High Energy Nuclear Physics with Spectator Tagging
Old Dominion University
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Tagged Structure Functions in Global PDF Analysis

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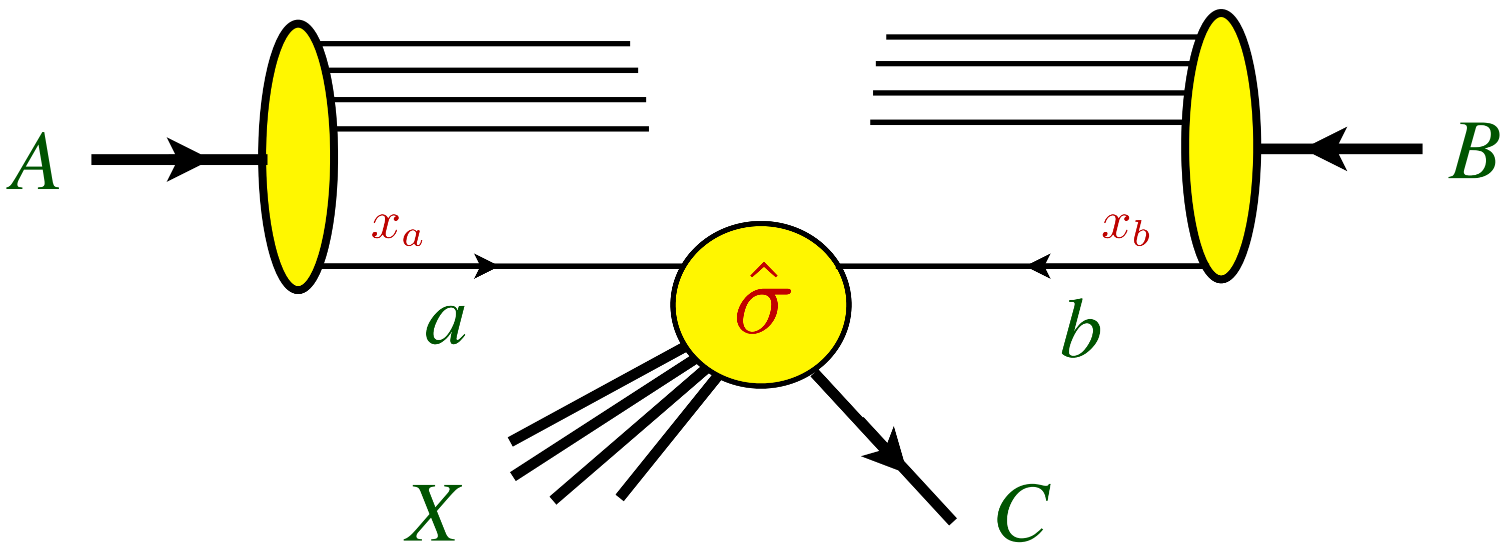
CTEQ-JLab (CJ) collaboration: http://www.jlab.org/CJ
(with A. Accardi, E. Christy, C. Keppel, P. Monaghan, J. Owens, N. Sato)

Parton distributions in nucleons

- Inclusive particle production $A\,B \to C\,X$



$$\sigma_{AB\to CX}(p_A,p_B) = \sum_{a,b} \int dx_a\, dx_b\, f_{a/A}(x_a,\mu)\, f_{b/B}(x_b,\mu)$$
$$\times \sum_n \alpha_s^n(\mu)\, \hat{\sigma}^{(n)}_{ab\to CX}\,(x_a p_A, x_b p_B, Q/\mu)$$

→ universal functions $f_{a/A}$ characterize internal structure of bound state A

Parton distributions in nucleons

- PDFs extracted in global QCD analyses of data from deep-inelastic l-h scattering; lepton-pair, weak boson & jet production in h-h scattering, ...

	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

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

(more if include $A > 2$ nuclear data)

Parton distributions in nucleons

- PDFs extracted in global QCD analyses of data from deep-inelastic l-h scattering; lepton-pair, weak boson & jet production in h-h scattering, ...

- In modern fits, PDFs typically parametrized as

$$xf(x,\mu) = Nx^{\alpha}(1-x)^{\beta}\, P(x)$$

with polynomial $e.g.\ P(x) = 1 + \epsilon\sqrt{x} + \eta\, x$

- Needed to understand basic structure of QCD bound states – and for backgrounds in searches for physics beyond the Standard Model at high-energy colliders

$\longrightarrow$ Q^2 evolution feeds low x, high Q^2 from high x, low Q^2

Parton distributions in nucleons

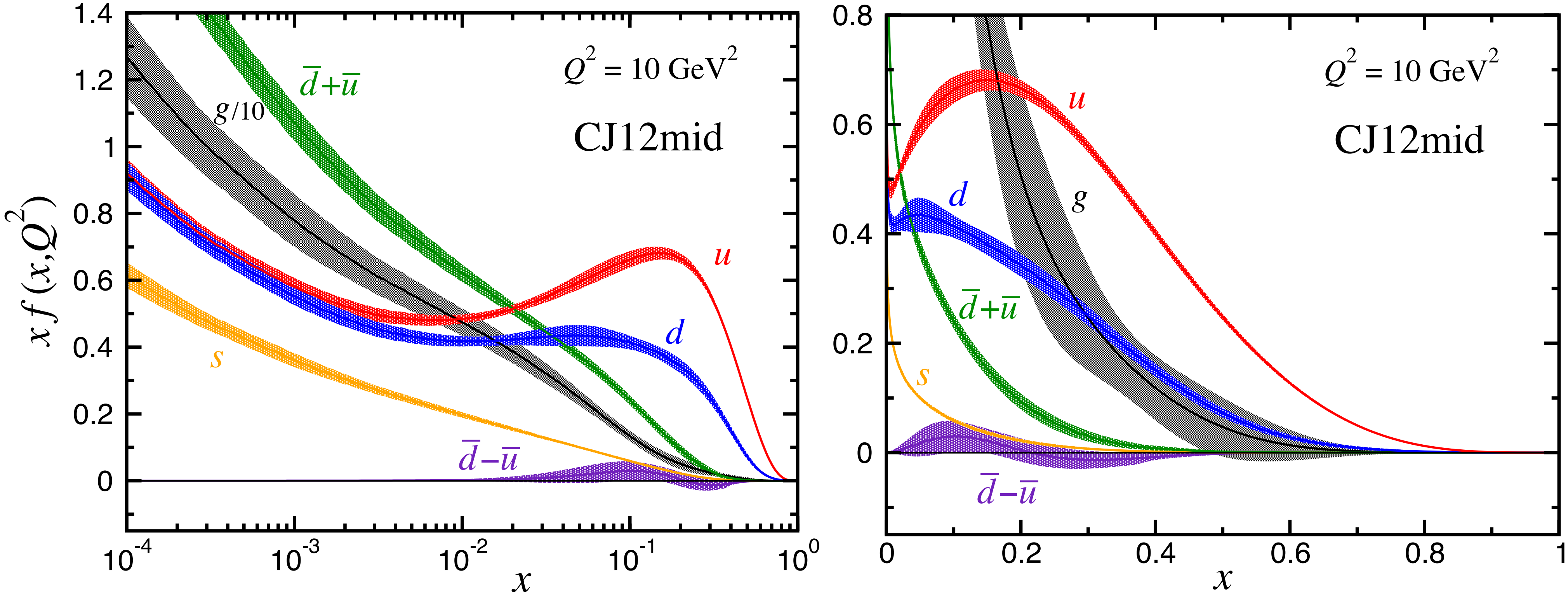
Several groups dedicated to global PDF analysis

- CTEQ (Coordinate Theoretical-Experimental Project on QCD)
  - CT (CTEQ-Tung et al.) — LHC focus
  - CJ (CTEQ-JLab) — includes high x, low Q^2
  - nCTEQ — nuclear PDFs
- MSTW (Martin-Stirling-Thorne-Watt) — LHC focus, strong data cuts
- ABM (Alekhin-Bluemlein-Moch) — LHC focus, some lower Q^2
- HERAPDF — only H1 & ZEUS data
- JR (Jimenez-Delgado–Reya) — dynamically generated from low Q^2
- NNPDF — "neural networks", strong data cuts

⟶ most use NLO, some use NNLO (partially known)

Parton distributions in nucleons

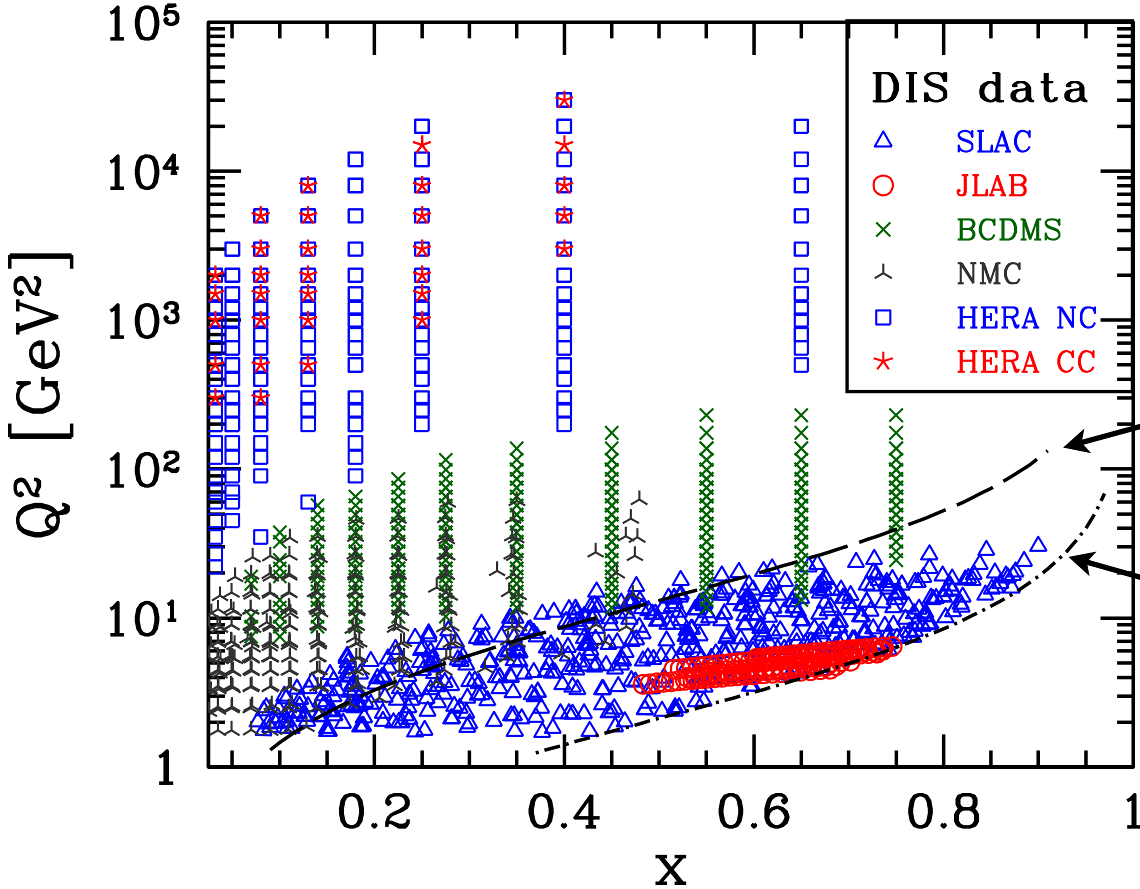
- Example of recent PDFs, from CJ12 analysis



