“CTEQ-JLab”

The CJ15 parton distributions

arXiv:1602.03154

Alberto Accardi
Hampton U. and Jefferson Lab

DIS 2016

DESY, Hamburg, April 12th, 2016

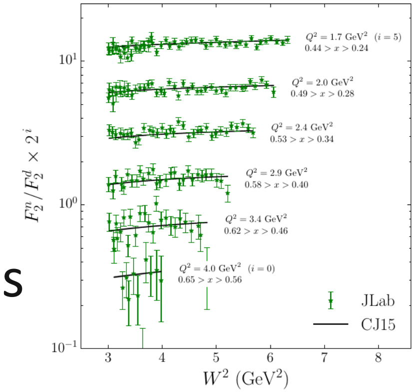
CJ15 at a glance

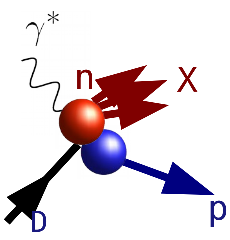
	JLab & BONUS	HERMES	HERA I+II	Tevatron new W,Z	LHC	ν+A di-μ	Large-*x* treatment			
							Nucl.	HT TMC	Flex *d*	low-W DIS
CJ15 *	✓	✓	✓	✓		✗	✓	✓	✓	✓
CT14			[WG1]	✓ ¤¤	✓	✓			✓	
MMHT14			¤¤¤	✓ ¤¤	✓	✓	✓			
NNPDF3.0					✓	✓		(✓)		
JR14	✓				✓	✓	✓	✓		
ABM15				✓ ¤¤	✓	✓	✓	✓		✓
HERAPDF2.0			✓	¤						

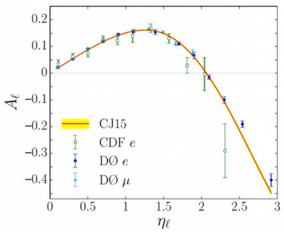
* NLO only ** No jet data ¤ see 1503.05221 ¤¤¤ see 1508.06621 ¤¤ no reconstructed W

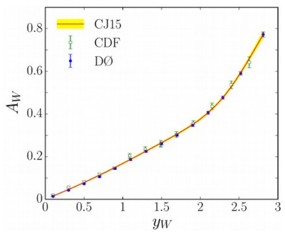
New in CJ15

- s-ACOT scheme for heavy flavors
- **New data:**
  - BONUS spectator tagged DIS on neutrons
  - HERA I+II combination, HERMES F2
  - High-statistics D0 charge asymmetries









- **New off-shell nucleon treatment in deuteron targets (DIS and DY)**
  - Parametrized vs. modeled → absorbs wave function uncertainty
  - Comparison to extraction from DIS on heavier targets
- **NUCL / HEP symbiosis:**
  - *W* and *Z* → constrain d-quark → constrain deuteron corrections
  - Abundant DIS deuteron data → precise *u*/*d* flavor separation

CJ15 – data set

$W^2 > 3.5$ GeV^2 $\Longrightarrow$ $x \lesssim 0.85$

BONUS F_2^n/F_2^d

$x \lesssim 0.65$

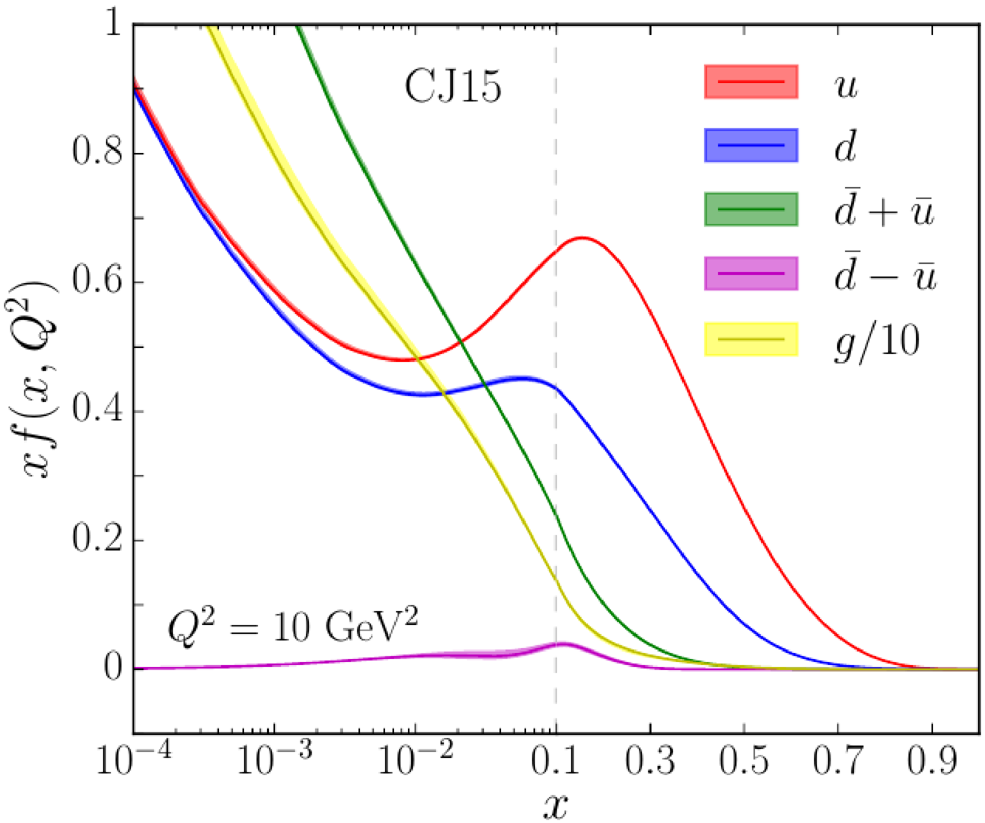
HERA I+II

D0 A_ℓ : $x \lesssim 0.5$

D0 A_W : $x \lesssim 0.85$

Observable	Experiment	# points	χ^2				
			LO	NLO	NLO (OCS)	NLO (no nucl)	NLO (no nucl/D0)
DIS F_2	BCDMS (p) [81]	351	430	**438**	436	440	427
	BCDMS (d) [81]	254	297	**292**	289	301	301
	SLAC (p) [82]	564	488	**434**	435	441	440
	SLAC (d) [82]	582	396	**376**	380	507	466
	NMC (p) [83]	275	431	**405**	404	405	403
	NMC (d/p) [84]	189	179	**172**	173	174	173
	HERMES (p) [86]	37	56	**42**	43	44	44
	HERMES (d) [86]	37	51	**37**	38	36	37
	Jefferson Lab (p) [87]	136	166	**166**	167	177	166
	Jefferson Lab (d) [87]	136	131	**123**	124	126	130
DIS F_2 tagged	Jefferson Lab (n/d) [21]	191	218	**214**	213	219	219
DIS σ	HERA (NC e^-p) [85]	159	325	**241**	240	247	244
	HERA (NC e^+p 1) [85]	402	966	**580**	579	588	585
	HERA (NC e^+p 2) [85]	75	184	**94**	94	94	93
	HERA (NC e^+p 3) [85]	259	307	**249**	249	248	248
	HERA (NC e^+p 4) [85]	209	348	**228**	228	228	228
	HERA (CC e^-p) [85]	42	44	**48**	48	45	49
	HERA (CC e^+p) [85]	39	56	**50**	50	51	51
Drell-Yan	E866 (pp) [29]	121	148	**139**	139	145	143
	E866 (pd) [29]	129	207	**145**	143	158	157
W/charge asymmetry	CDF (e) [88]	11	11	**12**	12	13	14
	DØ (μ) [17]	10	37	**20**	19	29	28
	DØ (e) [18]	13	20	**29**	29	14	14
	CDF (W) [89]	13	16	**16**	16	14	14
	DØ (W) [19]	14	39	**14**	15	82	—
Z rapidity	CDF (Z) [90]	28	100	**27**	27	26	26
	DØ (Z) [91]	28	25	**16**	16	16	16
jet	CDF (run 2) [92]	72	33	**15**	15	23	25
	DØ (run 2) [93]	110	23	**21**	21	14	14
γ+jet	DØ 1 [94]	16	17	**7**	7	7	7
	DØ 2 [94]	16	34	**16**	16	17	17
	DØ 3 [94]	12	34	**25**	25	24	25
	DØ 4 [94]	12	76	**13**	13	13	13
total		4542	5894	**4700**	4702	4964	4817
total + norm			6022	**4708**	4710	4972	4826
χ^2/datum			1.33	**1.04**	1.04	1.09	1.07

CJ15 - PDFs



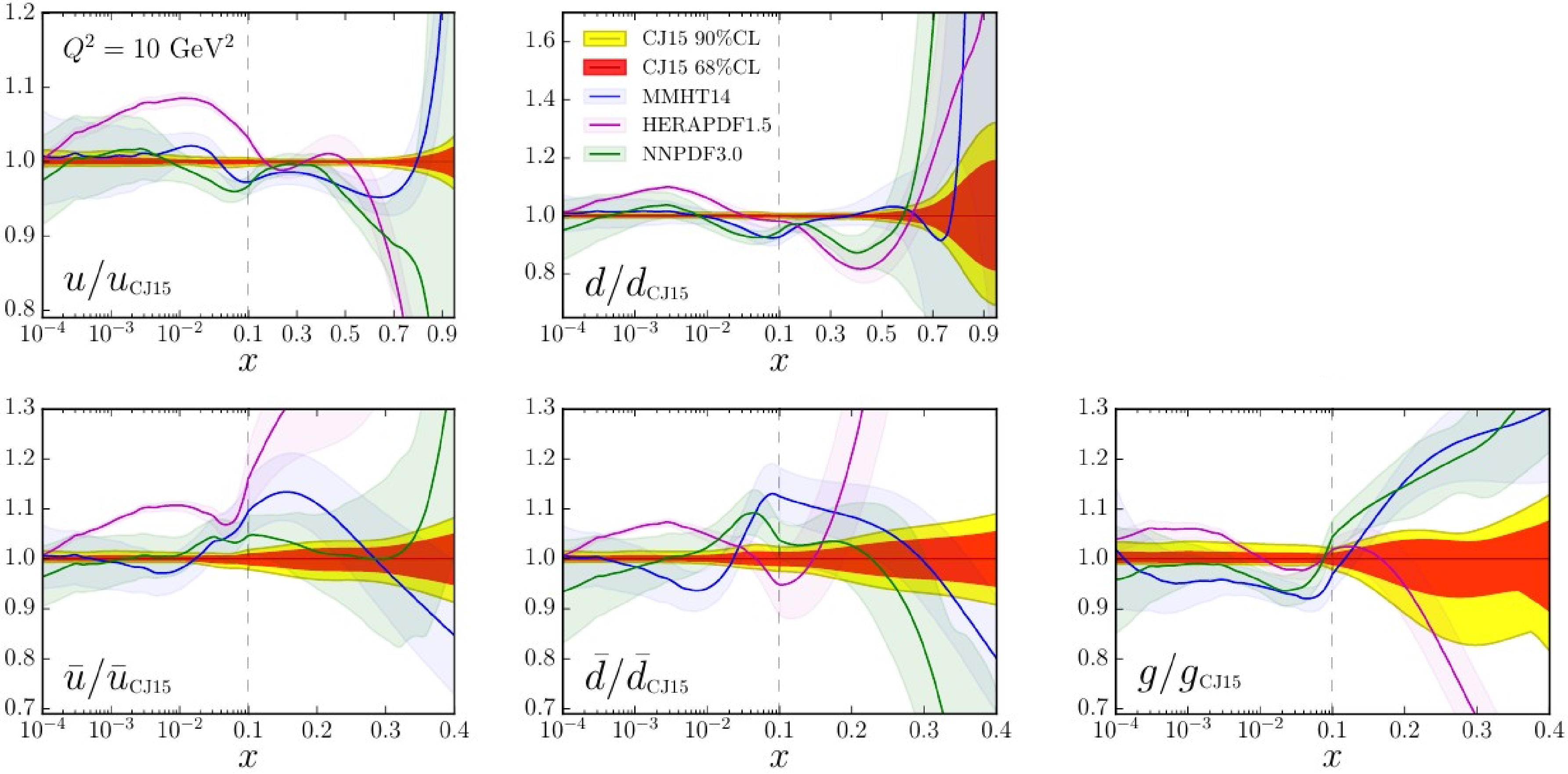
- Hessian error analysis
  - Correlated errors where available
- Error bands displayed for

$$\Delta\chi^2 = 2.71$$

(90% confidence level
in a perfect, Gaussian world)

