CTEQ-Jlab PDFs, structure functions at large x

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Hampton U. and Jefferson Lab

CTEQ-Jefferson Lab Collaboration

Quark Hadron Duality Workshop

James Madison U., 24 Sep 2018

Overview

- **The CJ15 global QCD analysis**
  - Controlled PDFs and nuclear corrections at large x
- **Connection to quark-hadron duality**
  - What extrapolation curve should we use?
  - How can we "test" duality?
- **Concluding thoughts**
  - What do we need to use duality to probe large *x* parton structure?

REFERENCES**:**

* Accardi, **PoS DIS2015 (2015) 001** – "PDFs from protons to nuclei"

* Accardi et al, **PRD 93 (2016) 114017** – the CJ15 global fit

The CJ15 global QCD analysis

The CTEQ-JLab global analysis

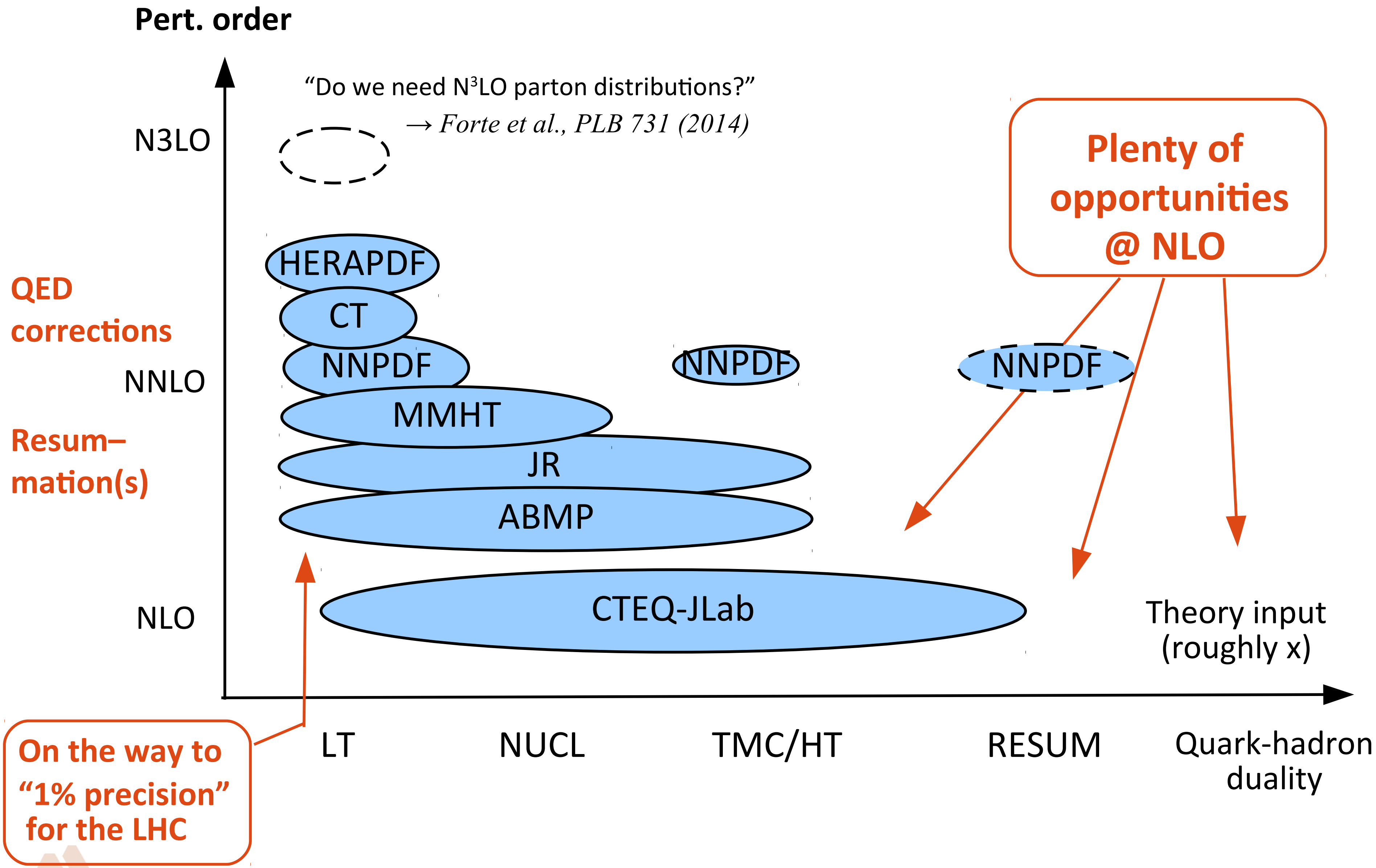
- **Collaborators:**
  - **Theory:** A. Accardi, W.Melnitchouk, J.Owens, N.Sato
  - **Experiment:** E.Christy, C.Keppel, P.Monaghan
- **All-*x* PDF global fits, focused on the "large" *x* region**
  - Maximize use of large-*x* data (esp. DIS)
  - Include all relevant large-*x* / small-Q^2 theory corrections
  - ***Quantitatively evaluate theoretical systematic errors***
  - ***Use PDFs as tools for nuclear and particle physics***
- **Latest public release: CJ15**
  - **Accardi, Brady, Melnitchouk, Owens, Sato,**
    PRD 93 (2016) 114017
    - www.jlab.org/cj
    - Included in LHAPDF