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

CTEQ–JLab PDFs

- High-x region requires use of data at lower W & Q^2



$$W^2 = M^2 + Q^2 \frac{(1-x)}{x}$$

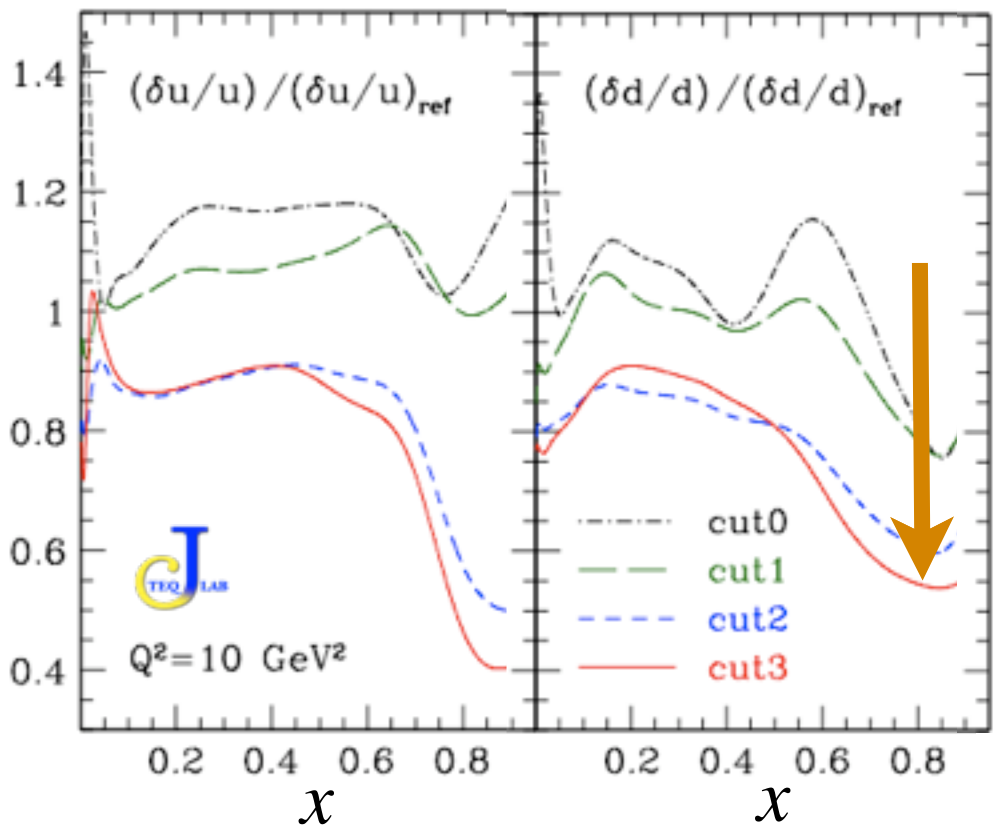
strong cut:
$Q > 2$ GeV, $W > 3.5$ GeV

weak cut:
$Q > 1.3$ GeV , $W > 1.73$ GeV

→ factor 2 increase in # of DIS data points when relax strong cut (excludes most SLAC, all JLab data) → weak cut