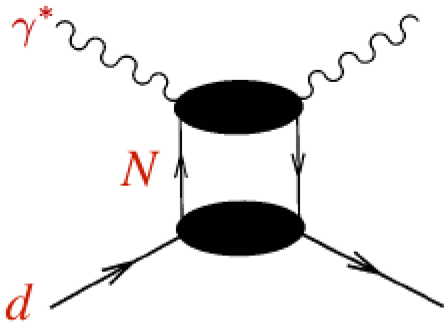
- NLO fit gives $\chi^2/\text{datum} = 1.04$
- LO fit much worse – cannot accommodate Q^2 dependence of data

CJ15 vs. others



Nuclear corrections

- At large x, DIS dominated by incoherent scattering from individual nucleons



$$q^d(x,Q^2) = \int \frac{dz}{z} dp^2\, f_{N/d}(z,p^2)\, \widetilde{q}^N(x/z,p^2,Q^2)$$

nucleon momentum distribution in d ("smearing function")

PDF in bound (off-shell) nucleon

$$\rightarrow \quad z = \frac{p\cdot q}{p_d \cdot q} \approx 1 + \frac{p_0 + \gamma p_z}{M} \quad \left[p_0 = M + \varepsilon, \quad \varepsilon = \varepsilon_d - \frac{\vec{p}^{\,2}}{2M} \right]$$

momentum fraction of d carried by N

$\rightarrow$ at finite Q^2, smearing function depends on $\gamma = \sqrt{1 + 4M^2x^2/Q^2}$

- Offshell expansion; parametrize first order coefficient, x_1 fixed with valence sum rule

$$\widetilde{q}^N(x,p^2) = q^N(x)\left[1 + \frac{(p^2 - M^2)}{M^2}\,\delta q^N(x)\right]$$

$$\delta q^N = C_N(x - x_0)(x - x_1)(1 + x - x_0) \qquad \int_0^1 dx\, \delta q^N(x)\Big(q^N(x) - \bar{q}^N(x)\Big) = 0$$

NUCL / HEP symbiosis

Observable	Experiment	# points	χ^2			
			LO	NLO	NLO (OCS)	NLO (no nucl)
DIS F_2	BCDMS (p) [81]	351	430	**438**	436	440
	BCDMS (d) [81]	254	297	**292**	289	301
	SLAC (p) [82]	564	488	**434**	435	441
	SLAC (d) [82]	582	396	**376**	380	507
DIS F_2 tagged	Jefferson Lab (n/d) [21]	191	218	**214**	213	219
W/charge asymmetry	CDF (e) [88]	11	11	**12**	12	13
	DØ (μ) [17]	10	37	**20**	19	29
	DØ (e) [18]	13	20	**29**	29	14
	CDF (W) [89]	13	16	**16**	16	14
	DØ (W) [19]	14	39	**14**	15	82
Z rapidity	CDF (Z) [90]	28	100	**27**	27	26
	DØ (Z) [91]	28	25	**16**	16	16
	⋮	⋮	⋮	⋮	⋮	⋮
χ^2/datum			1.33	**1.04**	1.04	1.09

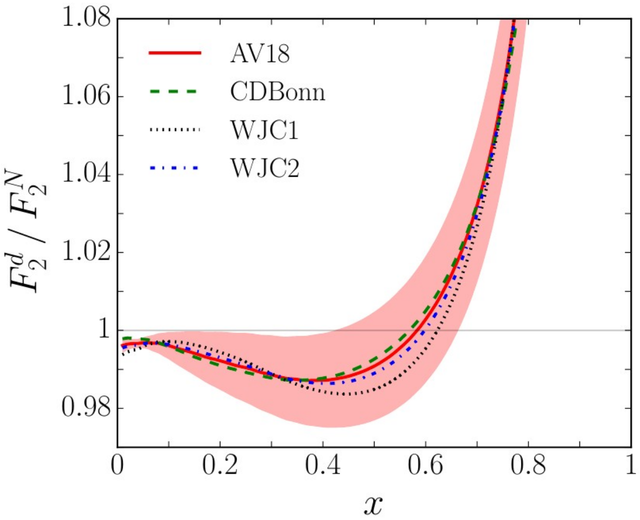
NUCL / HEP symbiosis

Observable	Experiment	# points	χ^2 LO	χ^2 NLO	χ^2 NLO (OCS)	χ^2 NLO (no nucl)
DIS F_2	BCDMS (p) [81]	351	430	**438**	436	440
	BCDMS (d) [81]	254	297	**292**	289	301
	SLAC (p) [82]	564	488	**434**	435	441
	SLAC (d) [82]	582	396	**376**	380	507
DIS F_2 tagged	Jefferson Lab (n/d) [21]	191	218	**214**	213	219
W/charge asymmetry	CDF (e) [88]	11	11	**12**	12	13
	DØ (μ) [17]	10	37	**20**	19	29
	DØ (e) [18]	13	20	**29**	29	14
	CDF (W) [89]	13	16	**16**	16	14
	DØ (W) [19]	14	39	**14**	15	82
Z rapidity	CDF (Z) [90]	28	100	**27**	27	26

- Ignoring nuclear dynamics, SLAC(d) and D0(W) pull d quark in opposite directions
  - **D0 (W) data determine nuclear corrections !!**
  - other asymmetries inconclusive by themselves
  - **BONUS data validate DO(W) analysis**

Nucleon off-shellness constrained by D0 data (!)

- The "wrong" nuclear corrections creates tension between DIS(D) and W asym
  - The fits then choses the "right" one

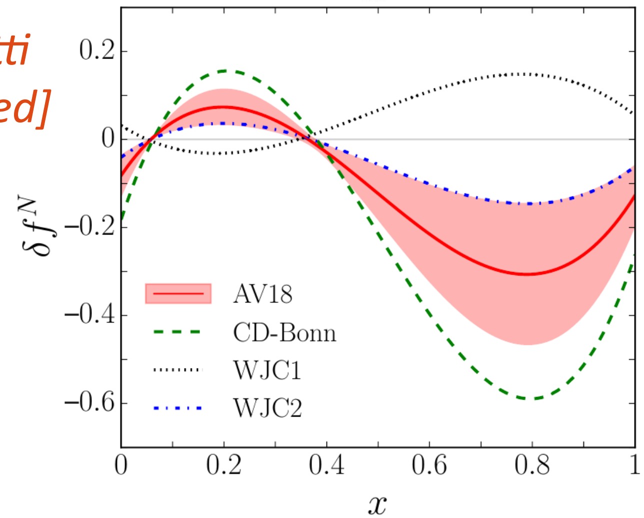


- **Deuteron to nucleon "EMC" ratio** D/(p+n)
  - Stable w.r.t. choice of nucleon w.fn.

    (WJC1 disfavored χ^2-wise)
  - No evidence for antishadowing

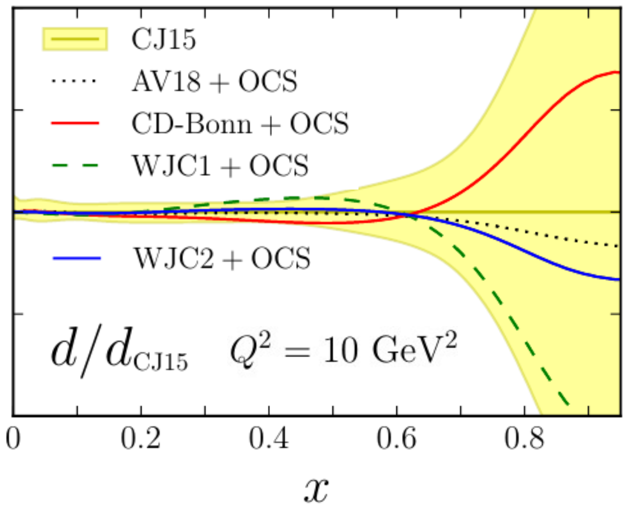
- **Off shell correction – first time in Deuteron!**
  - Good statistical precision!
  - Magnitude compensates for wave function's missing / excessive strength
  - Physical result or fitting away other physics?

→ also: R. Petti [WG1 – Wed]



$$\delta f^N = C(x - x_0)(x - x_1)(1 + x_0 - x)$$

Cross checks

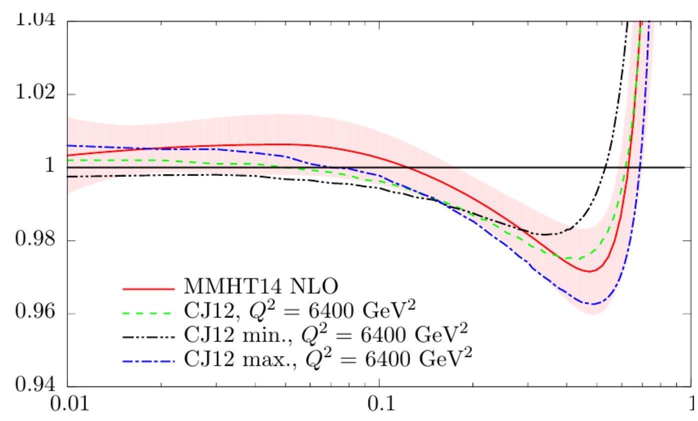


- Fit with with a 1-parameter model of the off-shell effects
  - Obtain comaptible *d* quarks

OCS = Off-shell Covariant Spectator model

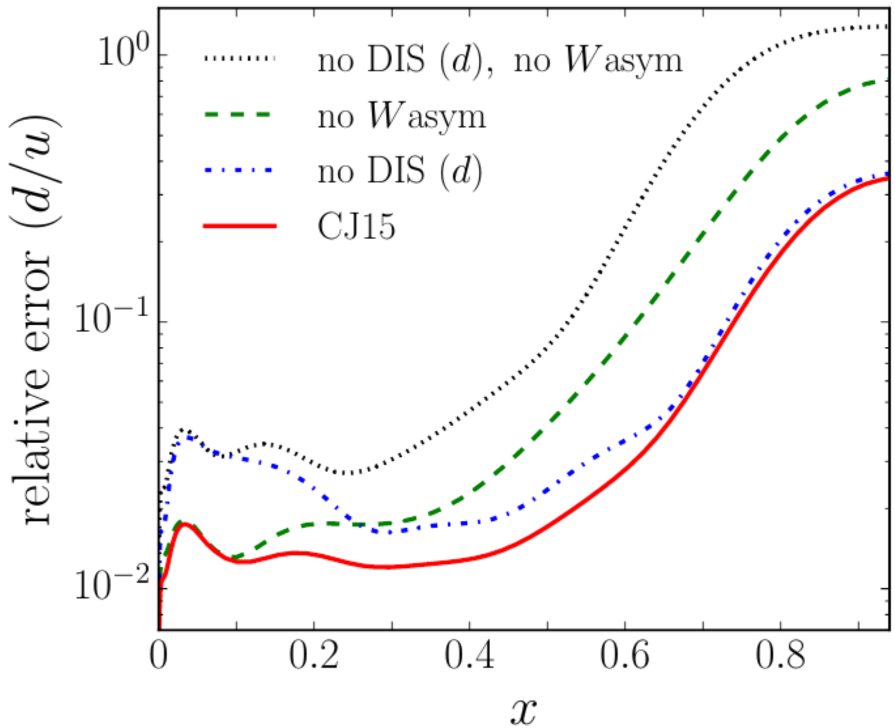
- MMHT14 parametrize the whole nuclear effect
  - Obtain similar result
  - (but cannot explore the nuclear dynamics)

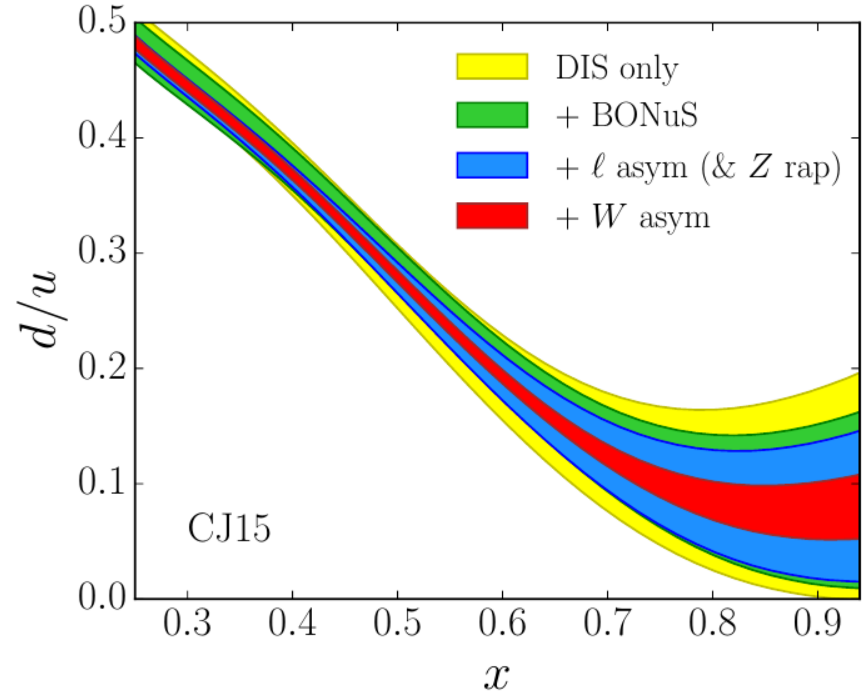
$$c(x) = F_2(D)/F_2(p+n)$$



MMHT14, EPJ C75 (2015) 204

What fits what?