35+ years of unpolarized global PDF fits

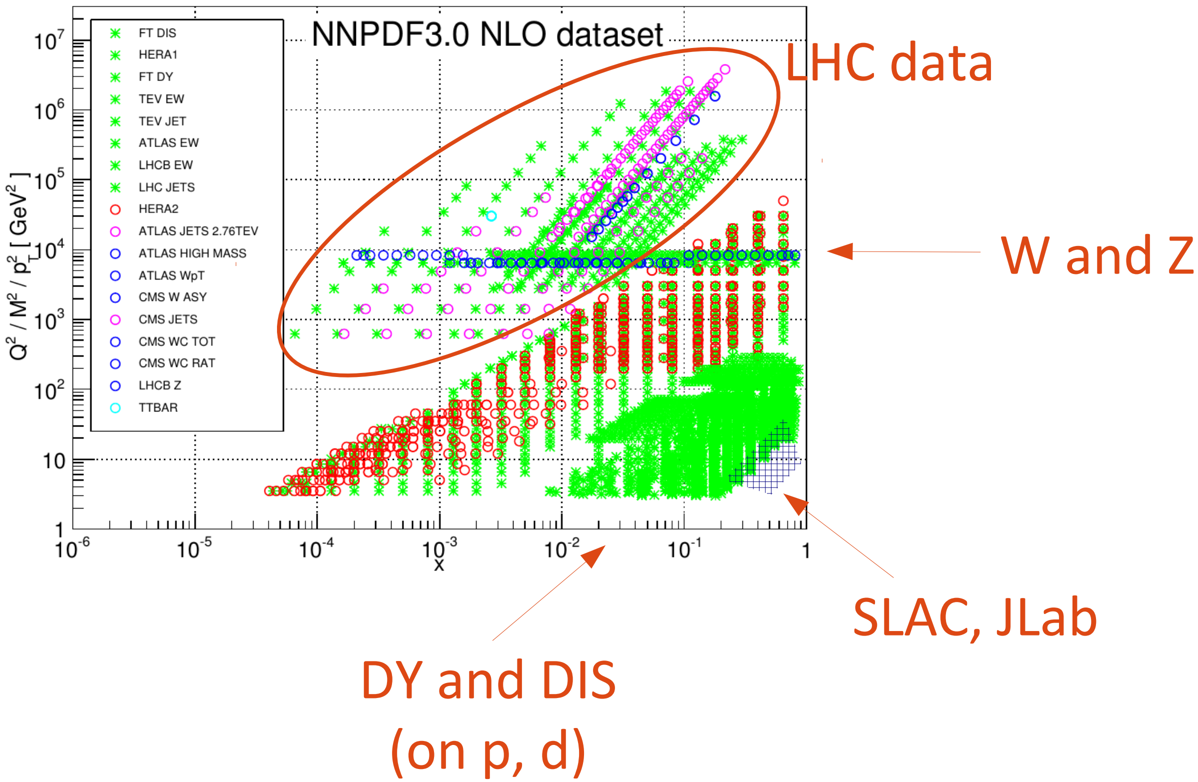
	JLab & BONUS	HER MES	HERA I+II	Tevatron new W,Z	LHC	ν+A di-μ	**Large-*x* treatment** Nucl.	HT TMC	Flex *d*	low-W DIS
CJ15 *	✓	✓	✓	✓	*in prog.*	✗	✓✓	✓	✓	✓
CT14			DIS 2016	✓ ¤¤	✓	✓			✓	
MMHT14			¤¤¤	✓ ¤¤	✓	✓	✓			
NNPDF3.1			✓		✓	✓		TMC only		
JR14	✓				✓	✓	✓	✓		
ABMP16/17 **				✓ ¤¤	✓	✓	✓✓	✓		✓
HERAPDF2.0			✓	¤						