CTEQ–JLab PDFs

- High-x region requires use of data at lower W & Q^2



$$W^2 = M^2 + Q^2 \frac{(1-x)}{x}$$

cut0: strong cut

cut3: weak cut

→ significant error reduction when cuts extended to low-W region

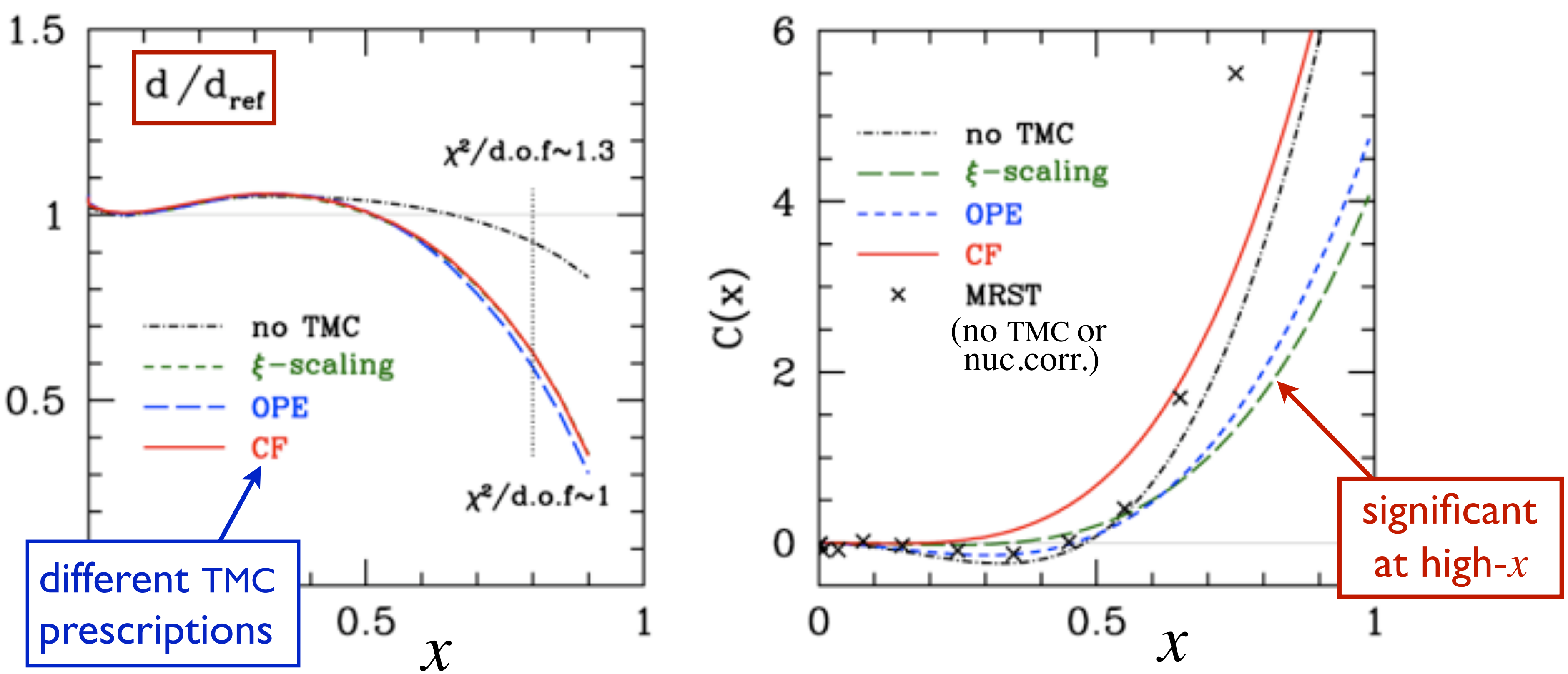
CTEQ–JLab PDFs

- Low-Q^2 data requires higher twist & target mass corrections

→ higher twists usually parametrized phenomenologically

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

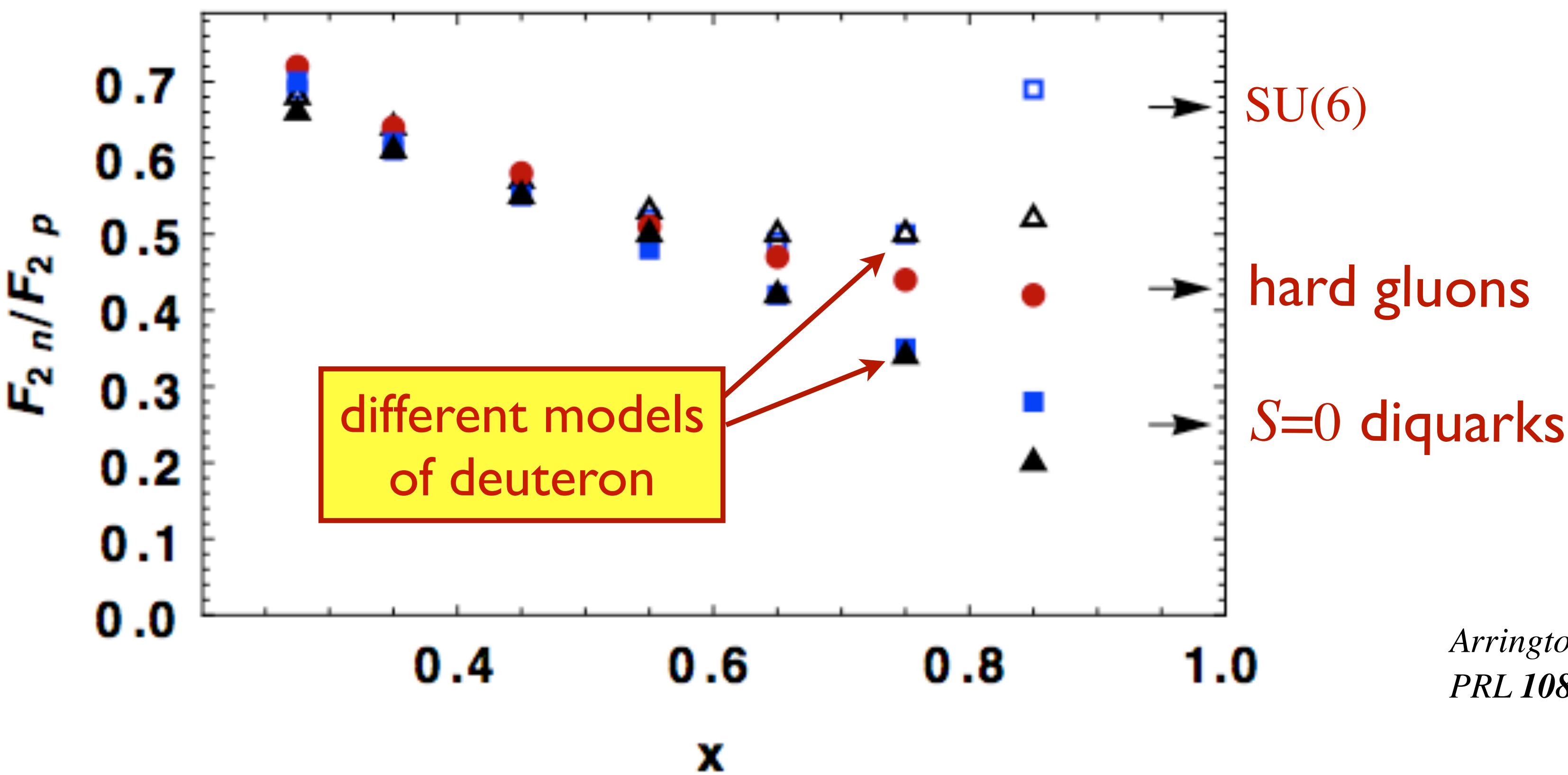
$C(x)$ polynomial



CTEQ–JLab PDFs

- u-quark PDF well constrained by proton data; d-quark PDF requires neutron data

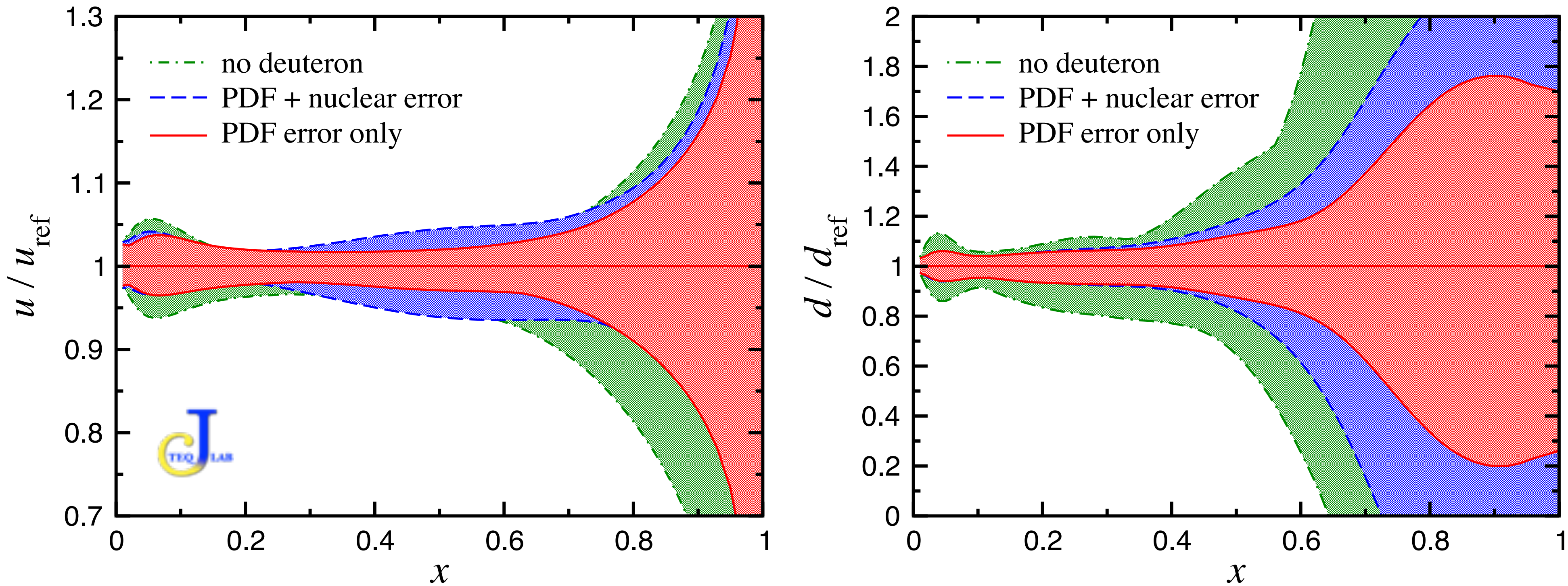
→ deuterium as "effective neutron" target, but need to correct for nuclear effects



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

CTEQ–JLab PDFs

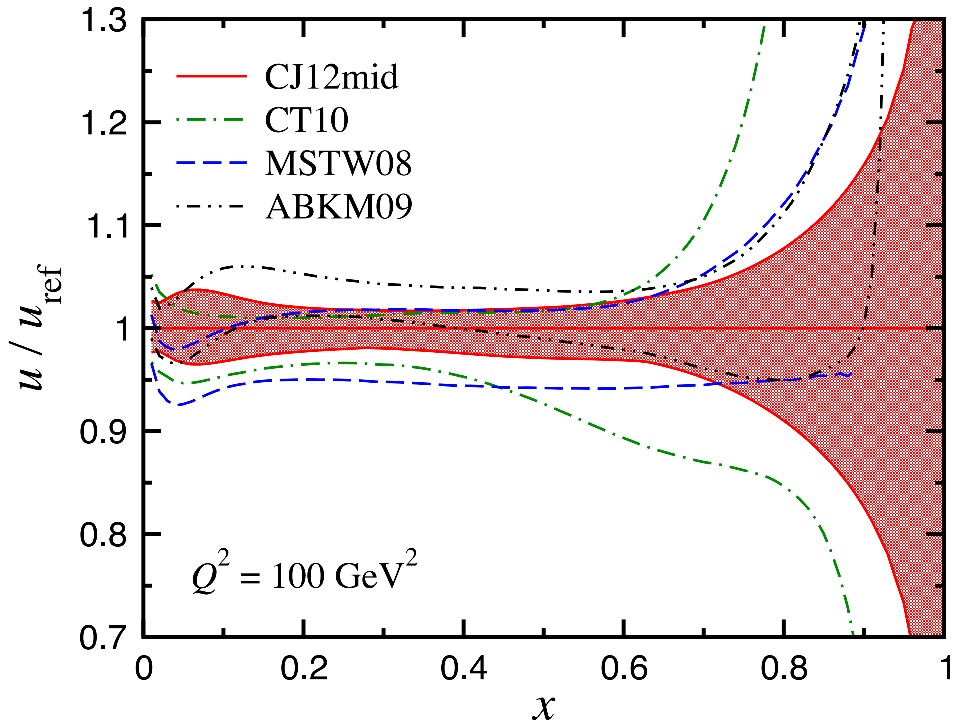
- Effect of nuclear corrections & statistics

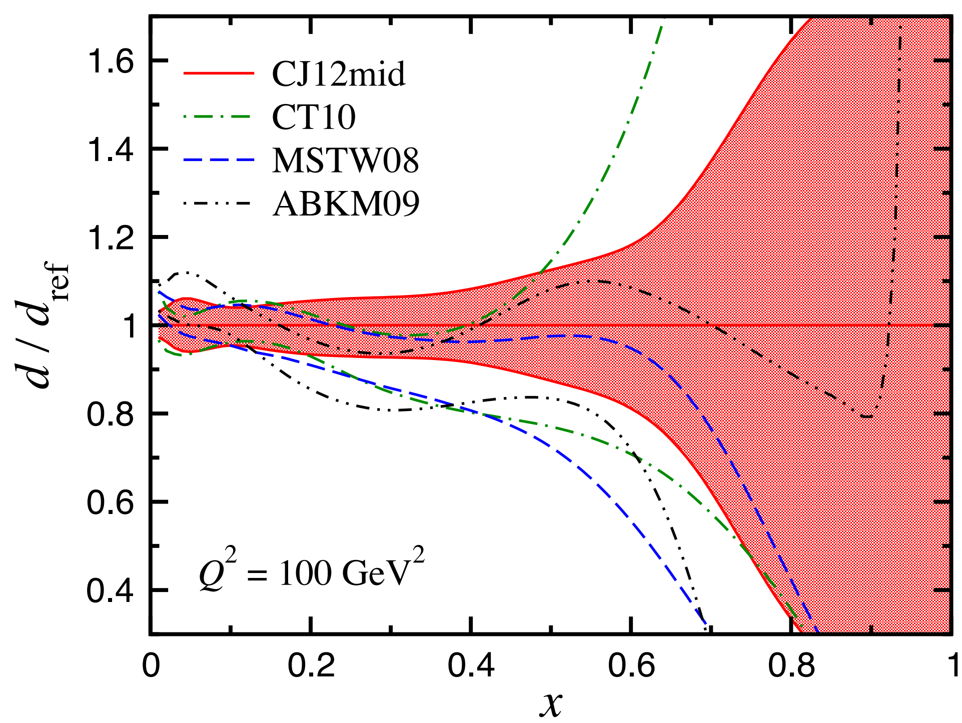


→ significant uncertainties in u for $x > 0.8$, d for $x > 0.6$

CTEQ–JLab PDFs

■ Effect of nuclear corrections & statistics



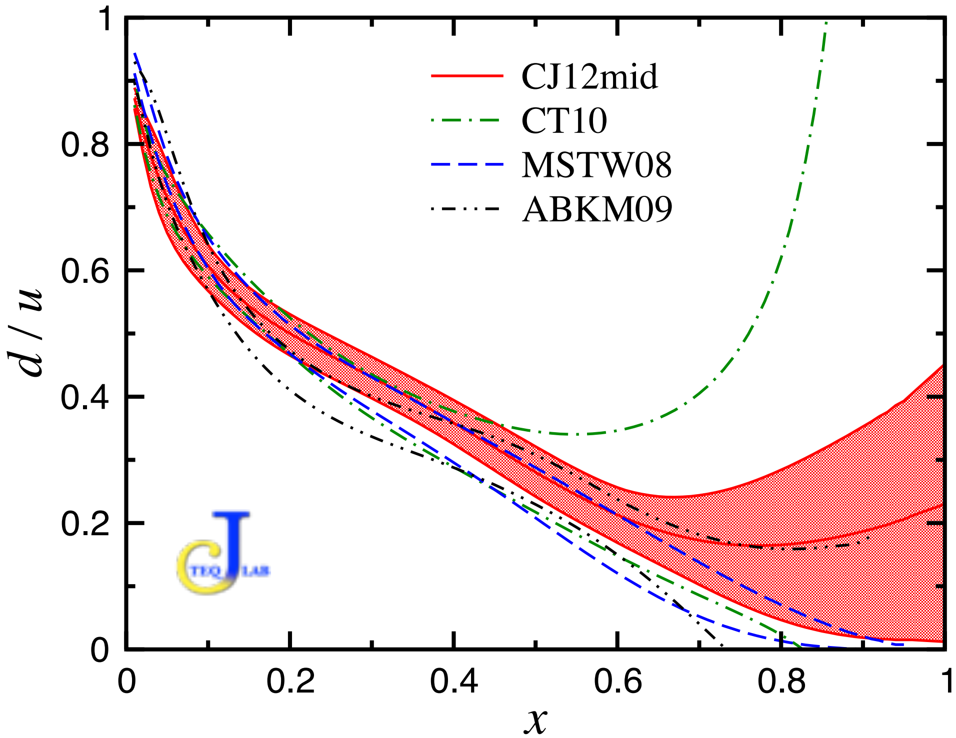


→ *increase* in PDF error from more realistic treatment of nuclear corrections

→ *reduction* of error from larger database

CTEQ–JLab PDFs

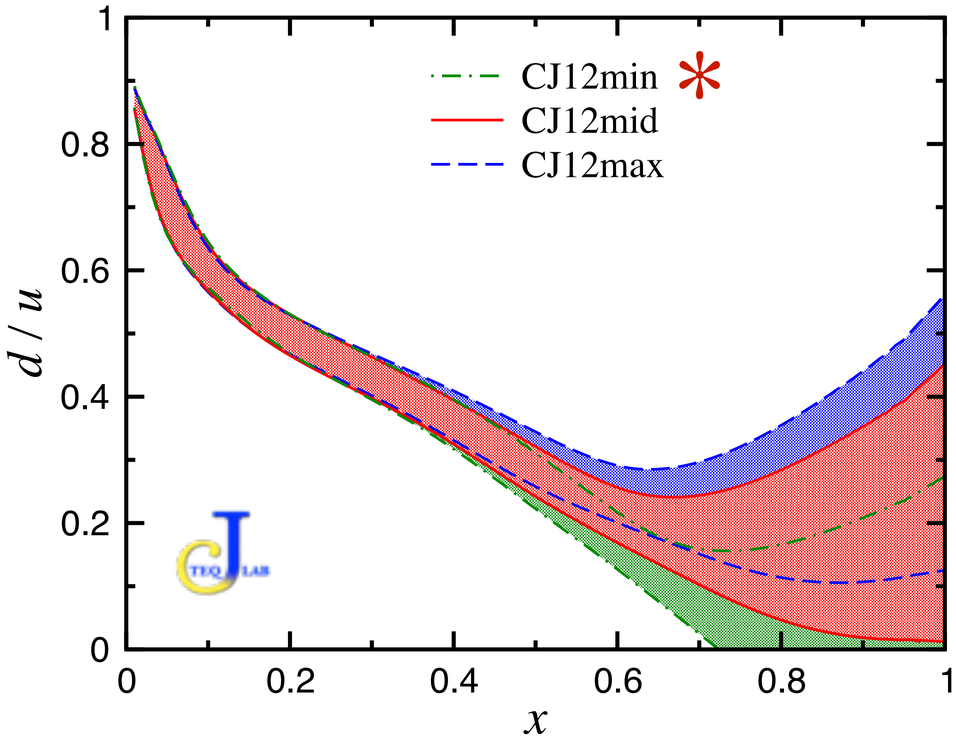
- Effect of nuclear corrections & statistics