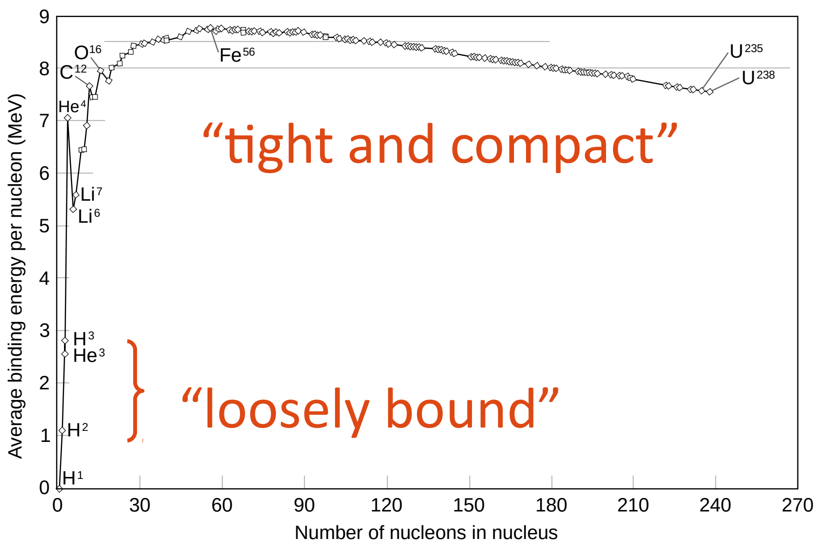


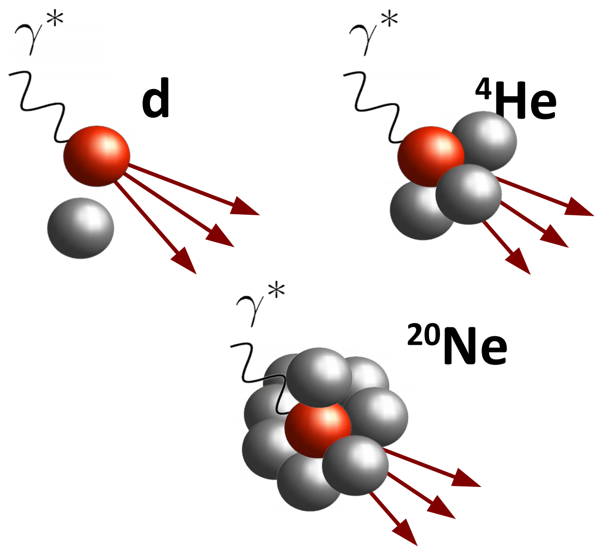


- **Large x > 0.3:**
  - D0's W-asymmetry determines the d-quark
  - SLAC(d)'s statistical power used to fit the off-shell function
- **Moderate x < 0.3:**
  - SLAC(d) enables precise d/u flavor separation

Nuclear physics output

- **QUESTION:** Does the nuclear environment affect the off-shell behavior of a nucleon?
  - For example, partial deconfinment *[Close, Jaffe, Roberts (1985)]*

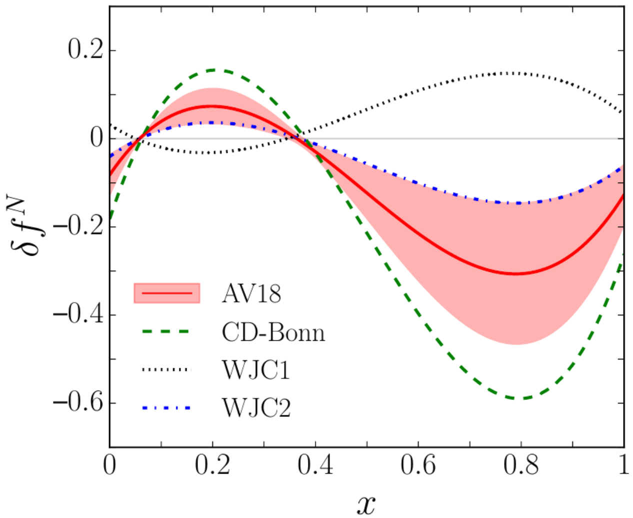




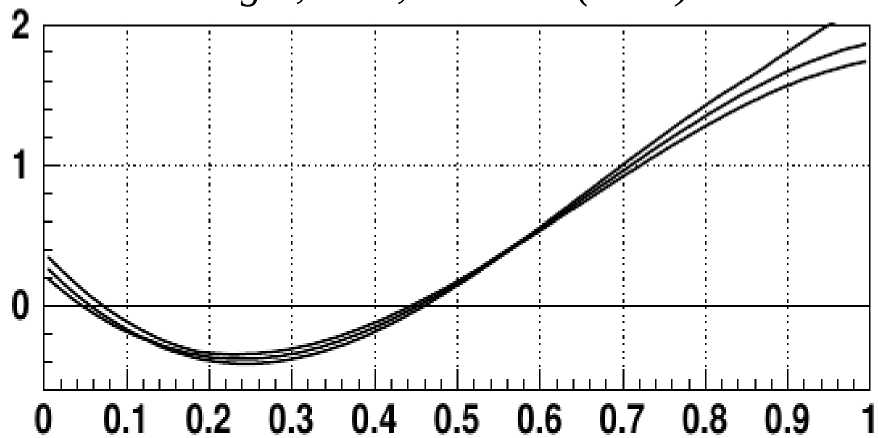
$$\delta q = \delta q(x; A) \ ??$$

Nuclear physics output

- **Compare to Kulagin-Petti fit to e+A collisions**
  - Same functional form (but different normalization)



Kulagin, Petti, NPA 765 (2006) 126-187



- Different shape and size

  → no nuclear universality ?? δf_N

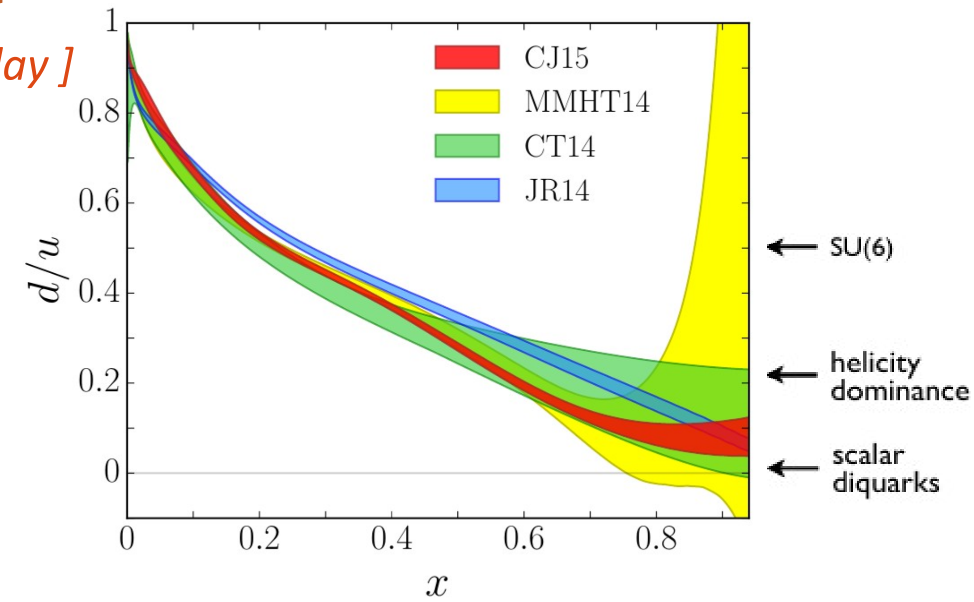
  → too hard nuclear spectral function at large momentum ??

see also: R. Petti [WG1 – Wed] S.Kulagin [WG1 – Wed]

Hadronic physics output

→ *see also: E.Nocera [WG1 – Wednesday]*

→ d/u ratio at high x of interest for nonperturbative models of nucleon



→ **CJ15:**

more flexible parametrization

$$d \rightarrow d + b\,x^c\,u$$

allows finite, nonzero $x = 1$ limit

(standard PDF form gives 0 or ∞ unless $a_2^d = a_2^u$)

MMHT14: fitted deuteron corrections
standard *d* parametrization
→ **"UNDERCONSTRAINED"**

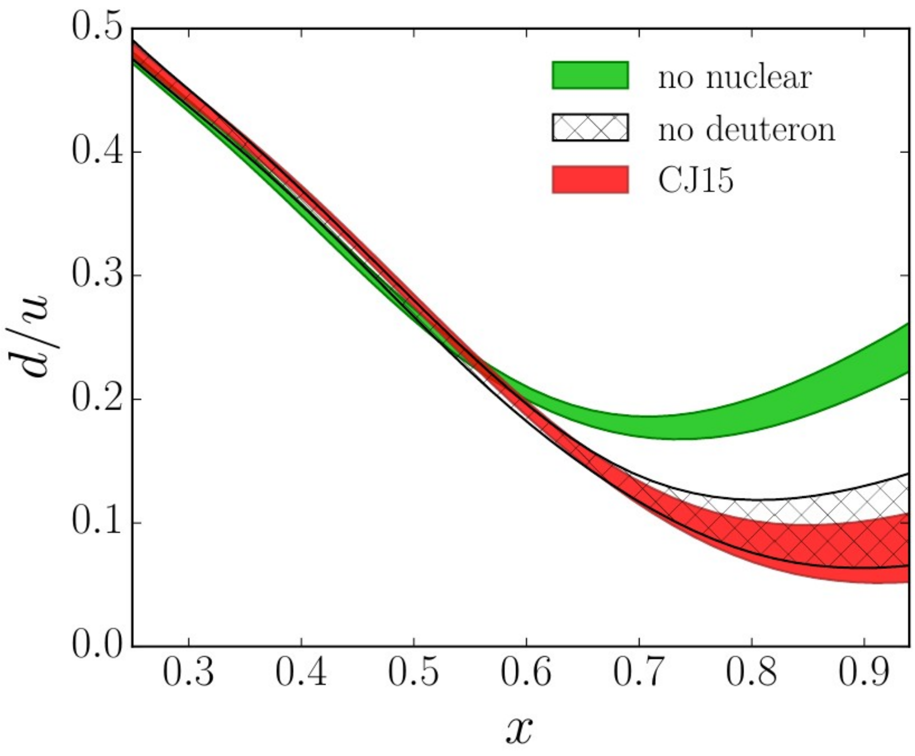
JR14 (and ABM12):
Similar deuteron corrections
standard *d* ; no lepton/W asym.
→ **"OVERCONSTRAINED"**

CT14: $\beta_u = \beta_d \implies d/u$ finite
No nuclear corrections

Very important:

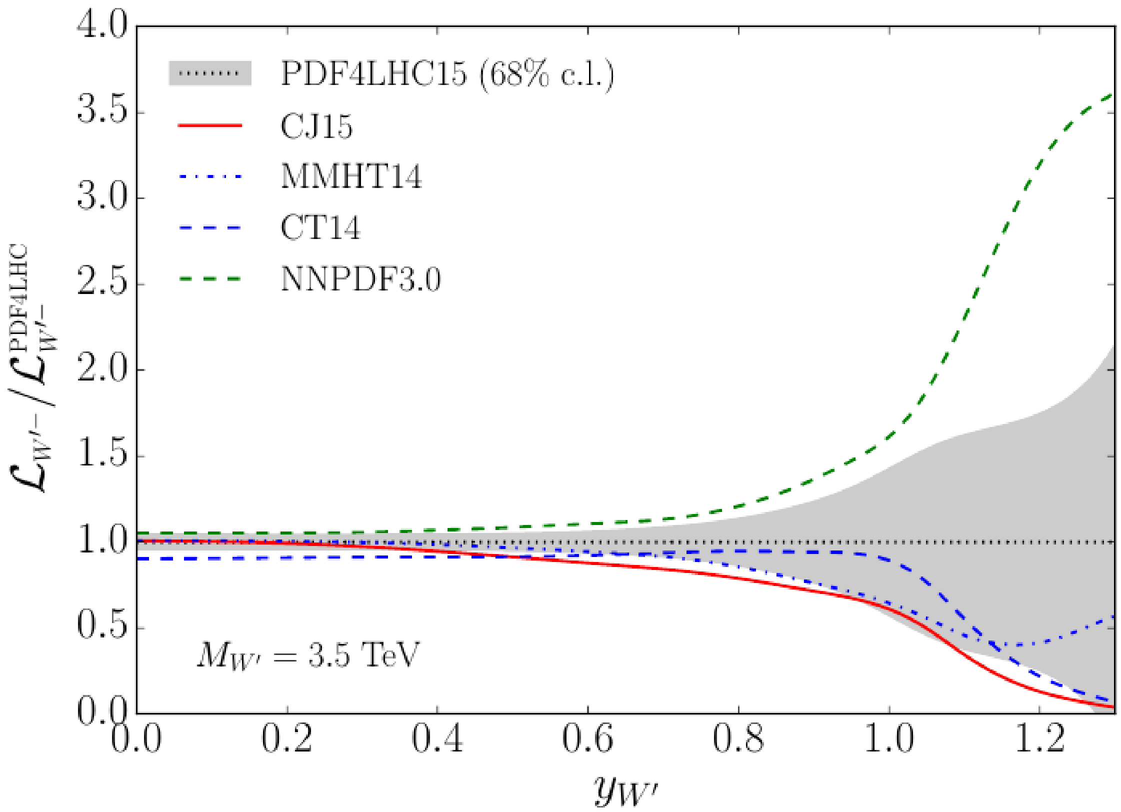
→ deuterium data, and proper treatment of nuclear corrections, are important for *accuracy* and *precision* of d/u determination at $x > 0.6$