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

A PDF landscape



Data coverage for PDF fits



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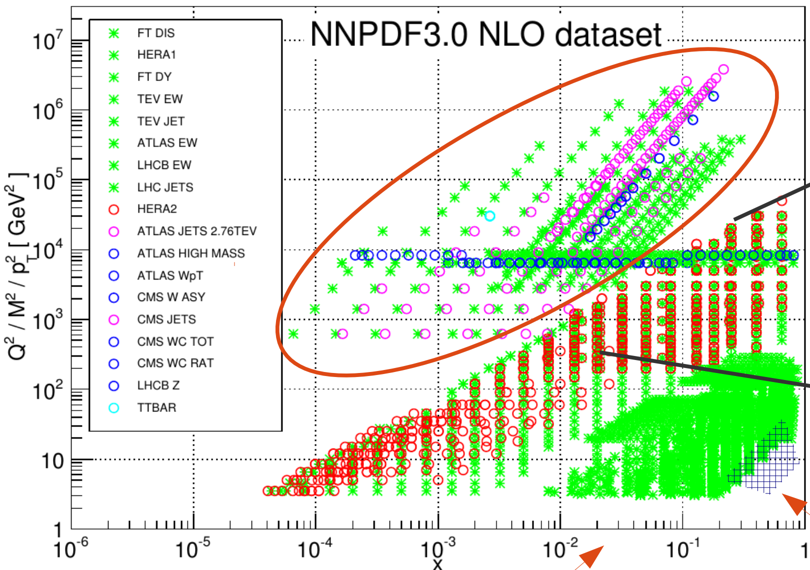
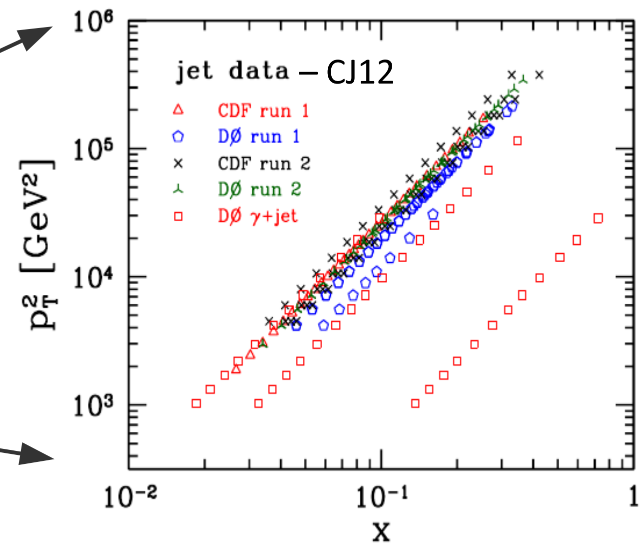


LHC data

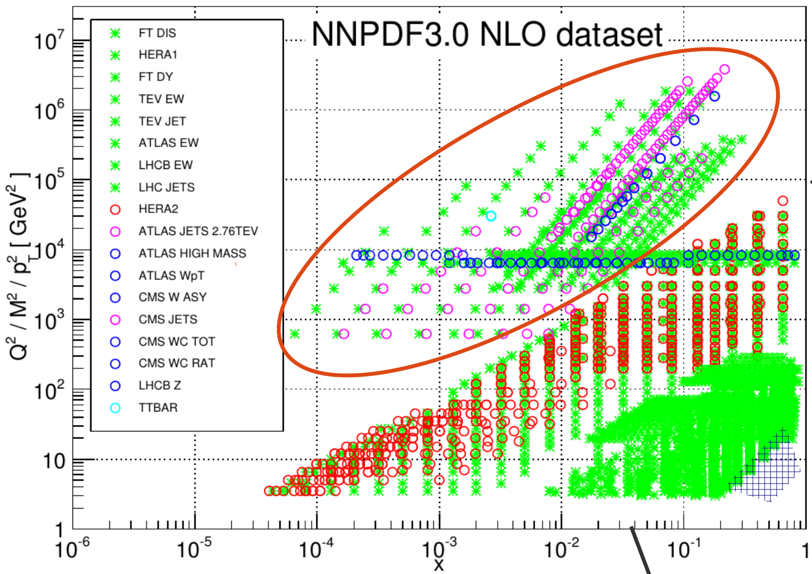
Tevatron Jets



SLAC, JLab

DY and DIS
(on p, d)

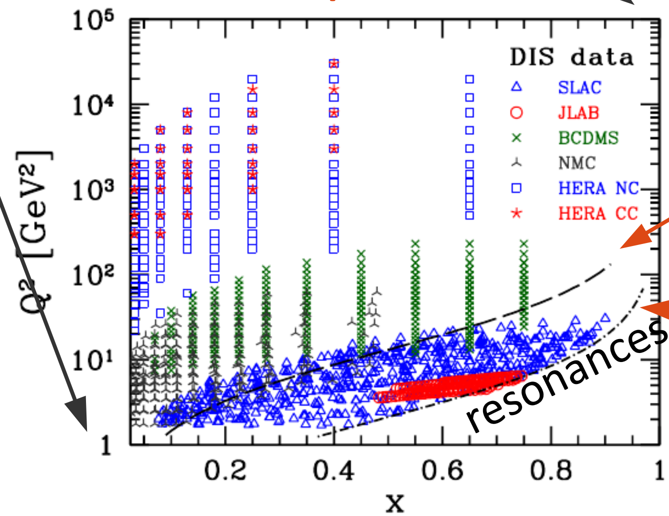
Data coverage for PDF fits



LHC data

Scant large-x coverage in DIS !

DIS – prot. & deut.