- with same functional form for u & d, most PDF fits assume either 0 or ∞ for $x \to 1$ limit

CTEQ–JLab PDFs

Effect of nuclear corrections & statistics



- flexible parametrization for $x \to 1$ behavior

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

- allows finite, nonzero $x = 1$ limit

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

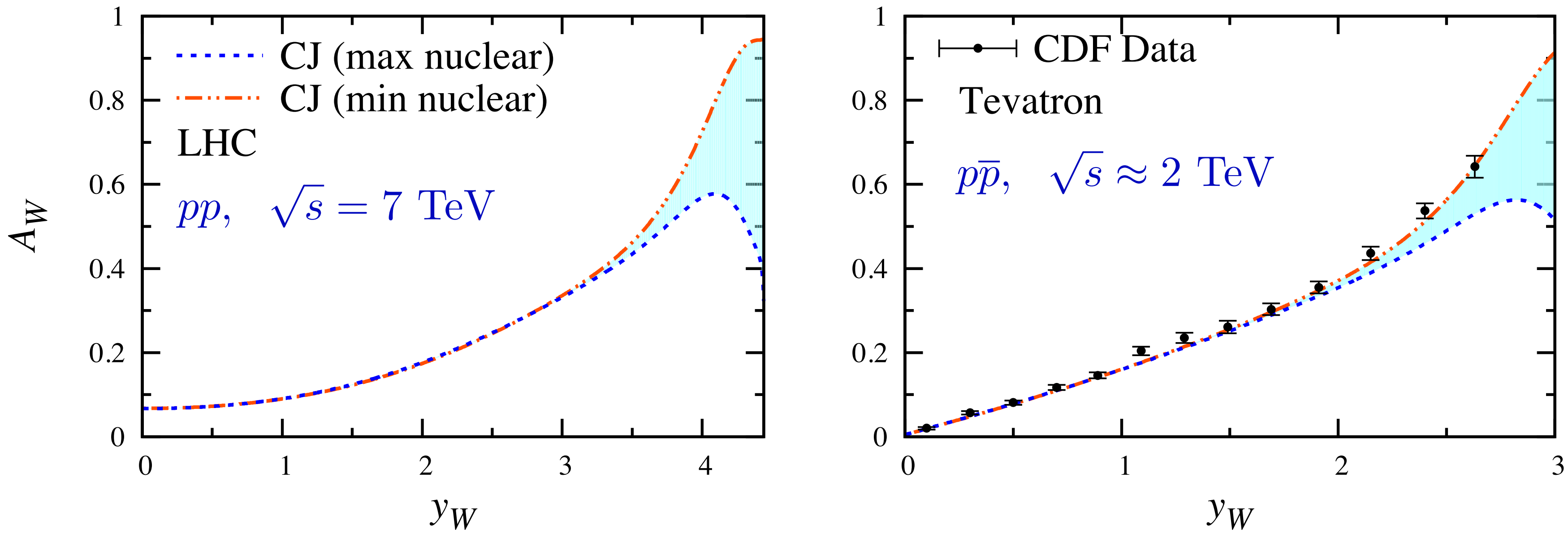
* CJ12min: WJC-1 + mild off-shell (0.3% nucleon swelling)
CJ12mid: AV18 + medium off-shell (1.2% swelling)
CJ12max: CD-Bonn + large off-shell (2.1% swelling)

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

Large-x PDF uncertainties have implications for colliders

→ rapidity $y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$

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



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

Large-x PDF uncertainties have implications for colliders

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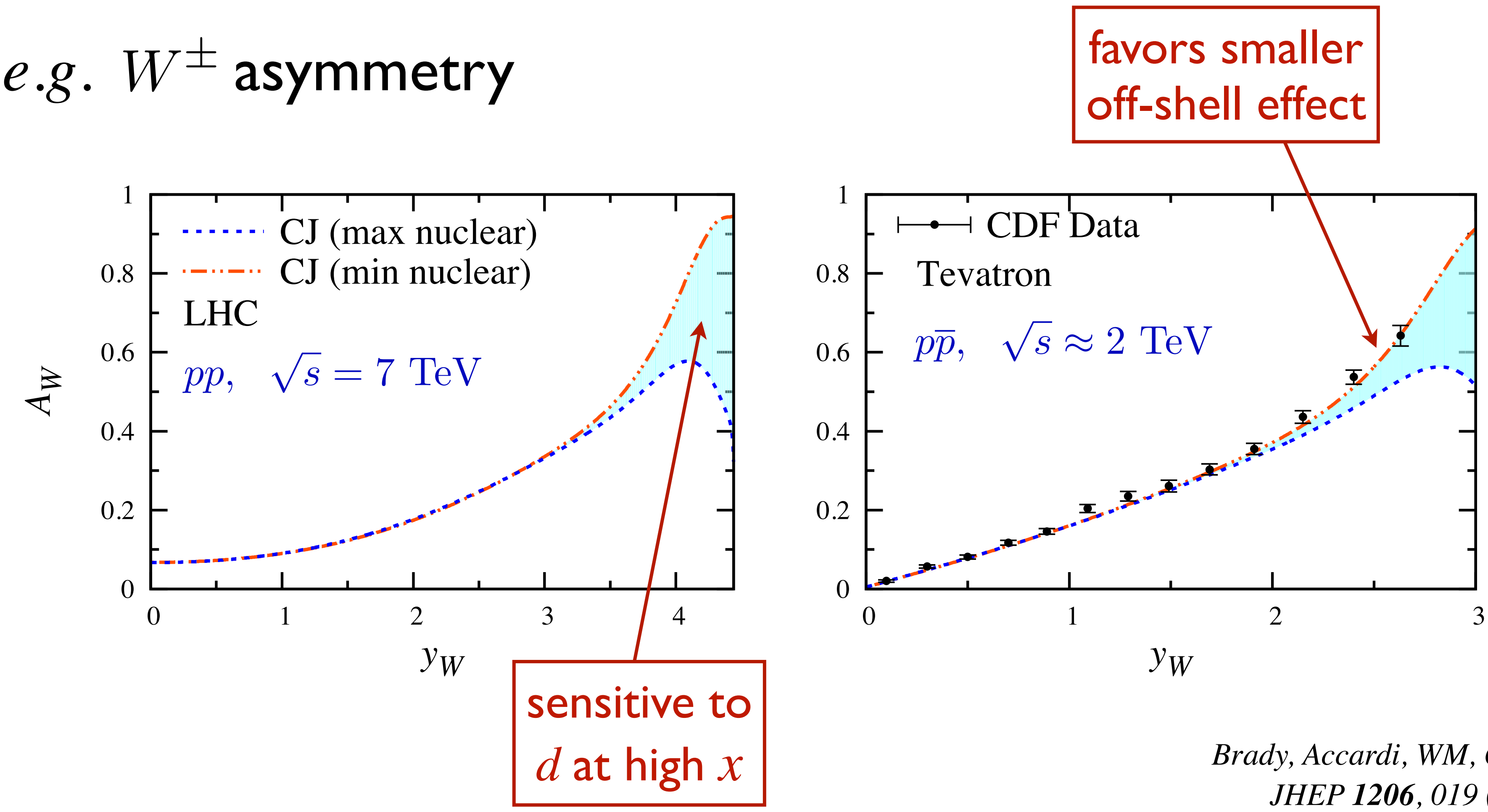


Brady, Accardi, WM, Owens
JHEP ***1206**, 019 (2012)*

CJ15 PDFs

- New CJ15 analysis includes several new theoretical developments (better treatment of heavy quarks; off-shell corrections to valence and sea distributions; improved $\bar{d}\,/\,\bar{u}$ parametrization) and new data sets (D0 W asymmetries; BONuS F_2^n/F_2^d)

- Explore whether new data can constrain PDFs, and nuclear corrections, at large x

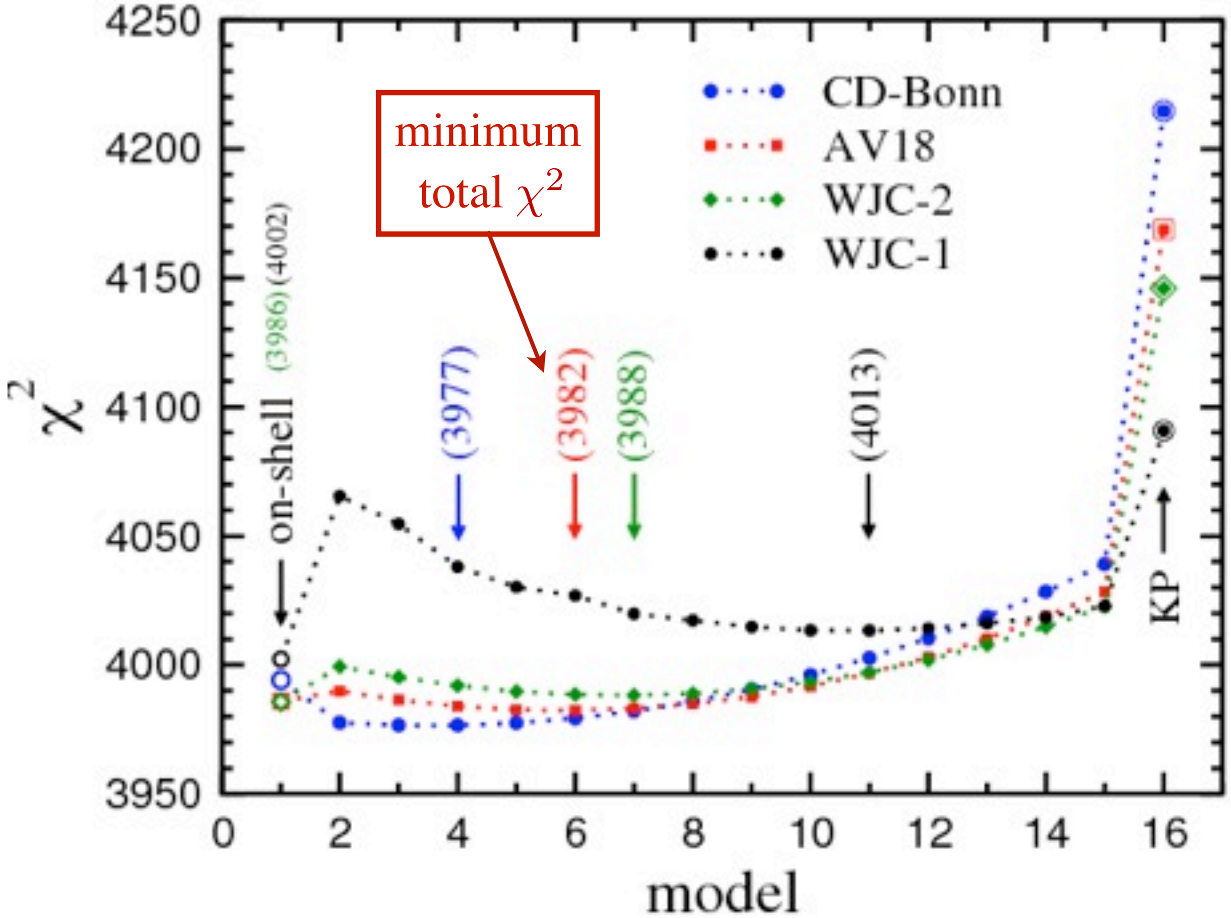
  → vary off-shell "rescaling" parameter $\lambda = \frac{\partial \log \Lambda^2}{\partial p^2}$ within "spectator diquark" model