→ **Same will be true also for dbar/ubar at large x**



BSM physics output

→ *see also: R.Placakyte [WG1 – Tue]*

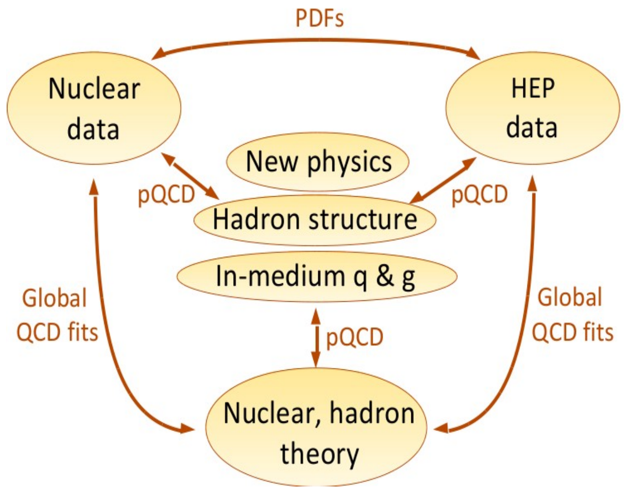


$$\mathcal{L}_{W'^-} = \frac{2\pi G_F}{3\sqrt{2}} x_1 x_2 \Big[\cos^2\theta_C \big(\bar{u}(x_2) d(x_1) + \bar{c}(x_2) s(x_1) \big) + \sin^2\theta_C \big(\bar{u}(x_2) s(x_1) + \bar{c}(x_2) d(x_1) \big) \Big] + (x_1 \leftrightarrow x_2)$$

Conclusions

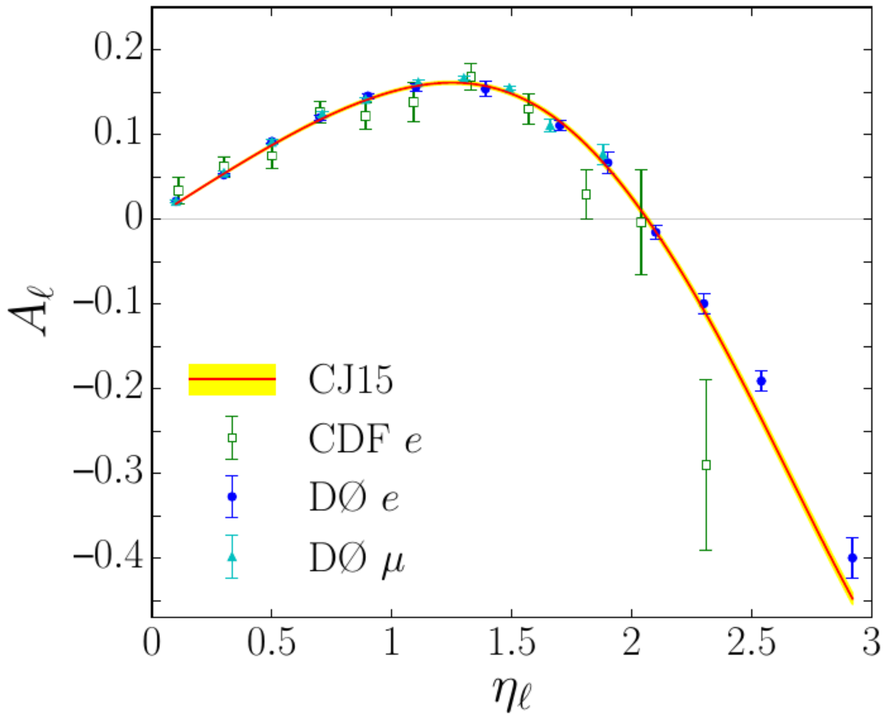
- **Entering a new precision era in large-x PDFs**
  - Most groups are finally on board
    - Much to be learned from each other
  - New data (now and in the future), new fitting approaches
  - Conquering nuclear corrections
  - Time for threshold resummation ?

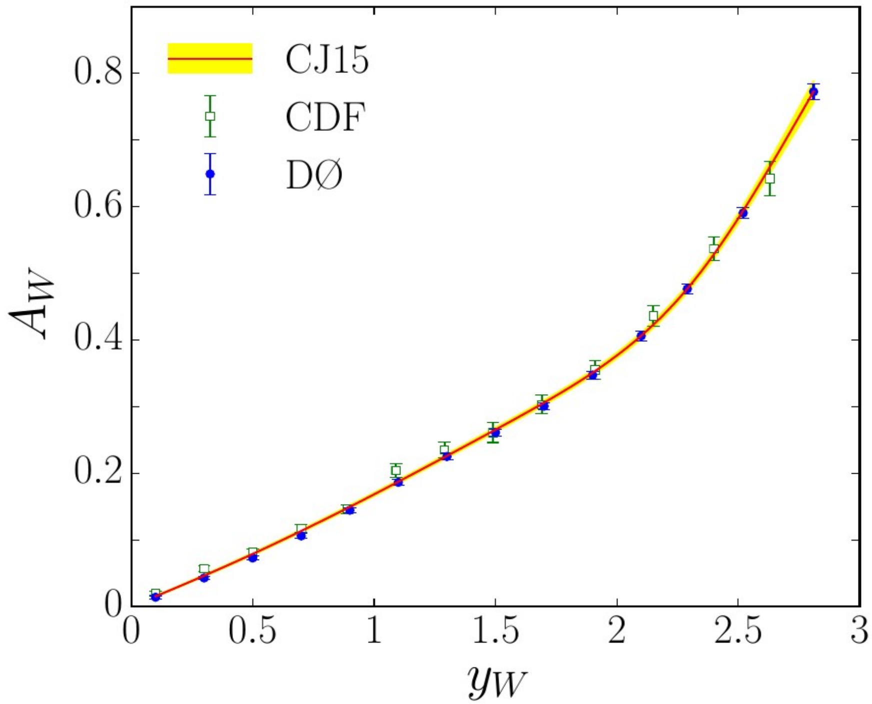
- **High-energy and nuclear physics need to work together!**
  - Progress in hadron / nuclear structure
  - Precision PDFs for BSM searches



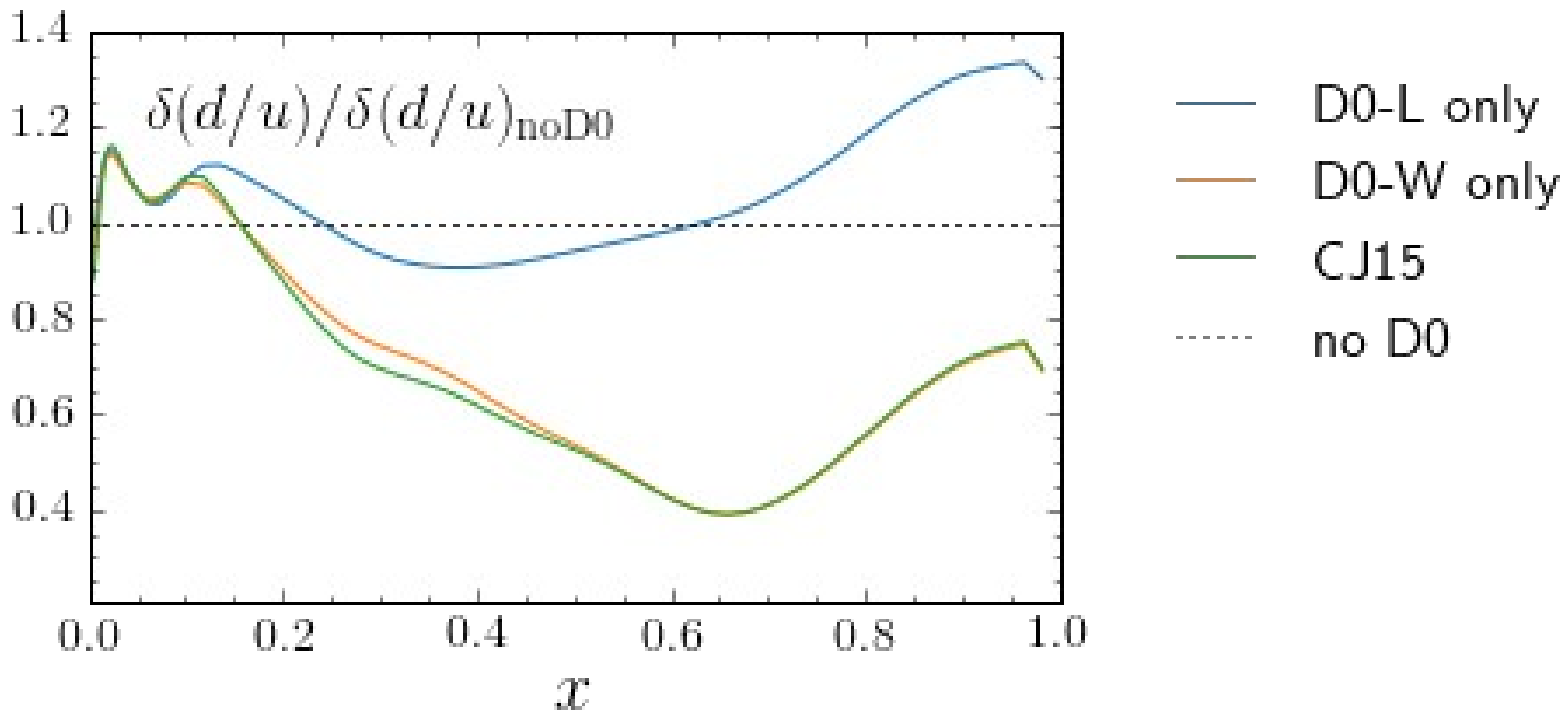
Backup

W-lepton and W asymmetry at Tevatron





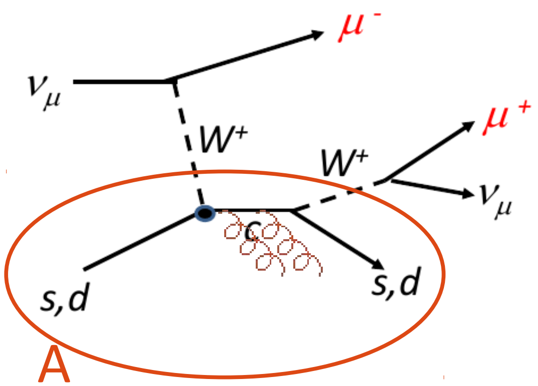
W-lepton and W asymmetry at Tevatron



Strangeness and strangeness asymmetry

$$s^{\pm}(x) = s(x) \pm \bar{s}(x) \qquad [s^{\pm}] = \int_0^1 dx\, x\, s^{\pm}(x)$$

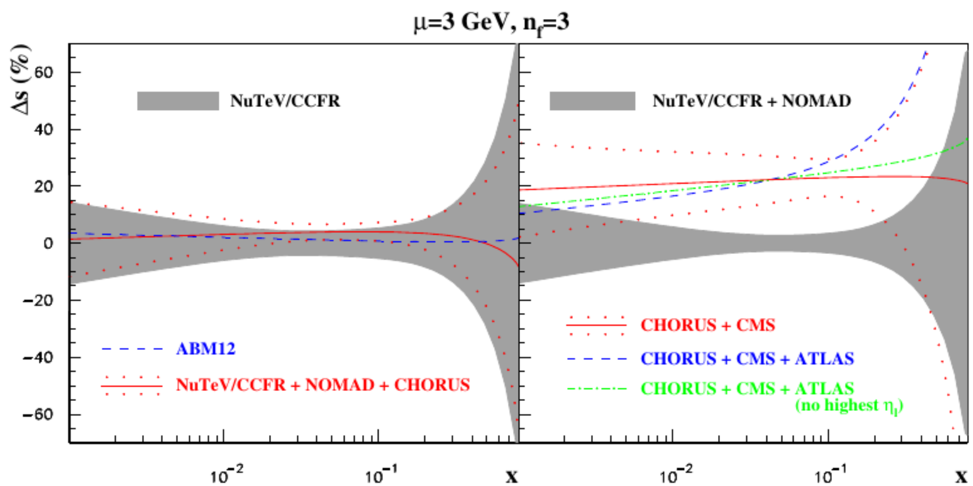
- In pre-LHC fits, mostly constrained by ν+A data
  - CCFR inclusive DIS
  - NuTeV muon pair production
  - NOMAD and CHORUS