standard cut

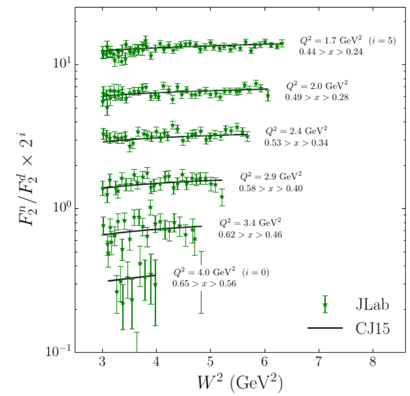
$W^2 \gtrsim 14\ \mathrm{GeV}^2$

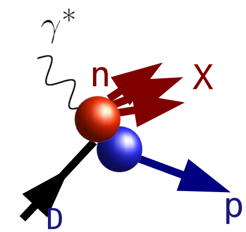
CJ15

$W^2 \gtrsim 3.5\ \mathrm{GeV}^2$

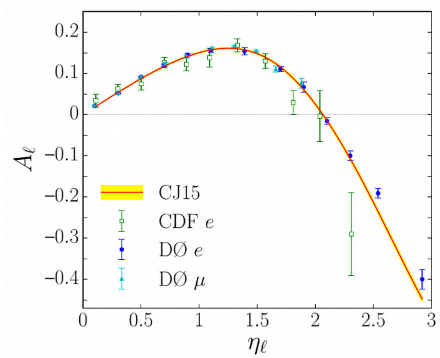
New in CJ15

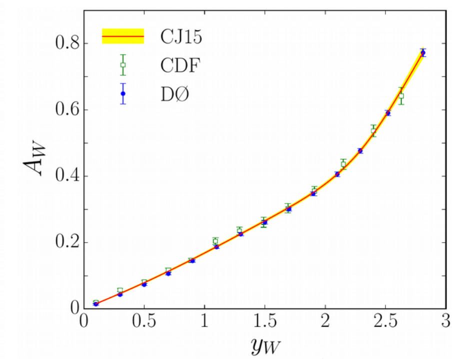
- s-ACOT scheme for heavy flavors

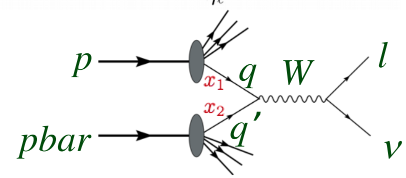


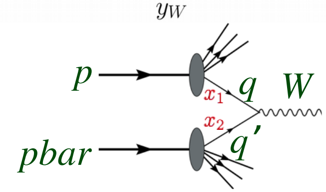


- **New data:**
  - BONUS spectator tagged DIS on neutrons
  - HERA I+II combination
  - HERMES F2
  - High-statistics W-boson charge asymmetries from D0



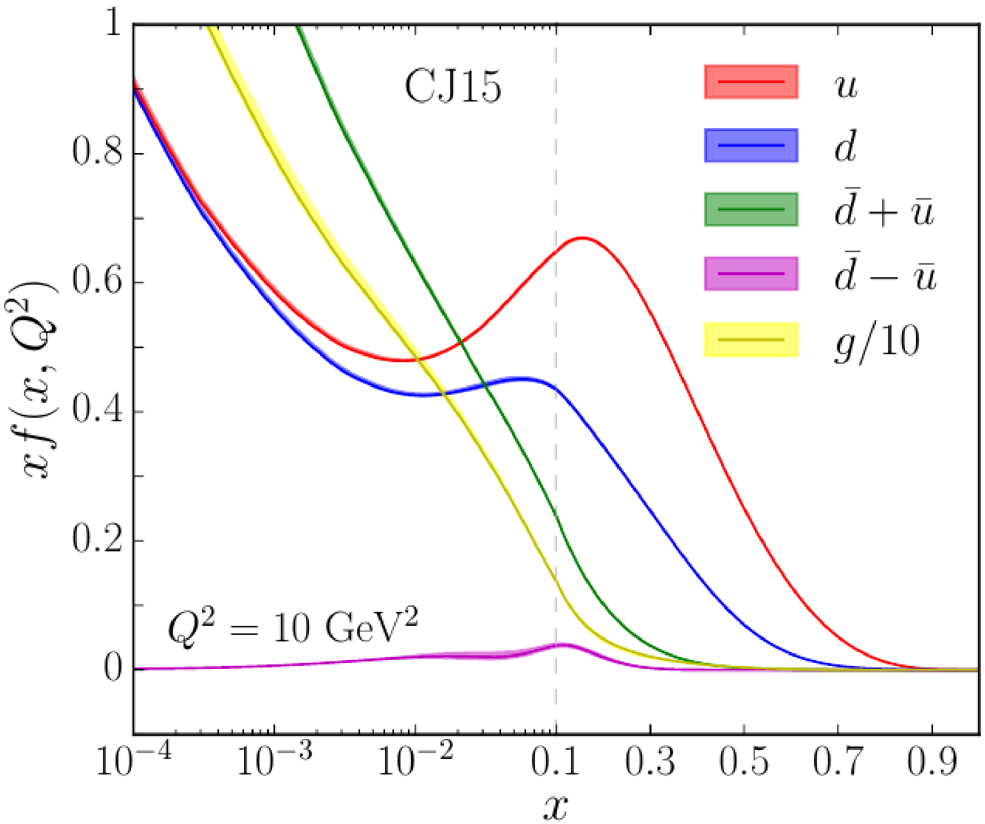






- **New off-shell nucleon treatment in deuteron targets (DIS and DY)**
  - Parametrized vs. modeled → absorbs wave function uncertainty
  - Comparison to extraction from DIS on heavier targets