Kulagin, Petti, NPA ***765****, 126 (2006)*
Owens et al., PRD ***87****, 094012 (2013)*

  → minimize χ^2 as a function of λ

CJ15 PDFs

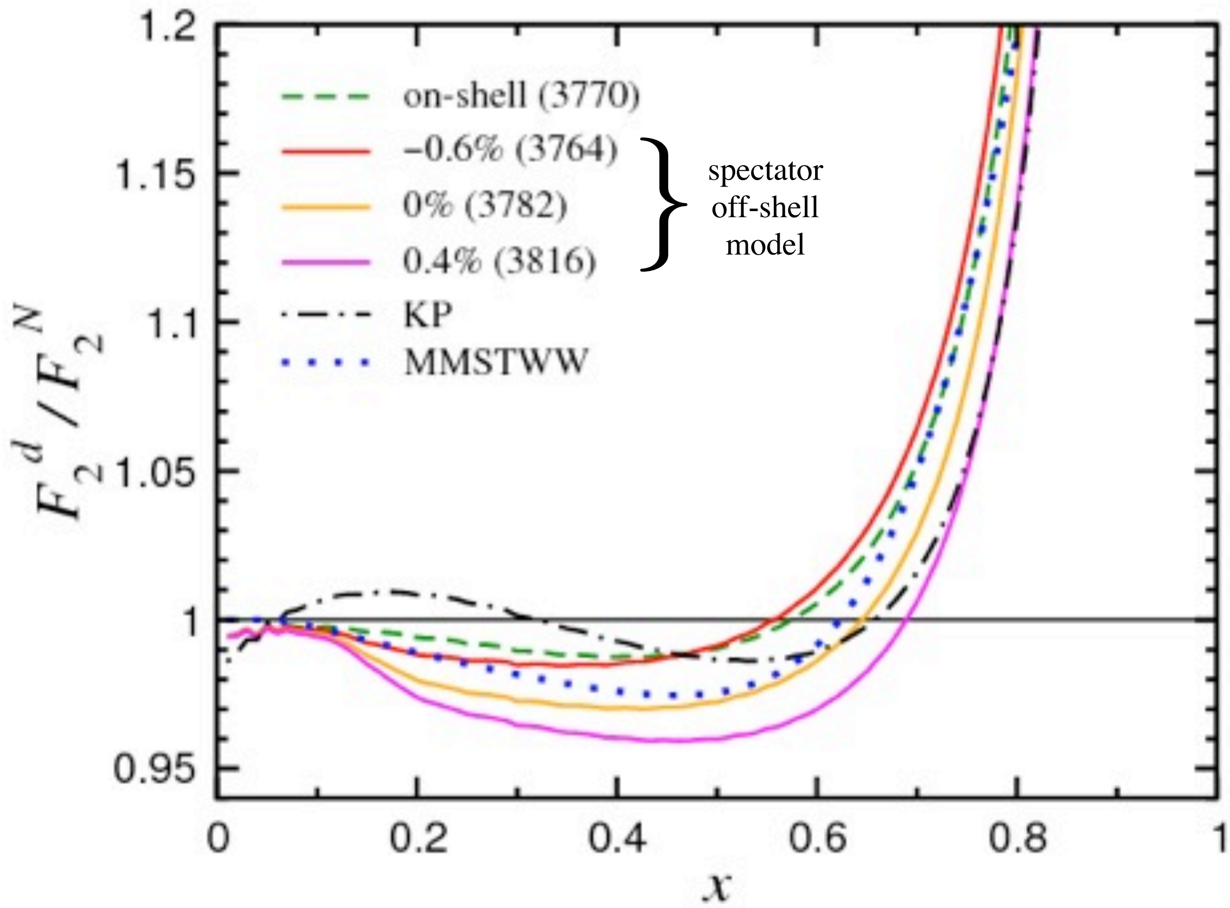
- Minimum total χ^2 for different deuteron wave function and off-shell models



models 2−15: $\lambda = \{-0.9\%, -0.8\%, ..., +0.4\%\}$

CJ15 PDFs

- Nuclear EMC effect in the deuteron for different nuclear models

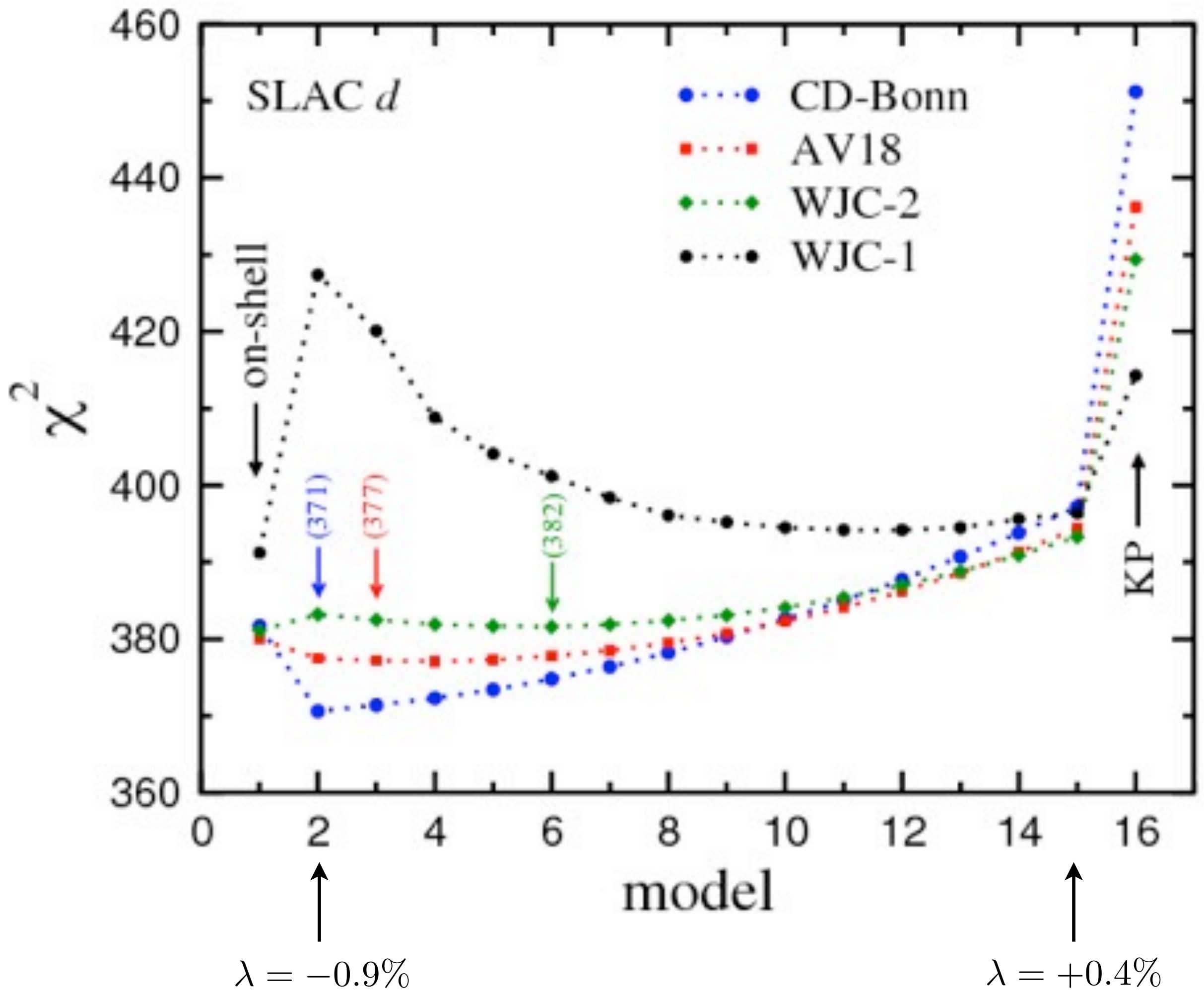


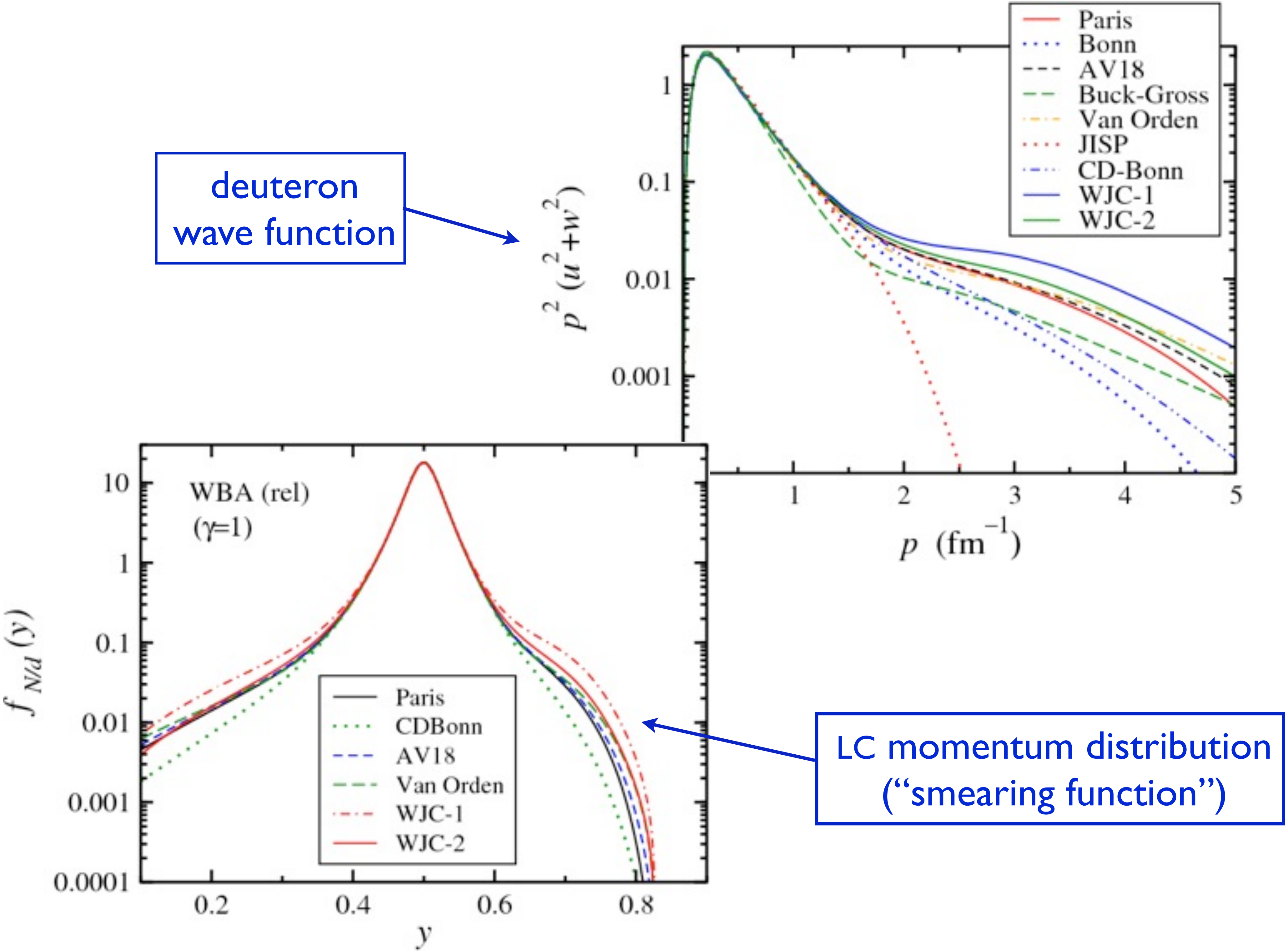
→ larger off-shell effects for larger λ, and for KP model