- **Nuclear corrections again...**
  - **<u>Initial state nuclear wave-function mods</u>**
    - Partly under control using **nPDFs**
    - But: double counting!! → either use in nPDF <u>or</u> in PDF fits !
  - **<u>Final state propagation of the charm quark / D meson</u>**
    - Not under theoretical / phenomenological control (*cf.* heavy quark "puzzle" in A+A at RHIC, LHC)

Strange tensions

- **ν+*A* → dimuons** *vs.* ***p+p* → *W+c* at LHC** *Alekhin et al., arXiv:1404.6469*



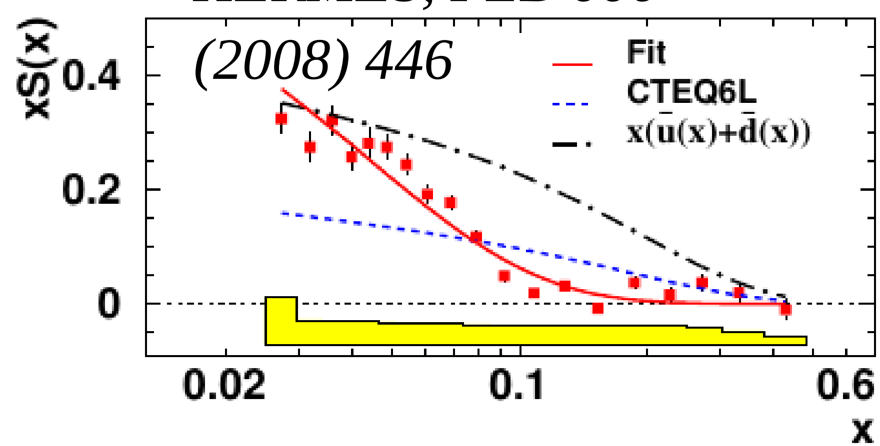
$$g\, s_p \to W\, c$$

FSI ?

$$\nu\, s_A \to \mu^- \mu^+ \nu_\mu\, s$$

- **Kaons in *e+p* at HERMES**
  - But.. fragmentation functions uncertainty

HERMES, PLB 666 (2008) 446

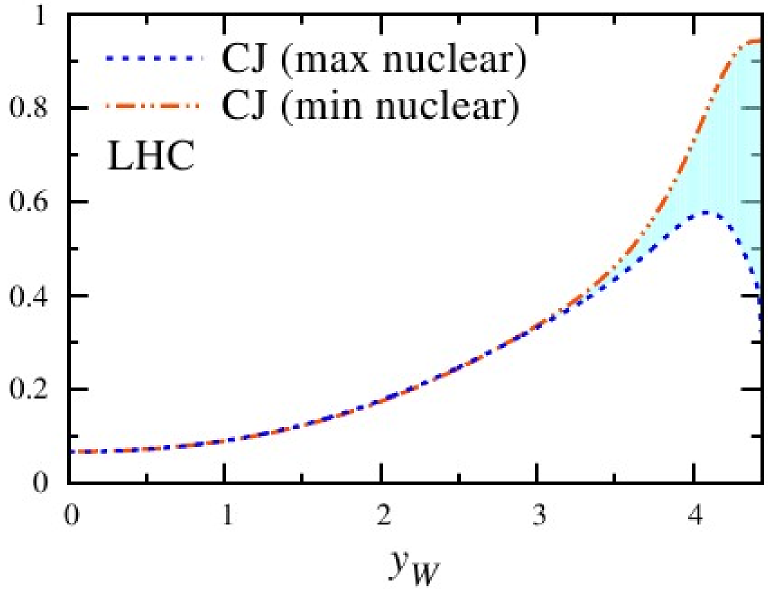


W charge asymmetry at LHC

Brady, Accardi, Melnitchouk, Owens, JHEP 1206 (2012) 019

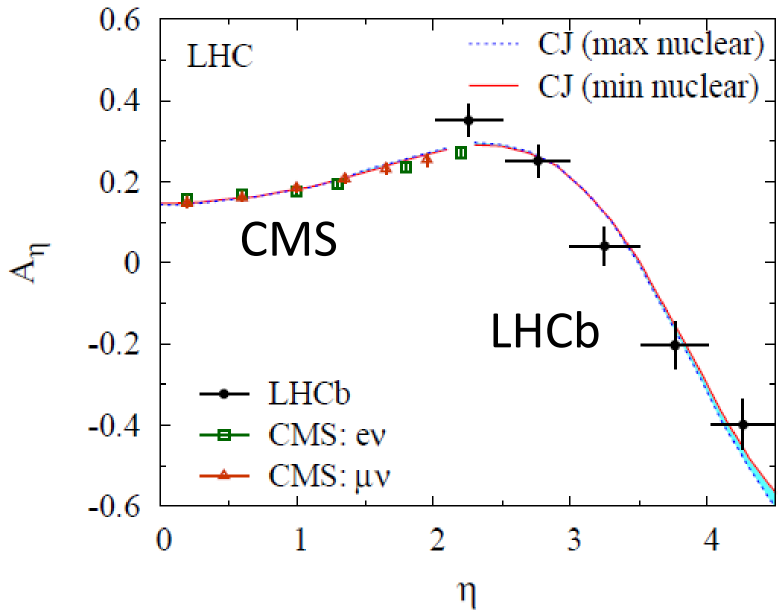
Directly reconstructed W:

- highest sensitivity to large *x*



From decay lepton W → l+ν:

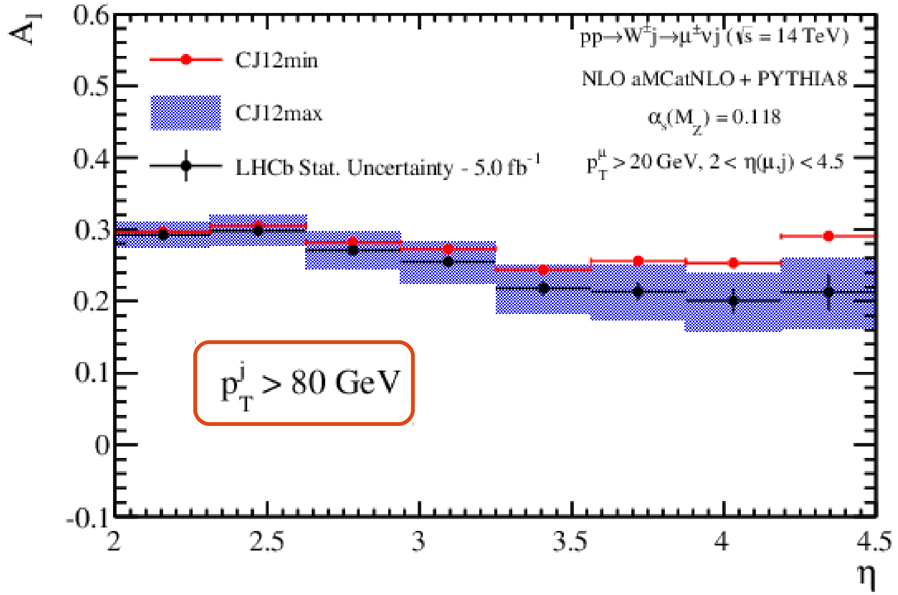
- smearing in *x*

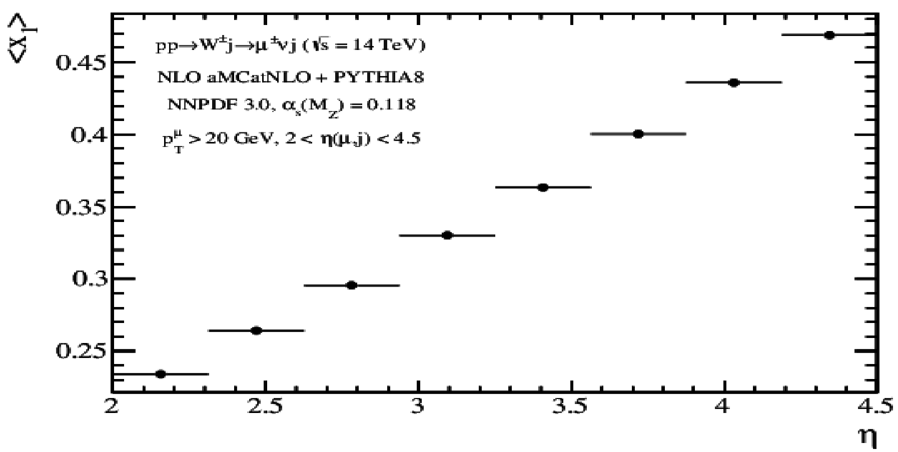


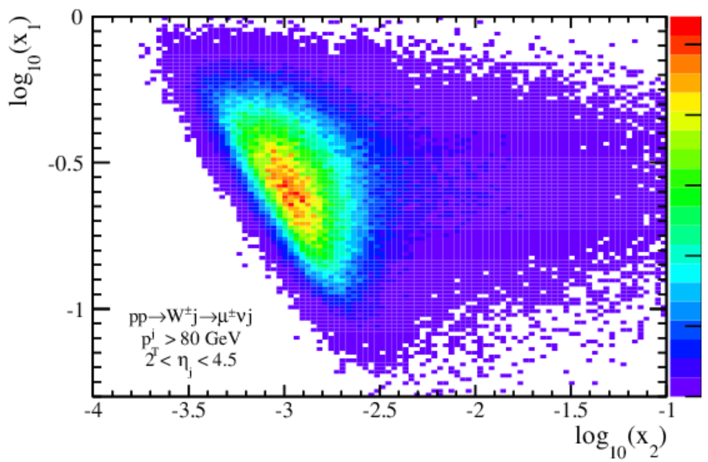
- **Would be nice to reconstruct *W* at**
  - **LHCb –** But I am told "too many holes"...
  - **RHIC –** how high in rapidity?
  - **AFTER@LHC ??**

W+c at LHCb

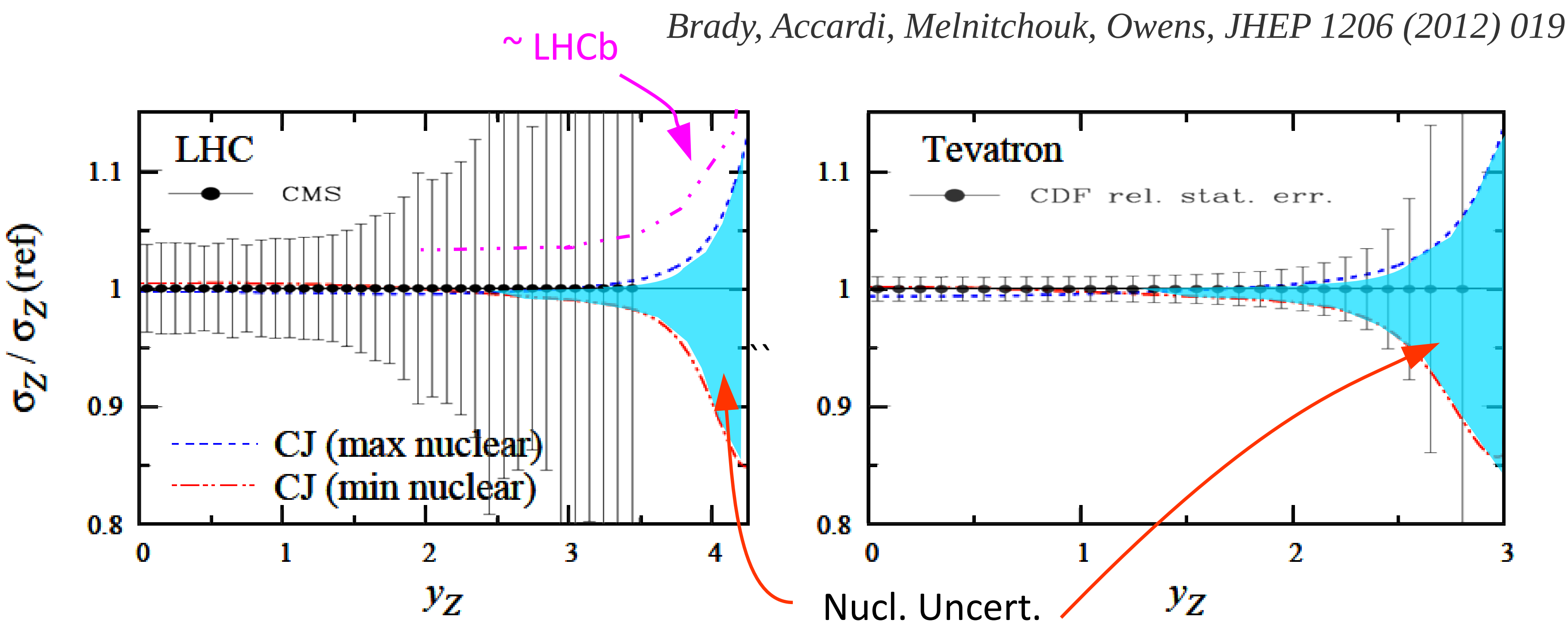
Farry and Gauld, PRD 93 (2016) 014008







Z rapidity distribution



- Direct Z reconstruction is unambiguous in principle, but:
  - **Needs better than 5-10% precision at large rapidity**
  - Experimentally achievable?
    - At LHCb? RHIC? AFTER@LHC?
    - Was full data set used at Tevatron?