CJ15 – PDFs



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

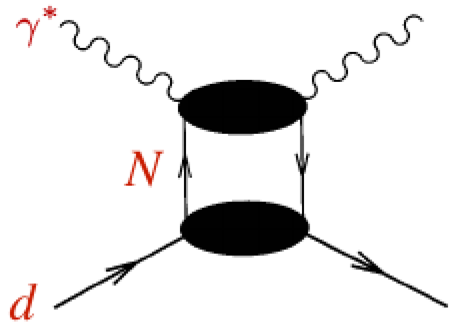
$$\Delta\chi^2 = 2.71$$

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

- Fitted with $\chi^2/\mathrm{datum} = 1.04$
- LO fit much worse – cannot accommodate Q^2 dependence of data

Nuclear corrections

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



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

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

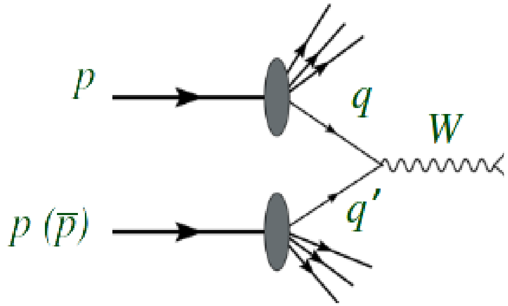
$$\tilde{q}^N(x,p^2) = q^N(x) \left[1 + \frac{(p^2 - M^2)}{M^2} \, \delta q^N(x) \right]$$

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

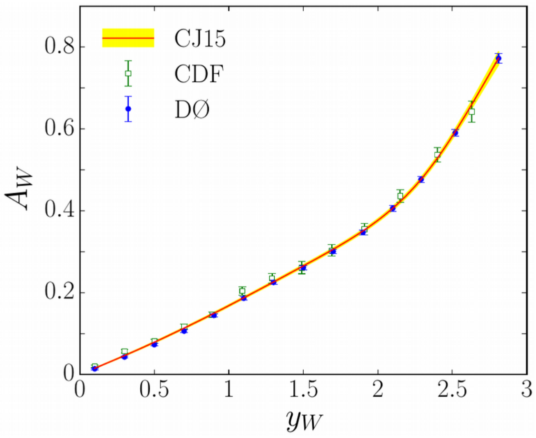
Tevatron as NUCL facility (!)

Accardi, Brady, Melnitchouk, Owens, Sato, PRD93 (2016) 114017

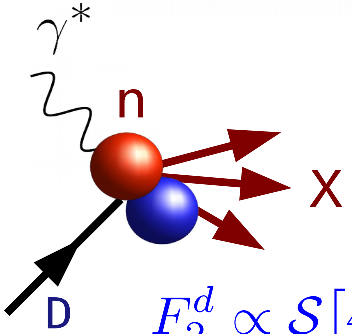
- ***Reconstructed W*** $\longrightarrow$ constrain ***d*-quark at largest x** on proton targets



$$A_W(y) \xrightarrow{y \to y_{max}} \frac{1 - d/u(x_1)}{1 + d/u(x_1)}$$



- Compare to abundant deuteron ***DIS data:***
  - $\longrightarrow$ constrain **deuteron corrections**
  - $\longrightarrow$ **precise *u, d*** flavor separation



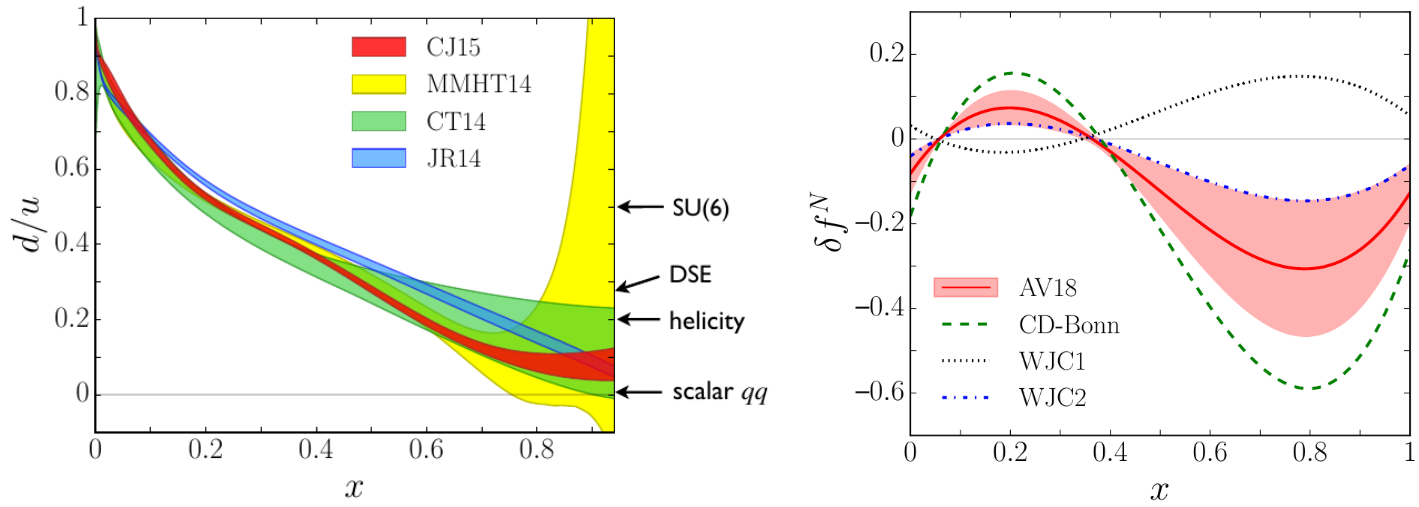
$$F_2^d \propto \mathcal{S}\left[4xu(x) + xd(x)\right]$$

- Currently, mostly a **DØ vs. SLAC(d) interplay**

Tevatron as NUCL facility (!)