→ enhancement at $x \sim 0.2$ in KP model

CJ15 PDFs

- SLAC deuteron data favor smaller off-shell corrections, disfavor (hardest) WJC-1 wave function

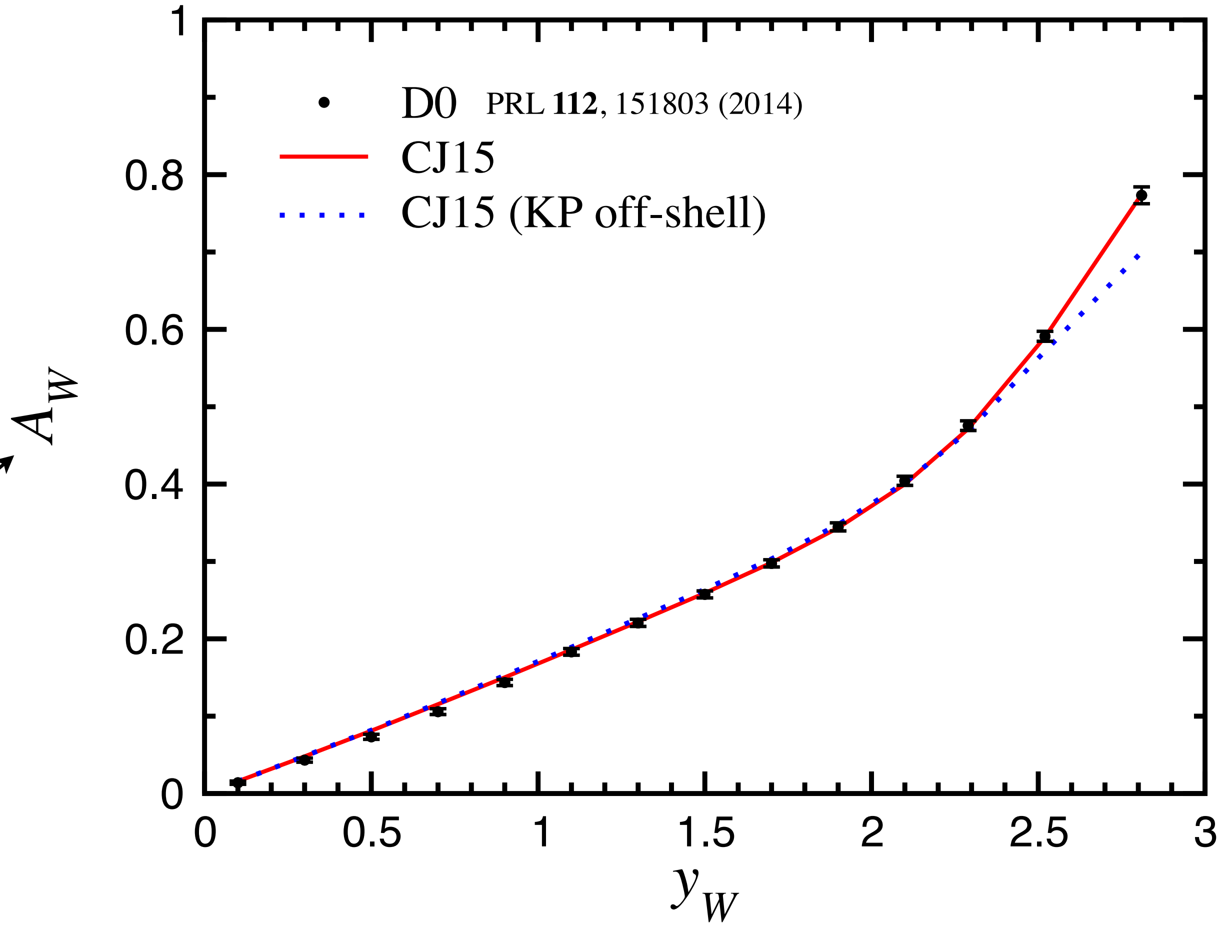



deuteron
wave function
Paris
Bonn
AV18
Buck-Gross
Van Orden
JISP
CD-Bonn
WJC-1
WJC-2
$p^2 (u^2+w^2)$
p (fm^{-1})
WBA (rel)
(γ=1)
Paris
CDBonn
AV18
Van Orden
WJC-1
WJC-2
$f_{N/d}(y)$
y
LC momentum distribution
("smearing function")

CJ15 PDFs

- D0 W-asymmetry data disfavor large nucleon off-shell corrections at high x

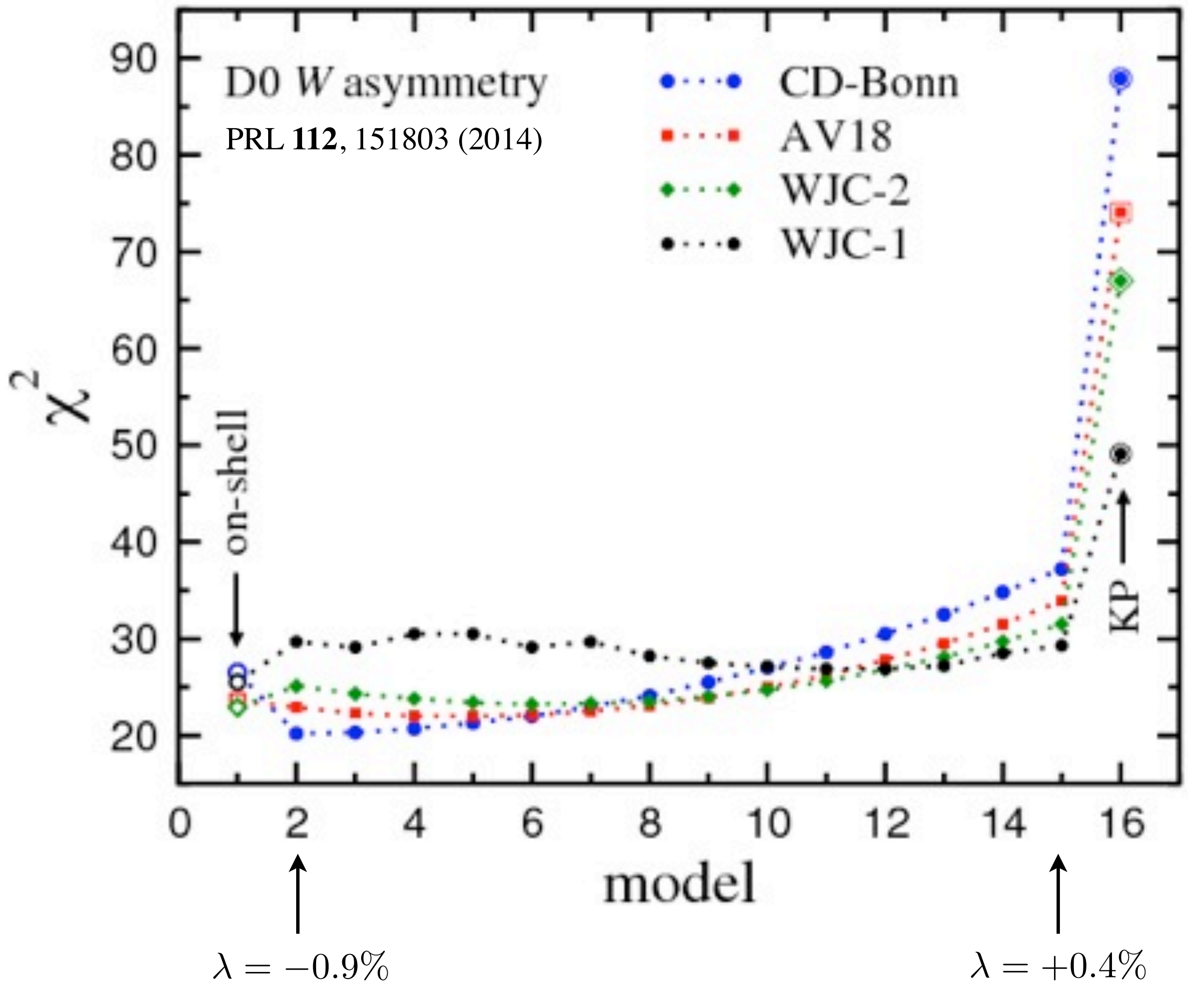
$$\frac{\sigma_{W+} - \sigma_{W-}}{\sigma_{W+} + \sigma_{W-}} \sim \frac{1 - d/u}{1 + d/u}$$



→ larger asymmetry at high rapidity corresponds to <u>smaller d-quark</u> PDF (smaller EMC effect) at high x