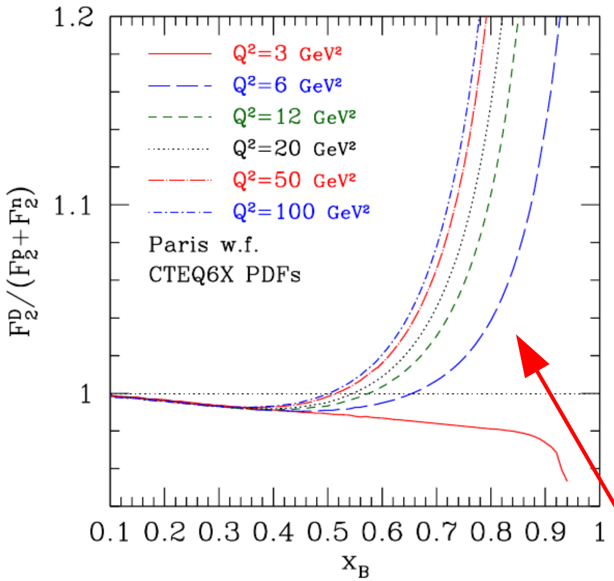
Appendix:
Nuclear corrections

CJ12 Deuteron corrections

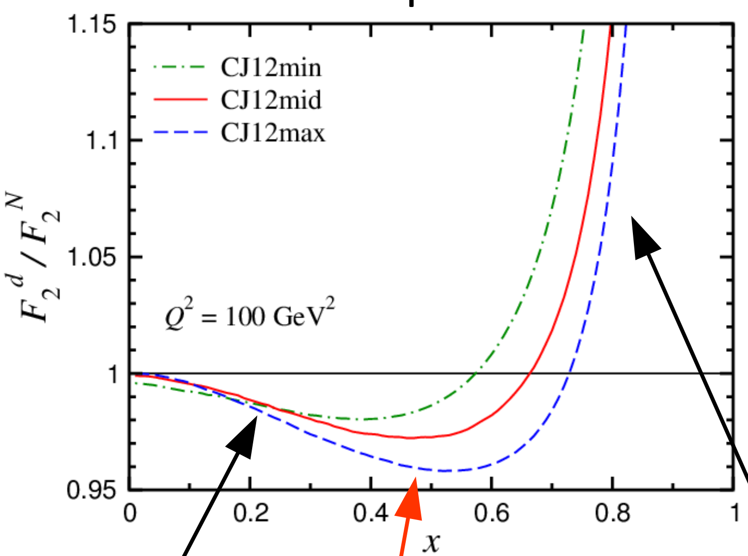
- No free neutron! Best proxy: Deuteron
  - Parton distributions (to be fitted)
  - nuclear wave function (AV18, CD-Bonn, WJC1, …)
  - Off-shell nucleon modification (model dependent)

} Theoretical uncertainty

$$F_{2d}(x_B, Q^2) = \int_{x_B}^{A} dy\, \mathcal{S}_A(y,\gamma) F_2^{TMC+HT}(x_B/y, Q^2) \left(1 + \frac{\delta^{off} F_2(x)}{F_2(x)}\right)$$



Bound vs. free proton+neutron



Strong Q^2 dependence at large x !

binding

off-shellness

Fermi motio

Nuclear corrections for p+d DY

Ehlers, AA, Brady, Melnitchouk, PRD90 (2014)

- Same nuclear model for DY cross sections

$$\sigma^{pd}(x_p, x_d) = \sum_N \int_{x_d}^{1} \frac{dz}{z} \left[f(z) + f^{(\mathrm{off})}(z)\, \delta\sigma^{pN}\left(x_p, \frac{x_d}{z}\right) \right] \sigma^{pN}\left(x_p, \frac{x_d}{z}\right)$$

Same as in DIS
(in Bj. limit)

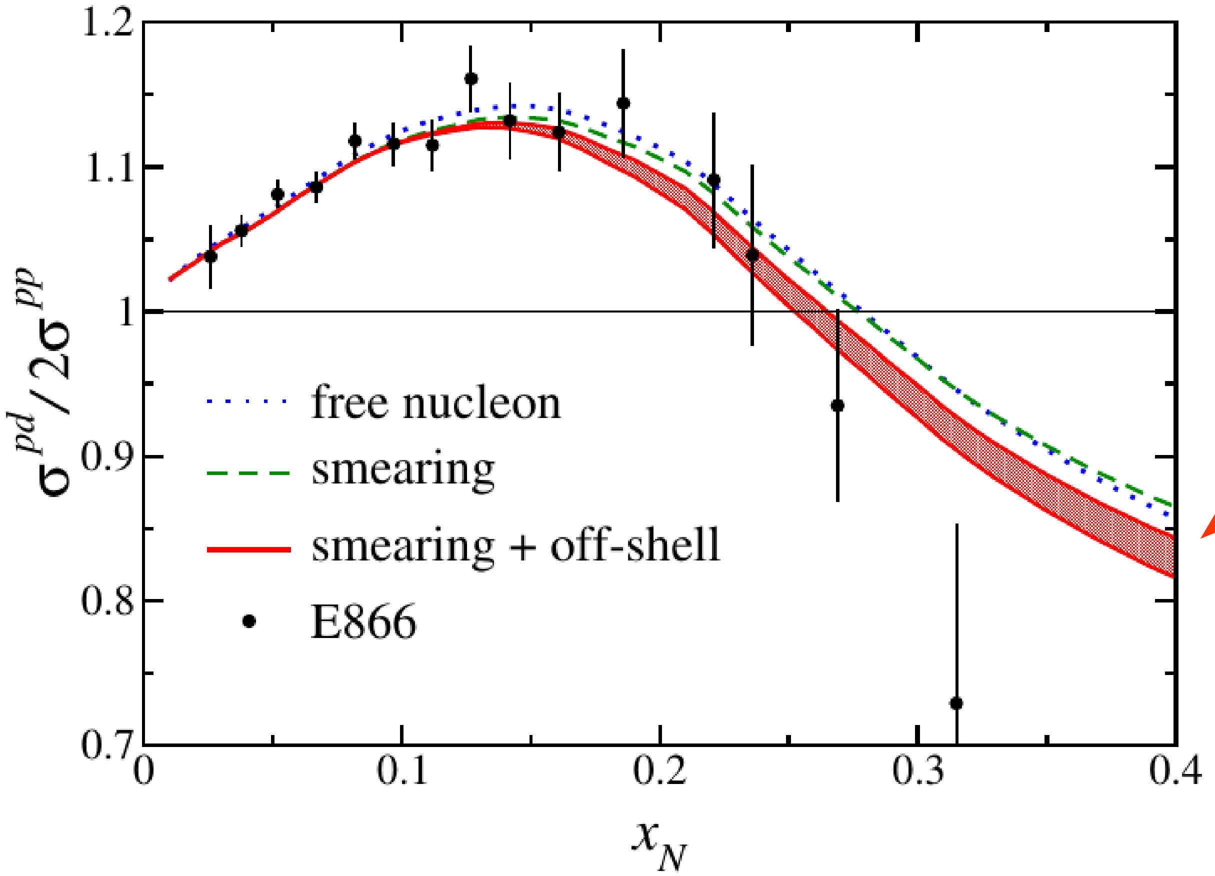
- Off-shell model extended to sea quarks and gluons
  - Spectral function in suitable spectator model

$$\widetilde{q}(x, p^2) = \int dw^2 \int_{-\infty}^{\hat{p}^2_{\max}} d\hat{p}^2\, D_q(w^2, \hat{p}^2, x, p^2)$$

- Pion-cloud effects also studied *Kamano, Lee, PRD86 (2012)*

Nuclear corrections…

Ehlers, AA, Brady, Melnitchouk, PRD90 (2014)

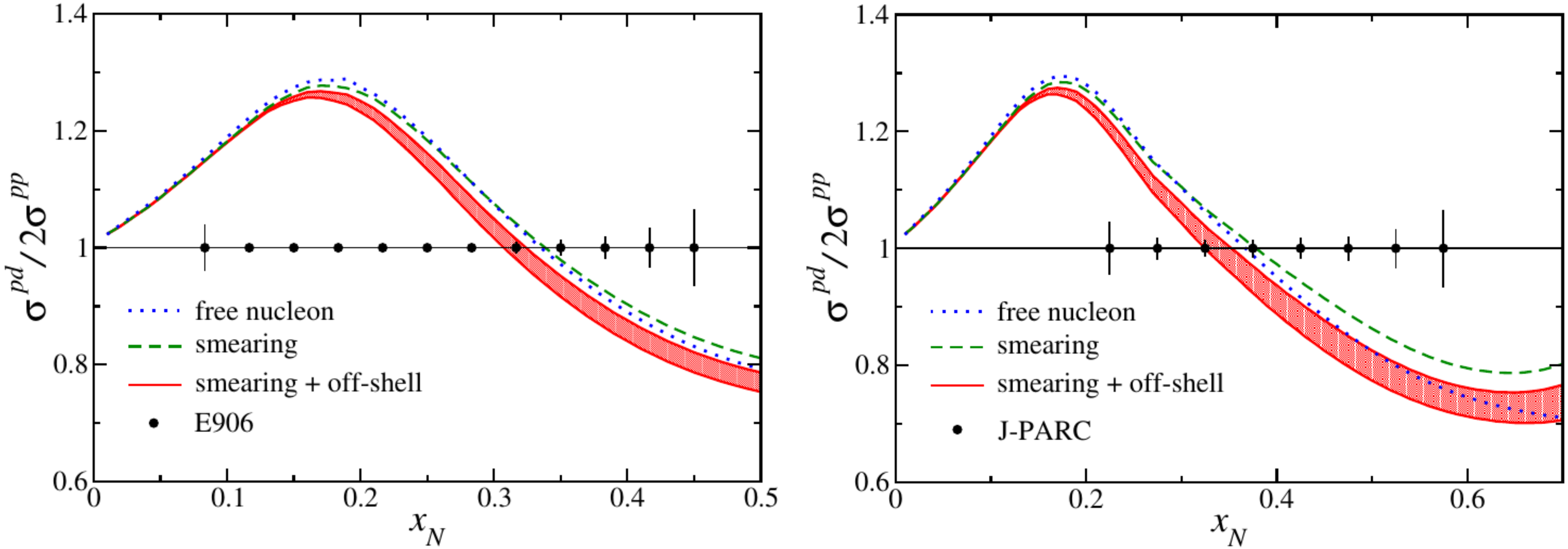


Red band: combined wave fn. & off-shell model uncertainty

- **Off-shell corrections help makes dbar-ubar stay positive**

Future DY reaches into large-x

Ehlers, AA, Brady, Melnitchouk, PRD90 (2014)



- **E906/Sea Quest:** off-shell effects even more important
- **J-PARC:** can cross-check nuclear smearing vs. DIS

Appendix: Large-x data

New Large-x data: a partial list

- **DIS data minimally sensitive to nuclear corrections**
  - DIS with slow spectator proton (BONUS / BONUS 12)
    - Quasi-free neutrons
  - ^{3}He/^{3}H ratios (Marathon)

- **Data on free (anti)protons, sensitive to *d***
  - *e+p*: parity-violating DIS **HERA** ***(e$^+$ vs. e$^-$), EIC, LHeC***
  - ν+*p*, $\bar{\nu}$+*p* : **ShiP, ELBNF Near Detector, MINERvA**
  - *p+p, p+p* at large positive rapidity
    - *W* charge asymmetry, *Z* rapidity distribution