Accardi, Brady, Melnitchouk, Owens, Sato, PRD93 (2016) 114017

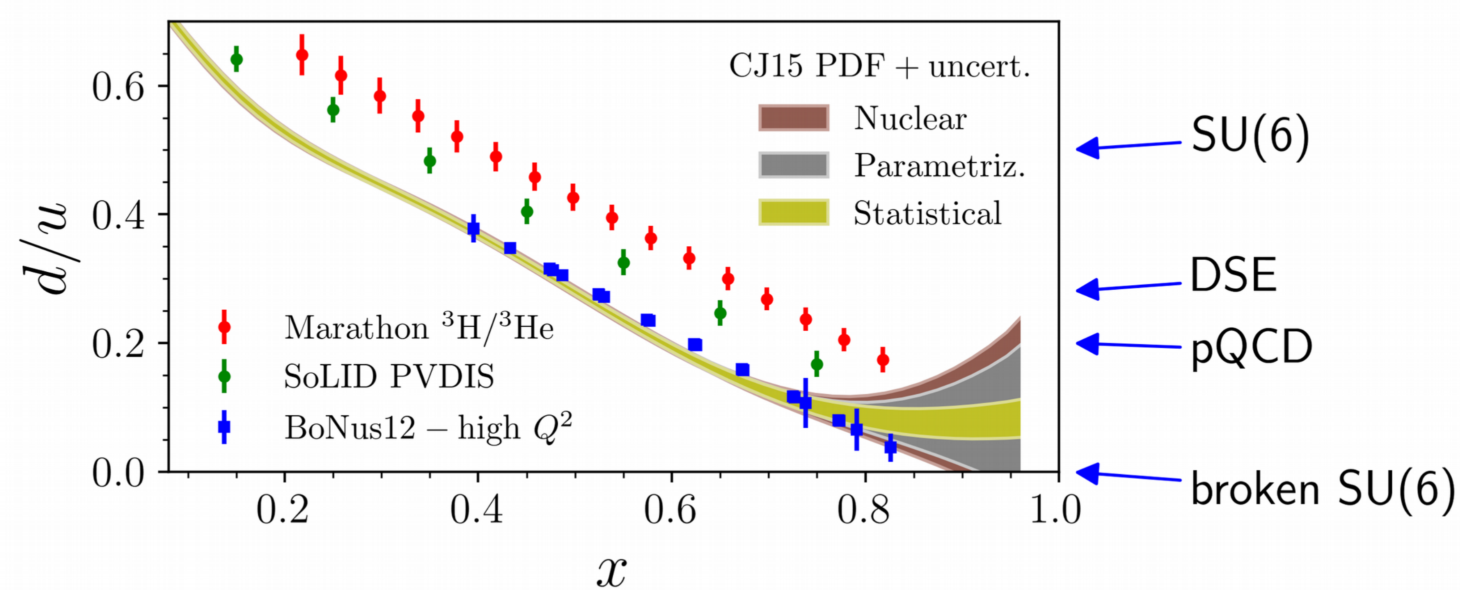
- **Universal fit: d/u and binding effects**
  - → confinement at large x (using flexible large-x d-quark)
  - → bound nucleon corrections in deuteron PDFs



- **Opens novel possibilities**: test nuclear theory ideas against <u>other</u> data:
  - Test "EMC effect" models (of course)
  - On the lattice: "nucleon response to external color field"
  - …

Summary: controlled PDFs at large x

- **CJ15 provides the most controlled large-x PDF fit on the market**
  - ABPM16 next-best choice / benchmark