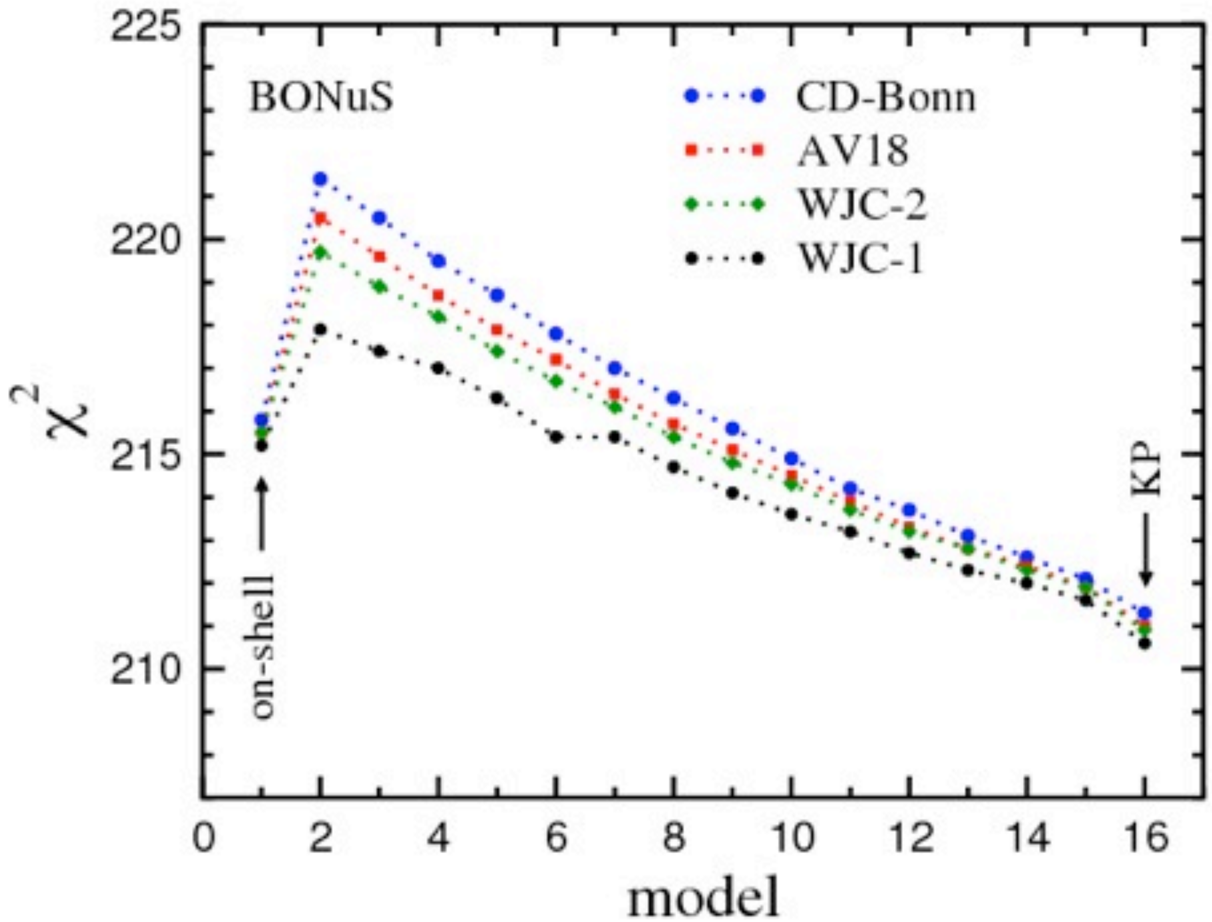
CJ15 PDFs

- D0 W-asymmetry data disfavor large nucleon off-shell corrections at high x



CJ15 PDFs

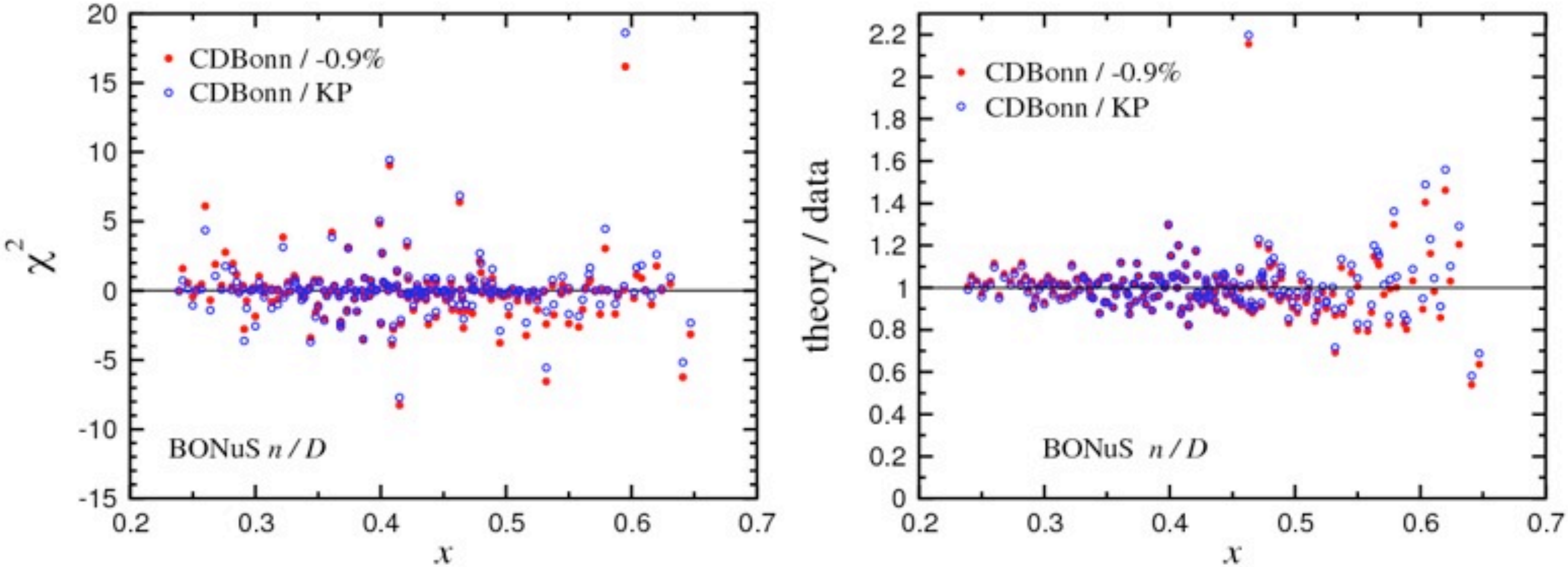
- BONuS F_2^n/F_2^d data favor larger nucleon off-shell corrections (and harder deuteron wave function)



→ $\lesssim 5\%$ improvement in χ^2 with KP model

CJ15 PDFs

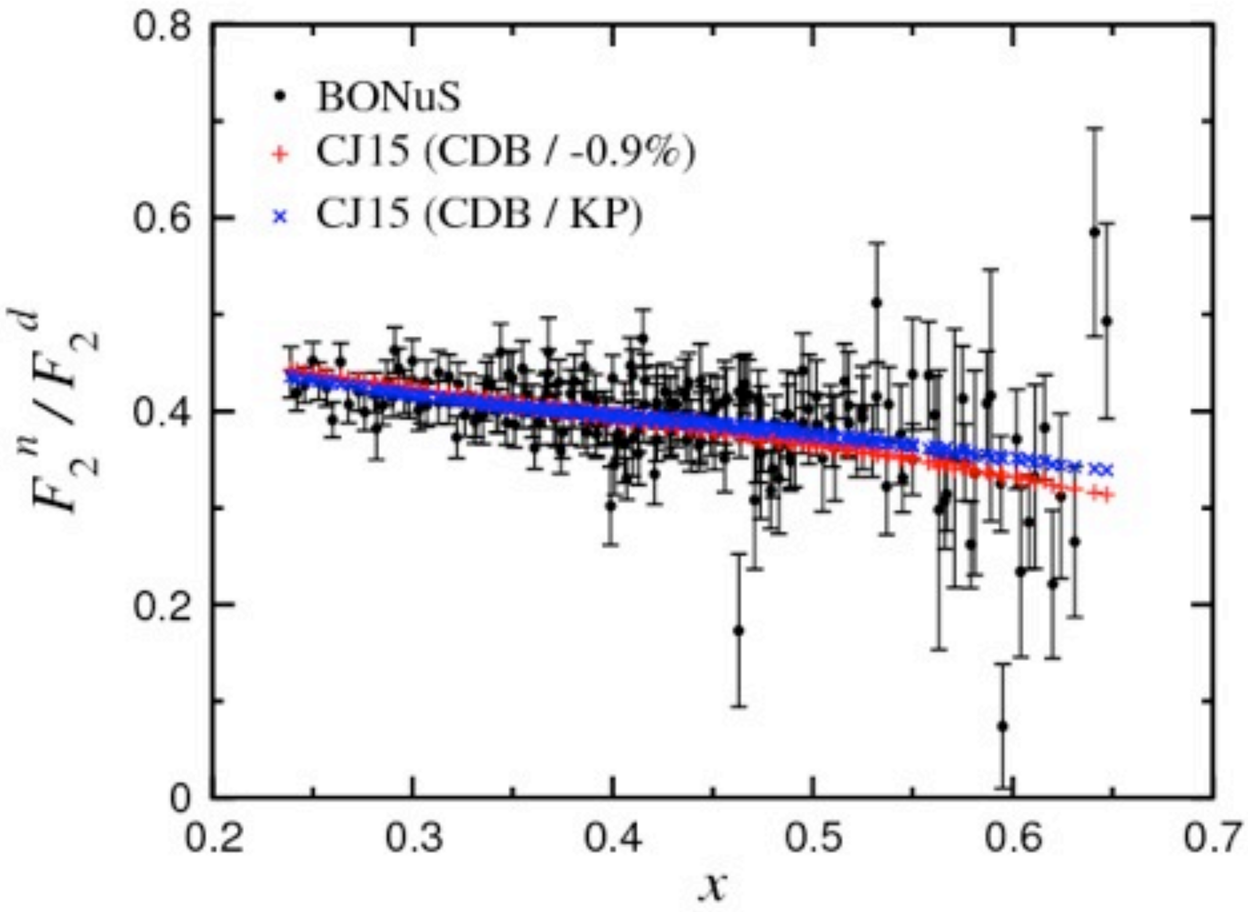
- Is χ^2 improvement from specific kinematics?



→ calculated F_2^n/F_2^d larger at high x with KP model

CJ15 PDFs

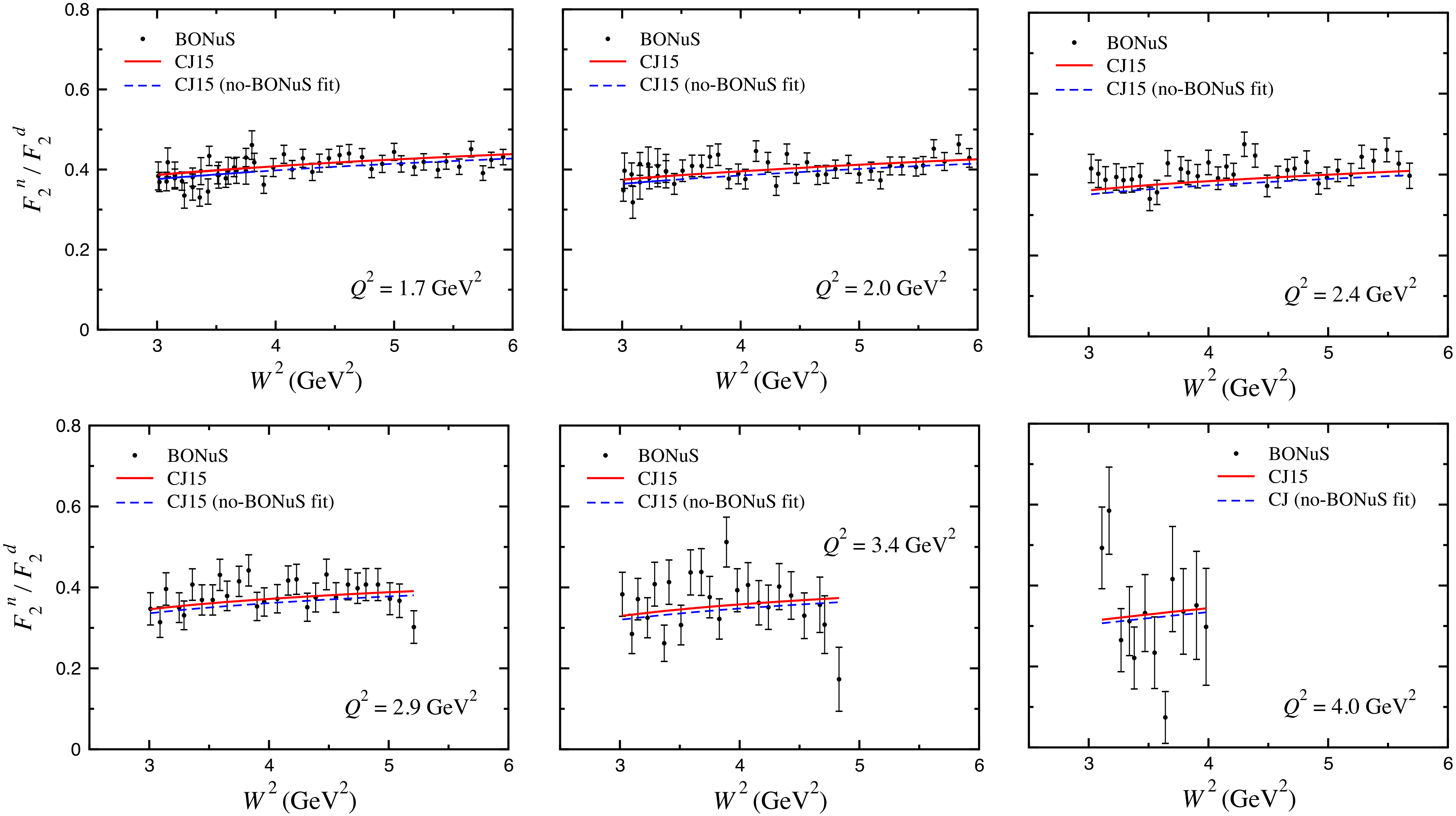
- Is χ^2 improvement from specific kinematics?