Jlab

LHCb(?) RHIC !!
AFTER@LHC

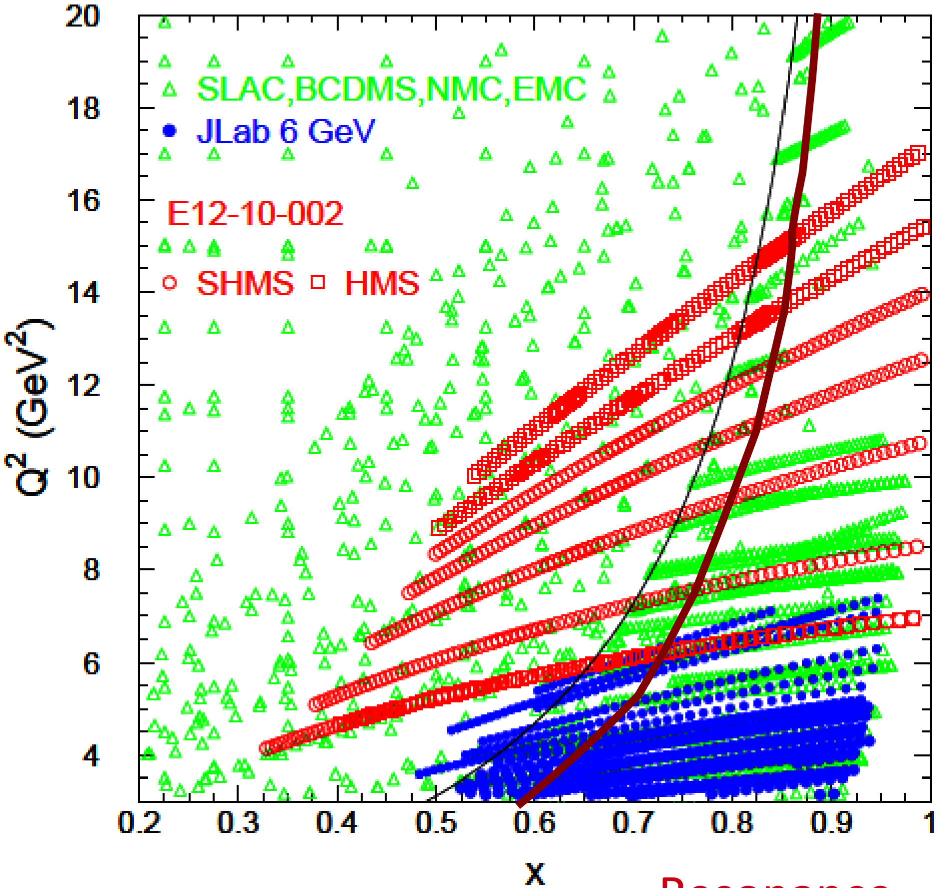
- **"Drell-Yan" data**
  - *Dimuons:* **E906, J-PARC (?)**
  - *p+d* at large <u>negative</u> rapidity – dileptons; *W*, *Z*
    - Sensitive to nuclear corrections, cross-checks *e+d*

RHIC ??
AFTER@LHC
…

JLab 12 - proton, deuteron structure functions

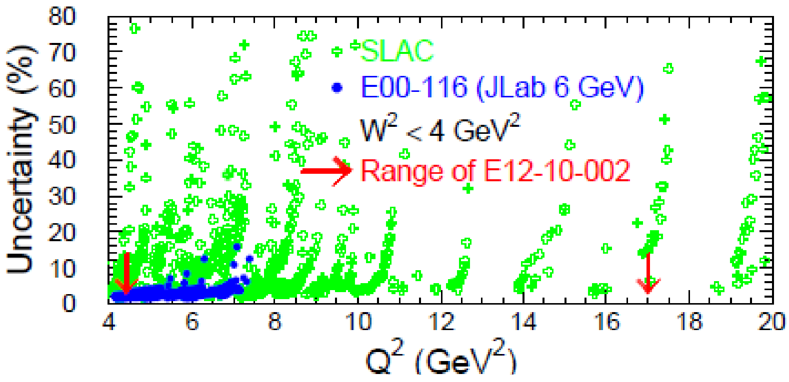
Jlab12 experiment E12-10-002

CJ cut: $W^2 > 3\ \mathrm{GeV}^2$



DIS region

Resonance region

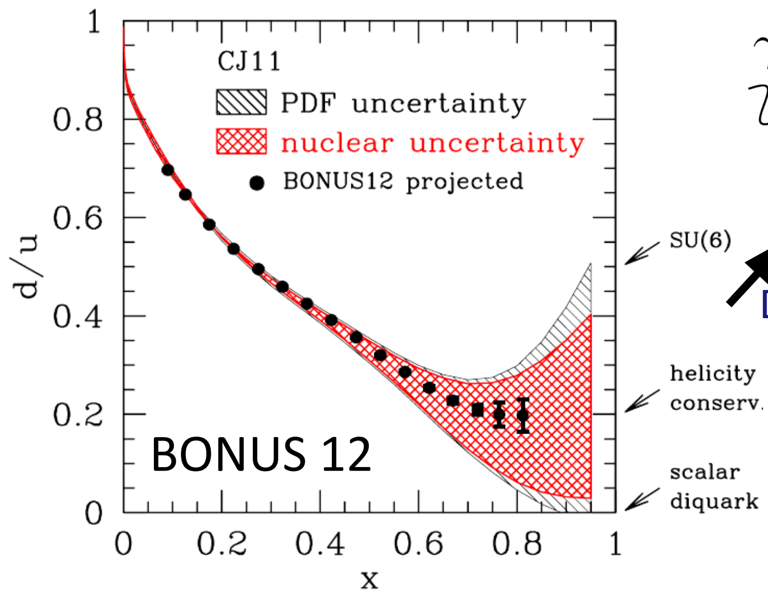


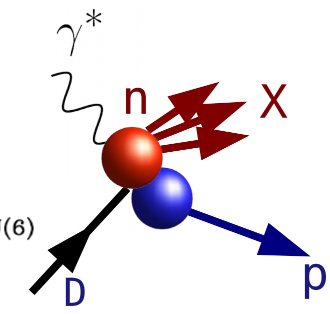
- **JLab 12 GeV**
  - More than double Q^2 range
  - Similar precision as JLab **6 GeV** (largely improve cf. **SLAC**)

JLab 12: Quasi-free neutrons for tomorrow

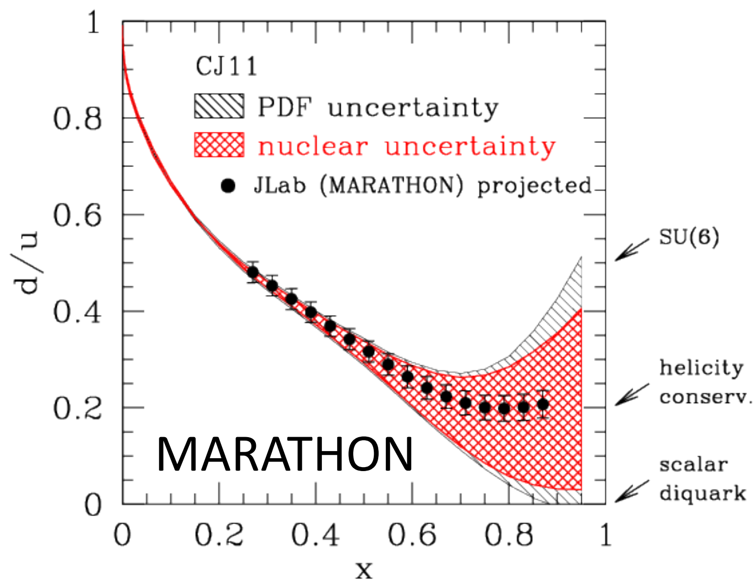
- Nuclear corrections largely cancel:
  - **Spectator tagging**
  - **$^3He/^3H$ cross sec. ratio**

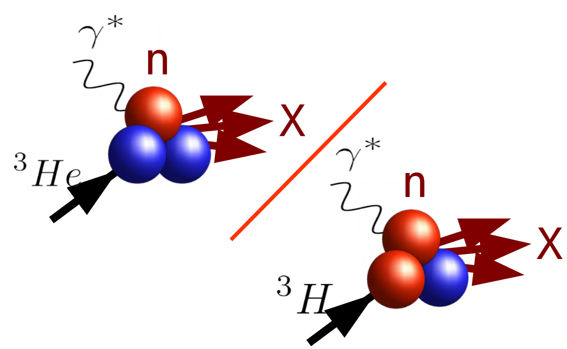
JLab E12-06-113





JLab E12-10-103



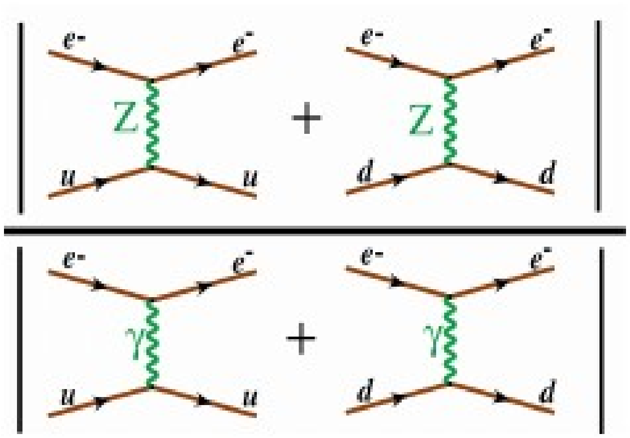


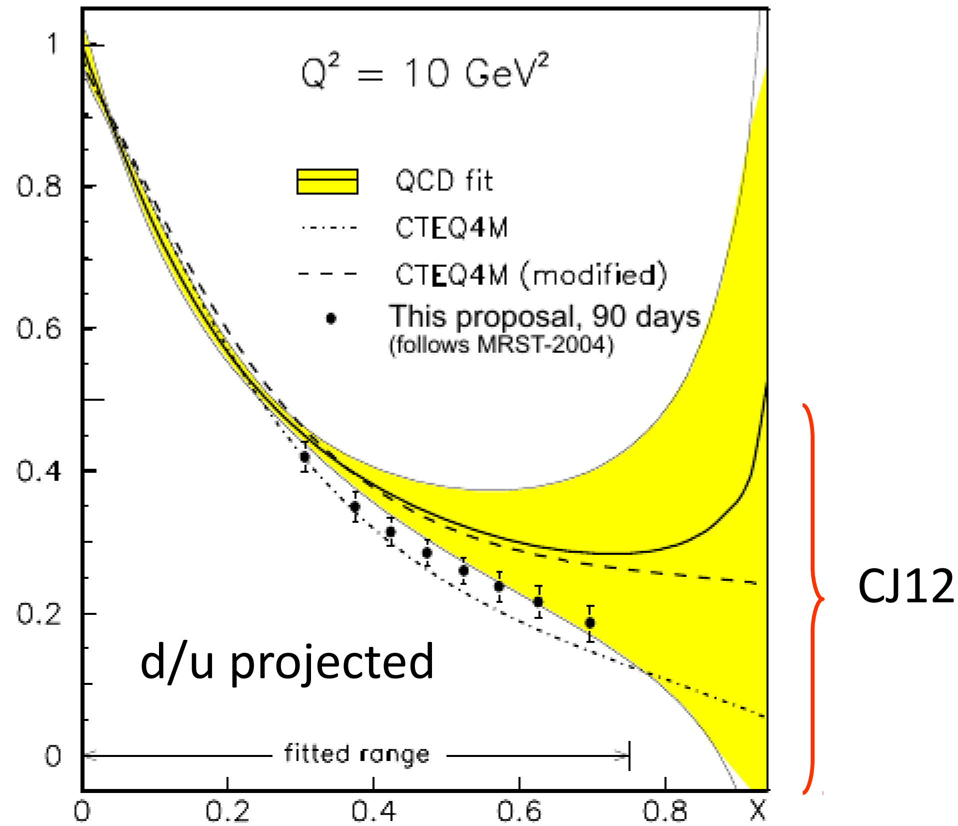
JLab 12: Parity-Violating DIS

Jlab12 experiment E12-10-007

- Longitudinally polarized electrons → PV asymmetry

$$A_{LR} = A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{\tilde{A}_Z}{A_\gamma}$$