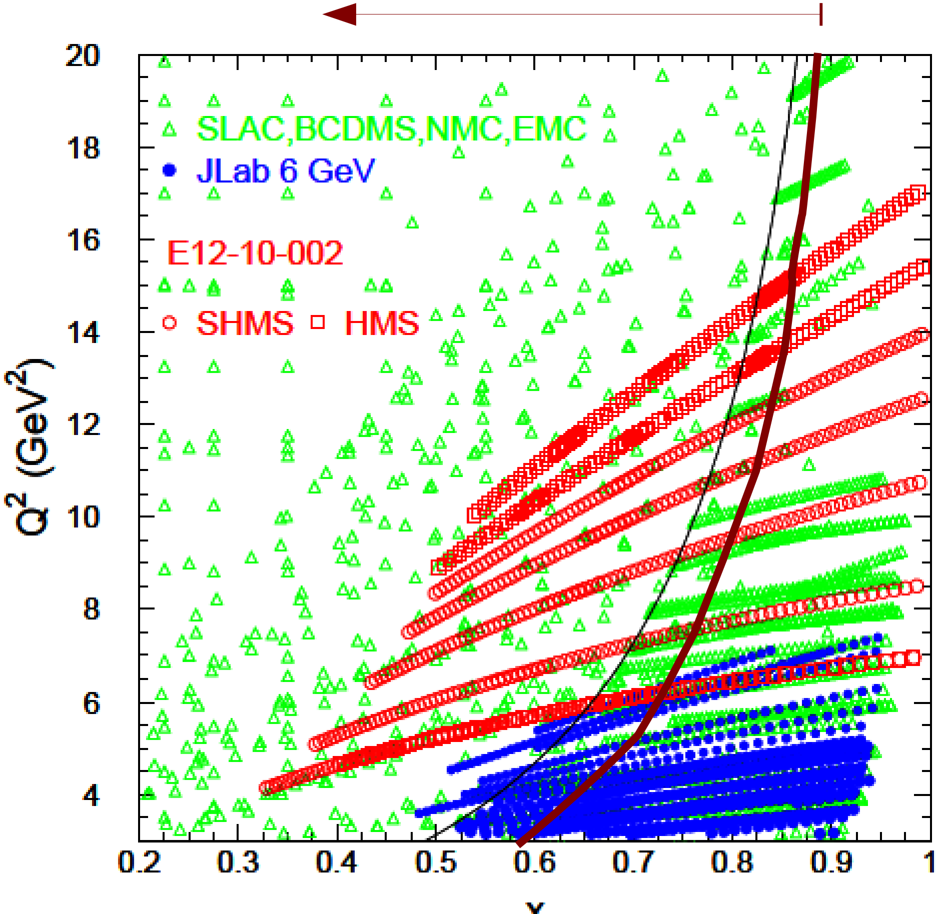


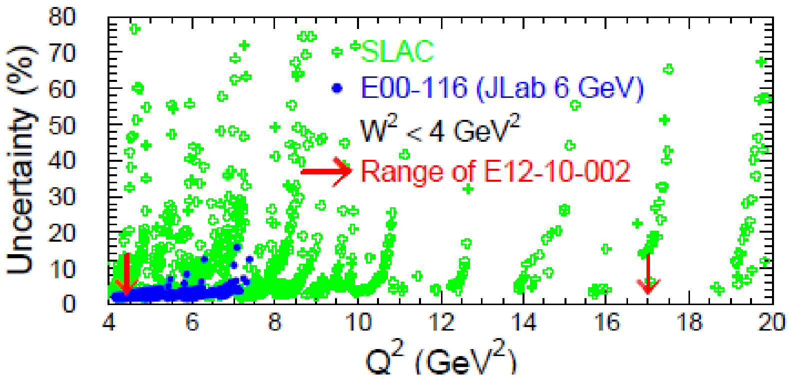
- Further progress needs **precise nucleus-free "control observables"...**
  - W asymmetry: RHIC
  - BoNus12, Marathon*, SoLID PVDIS
- **...and more p, d DIS**

JLab 12 - proton, deuteron structure functions

Jlab12 experiment E12-10-002

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



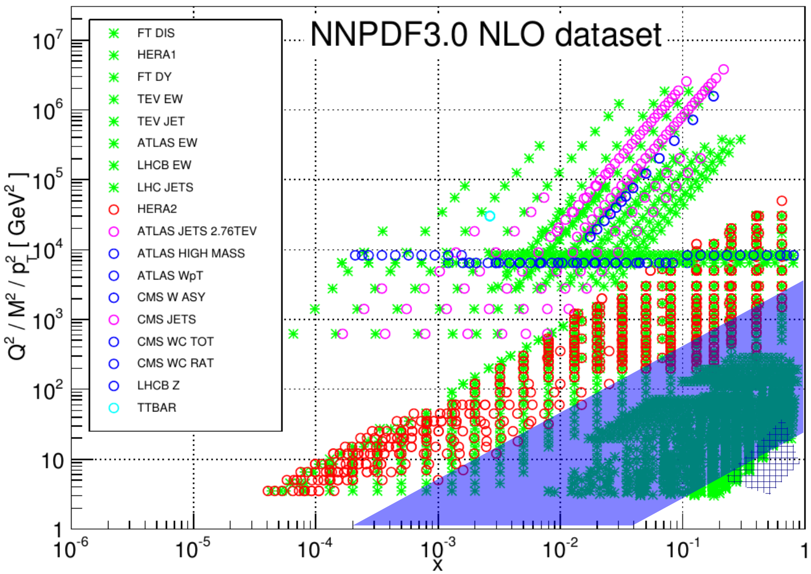


DIS region

Resonance region

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

Enters the EIC



- Interpolates fixed target and HERA
- Large Q^2 leverage
  - More evolution at large *x*
  - Better separation of LT and HT
- High luminosity → large *x* capabilities

→ EIC2 project under way (Hobbs, AA, Furletova, Yoshida)

- **Unique at the EIC**
  - “Easy” spectator tagging in DIS
    - Quasi-free neutron targets; neutron tagging ⟶ check vs real free *p*
    - Strong PID capabilities ⟶ F_2^c, F_2^{cc}, ...
  - High luminosity ⟶ CC, PVDIS ⟶ d/u, strange quarks, dbar/ubar, ...
  - Unpolarized & polarized scattering (also light ions)

