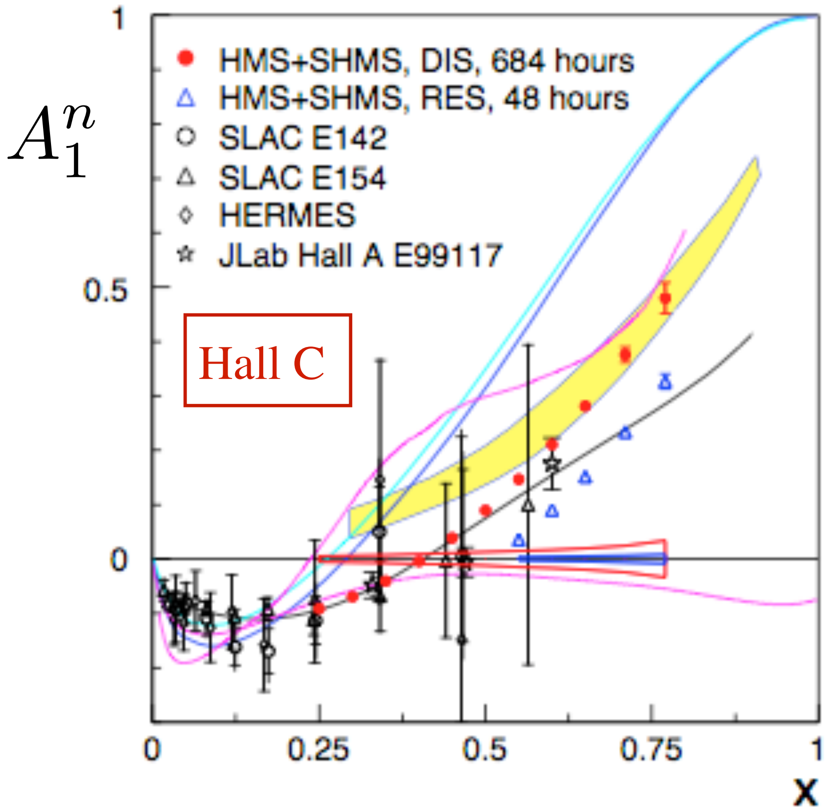
→ "OAM" and "OAM+" fits use

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

→ can also accommodate data, with similar overall χ^2

JLab 12 GeV plans

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



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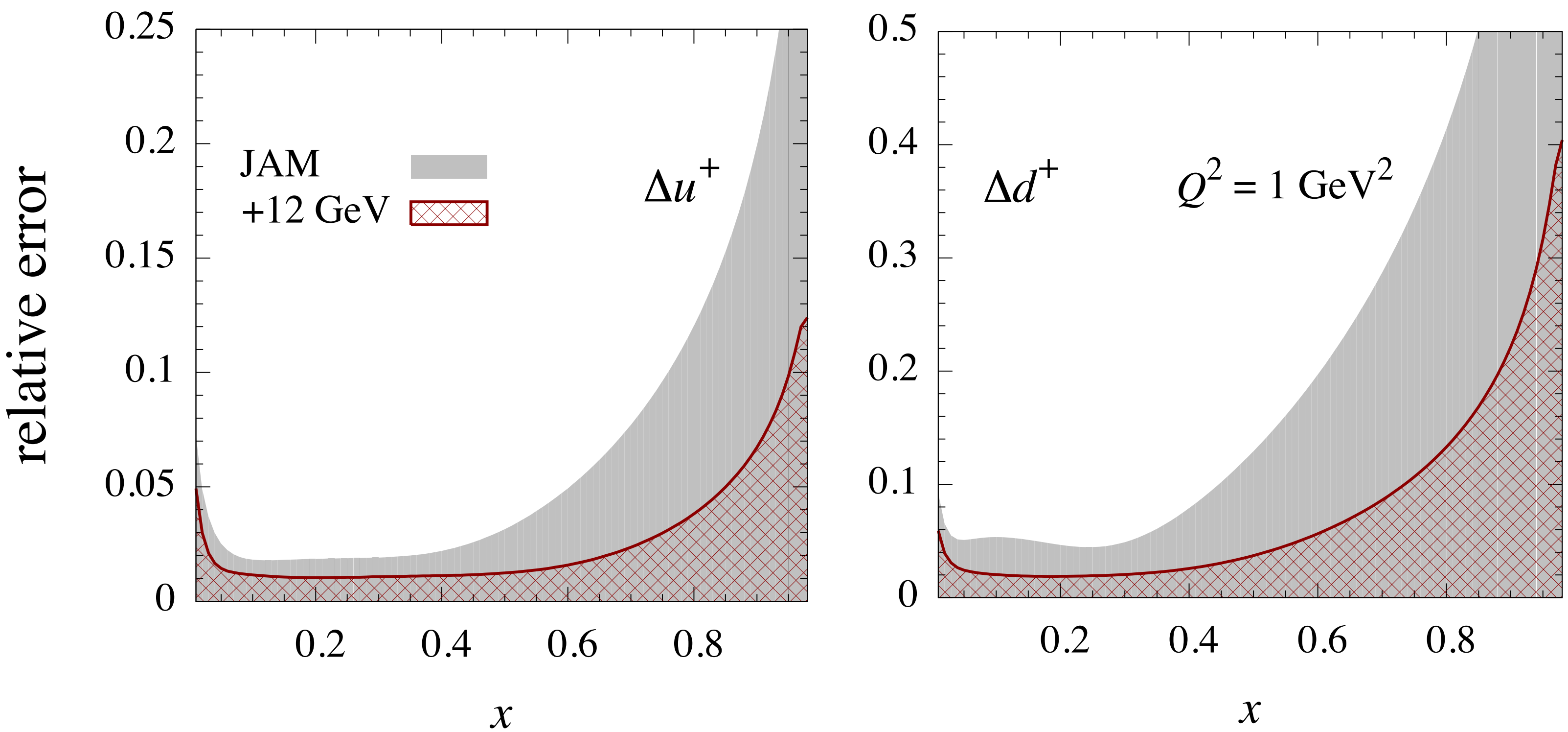

$\longrightarrow$ will significantly reduce PDF uncertainties at large x

Outlook

- Ongoing "CJ14" analysis includes new cross section data from JLab & collider experiments
  - → allow for different HTs for F_2, F_L & isospin dependence
  - → incorporate LHC ($W, Z,$ jet production), PVDIS data
  - → next release will include parametrisations of electroweak structure functions (down to low Q^2) in addition to PDFs

- Next phase of JAM analysis will study polarisation of sea quarks and gluons
  - → semi-inclusive DIS for flavour/antiflavour separation
  - → polarised pp cross sections (inclusive jet & pion production) sensitive to Δg

The End