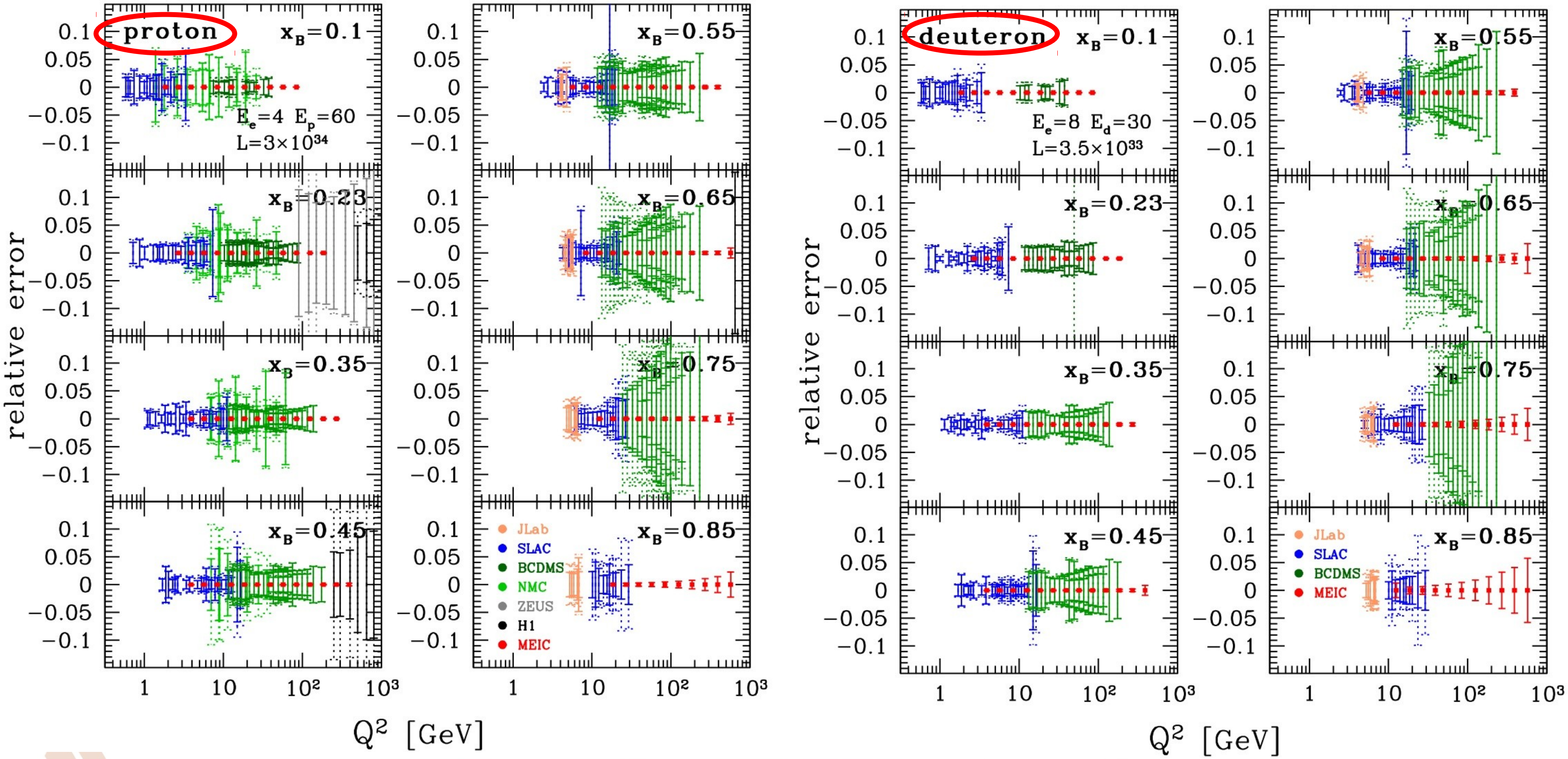




At the EIC

- **Neutral current DIS**
  - MEIC √s = 31 GeV (ca. 2010)
  - Pseudo data using "CTEQ6X" fits, L=230 (35) fb^{-1}

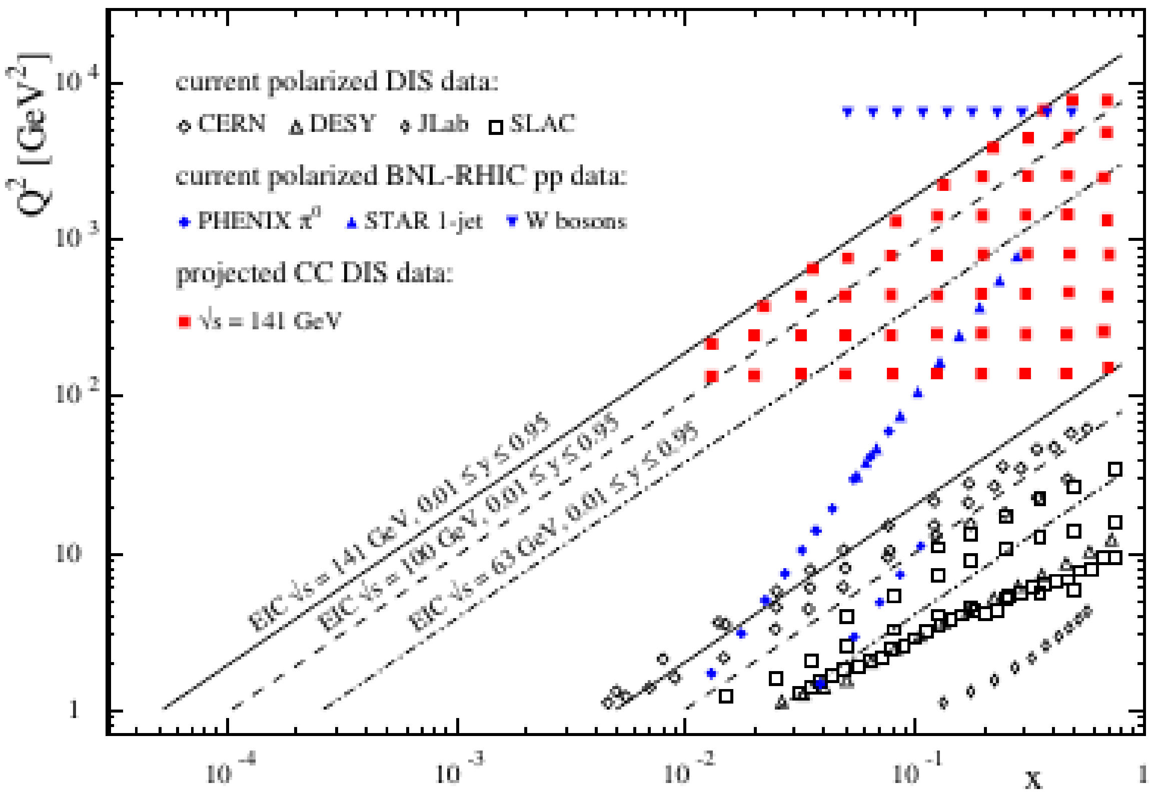
[Accardi, Ent, Keppel, 2010]



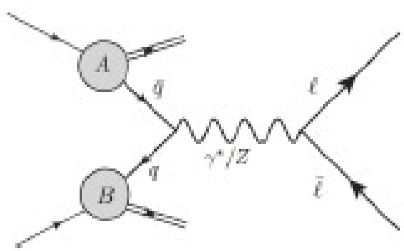
At the EIC

- **Charged current DIS**
  - plot for polarized scattering, similar for unpolarized
  - Not optimized at large-x: likely to add a bin around x = 0.85

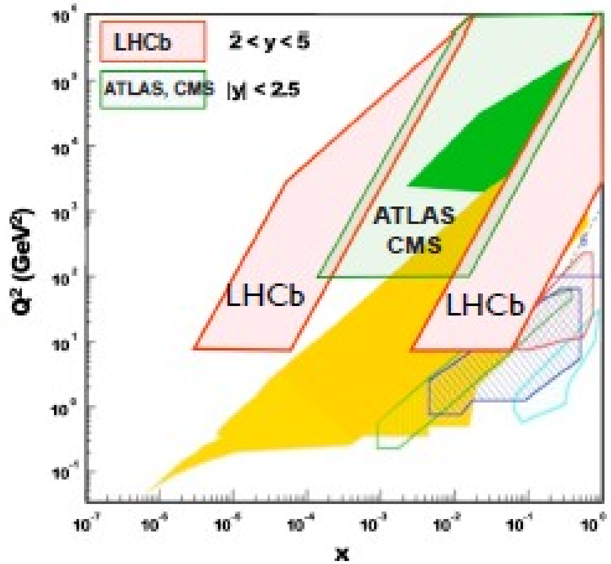
[Aschenauer et al, 2013]



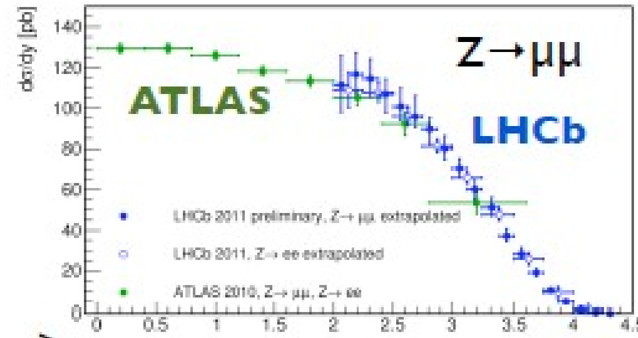
Constraints from the LHC: Electroweak Boson Production

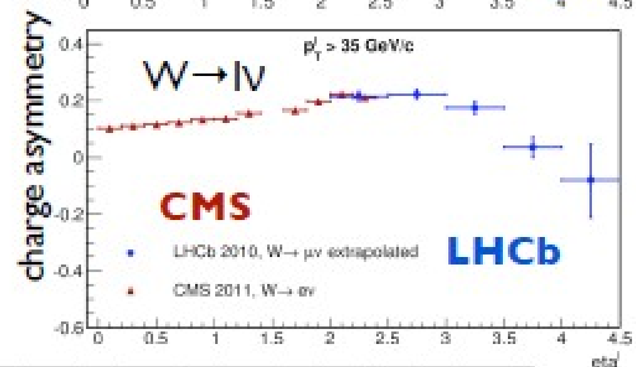


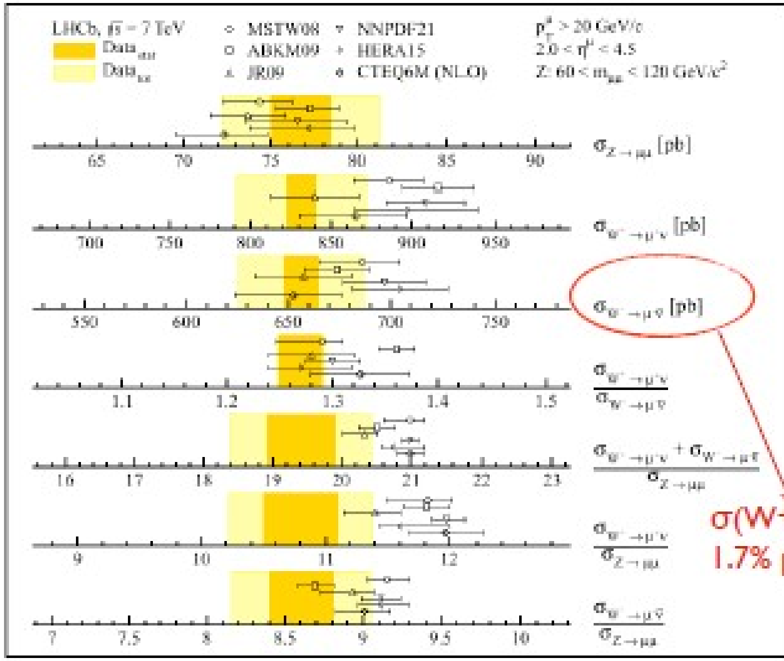
probe light quarks at low and high x



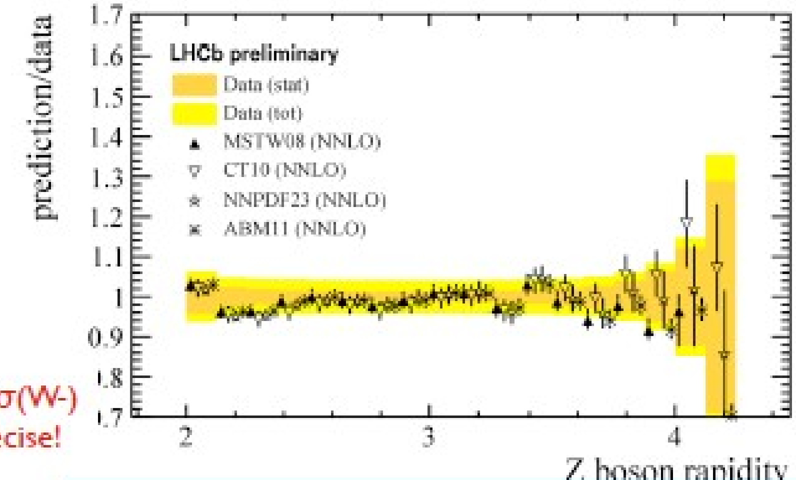
LHCb (S.Tourneur)







σ(W+)/σ(W-)
1.7% precise!



Systematic error comparable with PDF error
Benchmarking different PDF sets

K. Lipka, DIS’13 WG1 summary