→ calculated F_2^n/F_2^d larger at high x with KP model

CJ15 PDFs

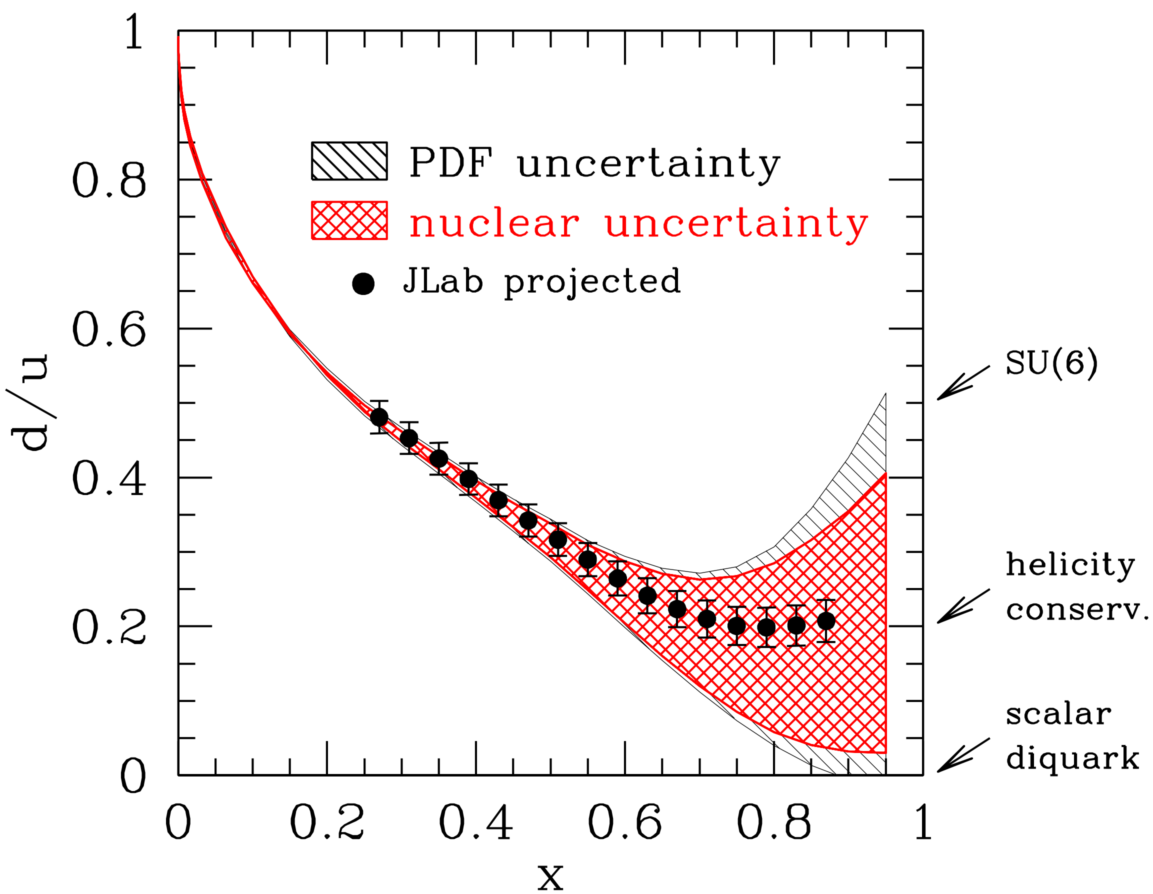
CD-Bonn & $\lambda = -0.7\%$



→ slightly larger neutron F_2 (hence d-quark) with BONuS

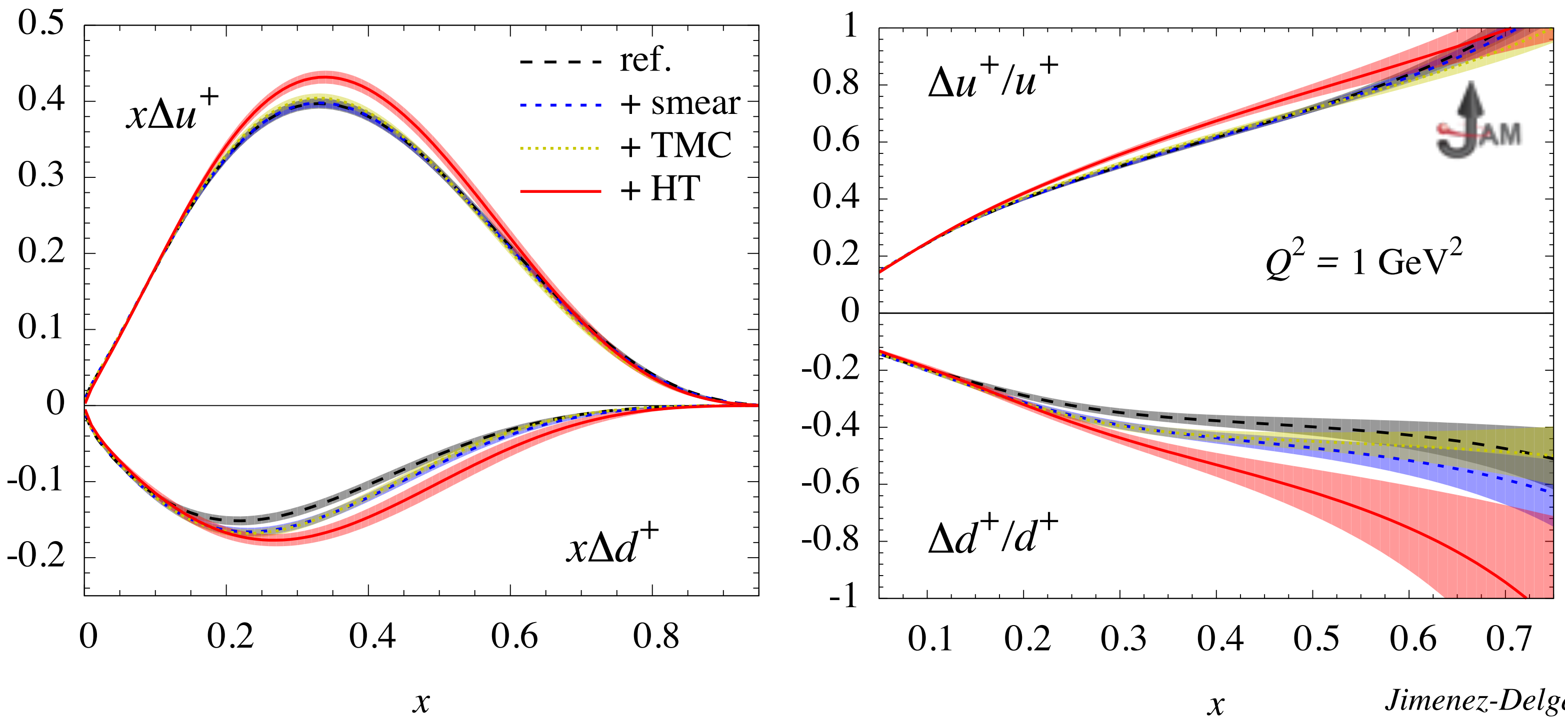
Outlook

- "BONuS6" data demonstrated how spectator tagging can be used to constrain PDFs; impact not dramatic...
  - "BONuS12" promises to extend range to $x \sim 0.85$ with reduced experimental & minimal nuclear uncertainties



Outlook

- Parallel effort in global analysis of spin-dependent PDFs — Jefferson Lab Angular Momentum (JAM) Collaboration
  (Nobuo Sato, A. Accardi, J. Ethier)



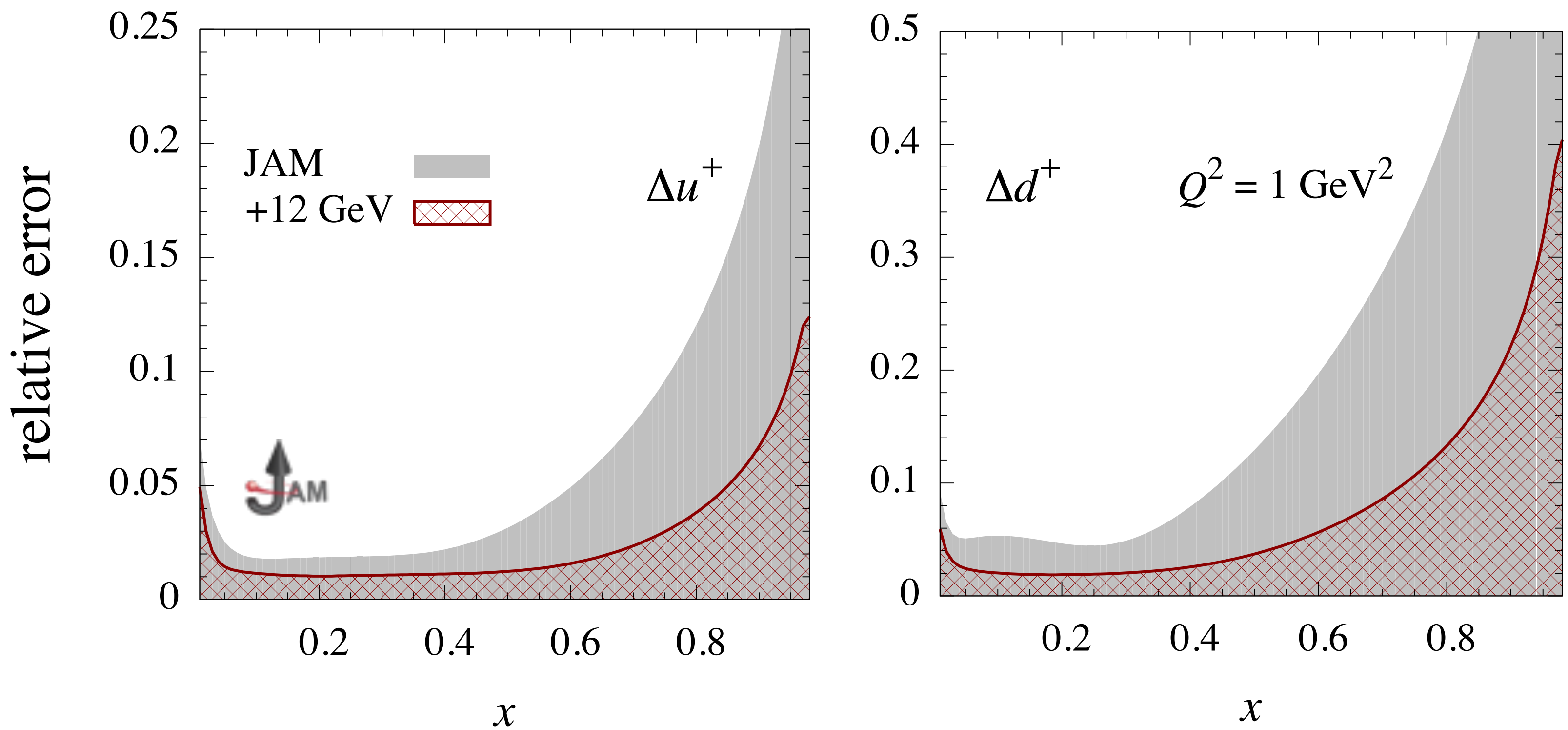
Jimenez-Delgado, Accardi, WM
*PRD **89**, 034025 (2014)*

→ currently assessing impact of new JLab6 data
(eg1b, eg1-DVCS, d2n, ...)

→ full JAM15 analysis will include SIDIS & RHIC-spin data

Outlook

- Upcoming 12 GeV experiments will measure inclusive and semi-inclusive polarization asymmetries up to $x \sim 0.8$



→ will significantly reduce PDF uncertainties at large x (~ 70% for $x \sim 0.6$–0.8)

The End