Connections
to Quark Hadron Duality

Structure functions for QHD studies

- **Question:**

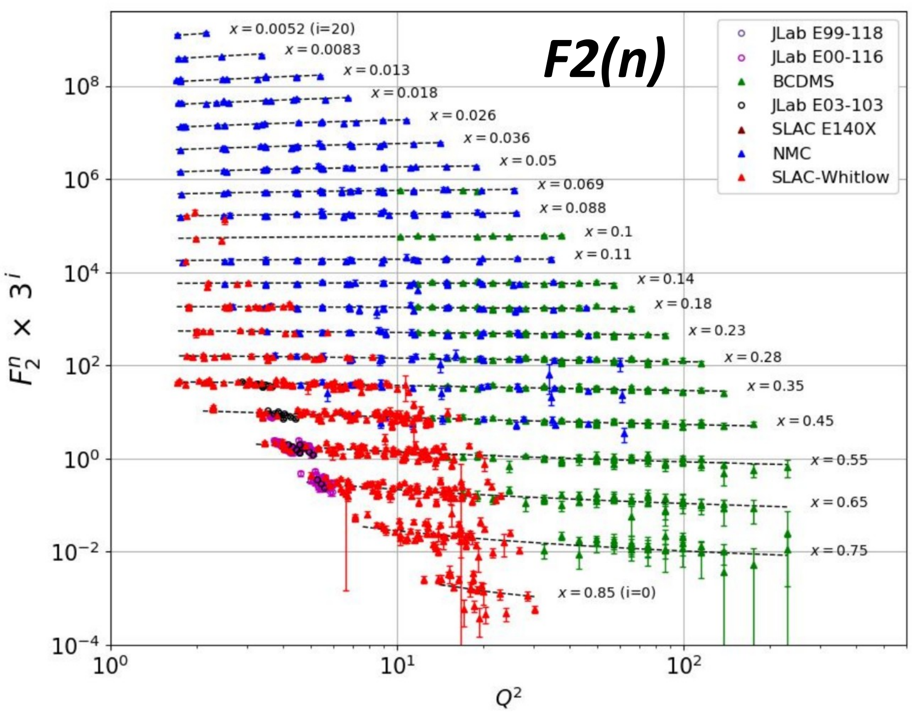
  "What DIS → resonance extrapolation curve should we use?"

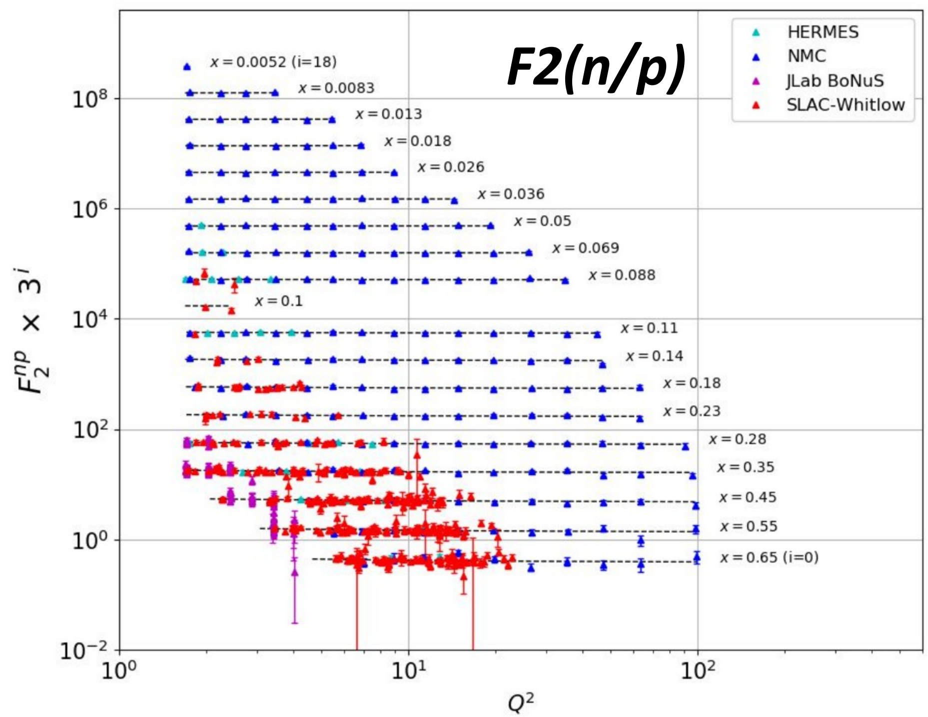
  – ***Answer: CJ15****, of course!*
  – Provide a controlled extrapolation from pQCD regime
  – Best available theory corrections: nuclear, HT, TMCs
  – DIS data as close as possible to resonance region

- **CJ15 structure functions soon publicly available**
  – I can give you **F2 p, d, and n** right now
    - 3 sets: LT, with TMC+HT, fully corrected
  – F2 uncertainties need some debugging
  – FL, F3, PVDIS in "near future"
    - Help is very welcome!

Neutron DIS "data" for QHD studies

- **F2(neutron) extraction –** *with Shujie Li*
  - Take F2(p) and either F2(d), F2(d/p), or F2(n/d) data
  - Apply CJ15 nuclear corrections
  - *Extract **F2(n) or F2(n/p)***





Neutron DIS "data" for QHD studies

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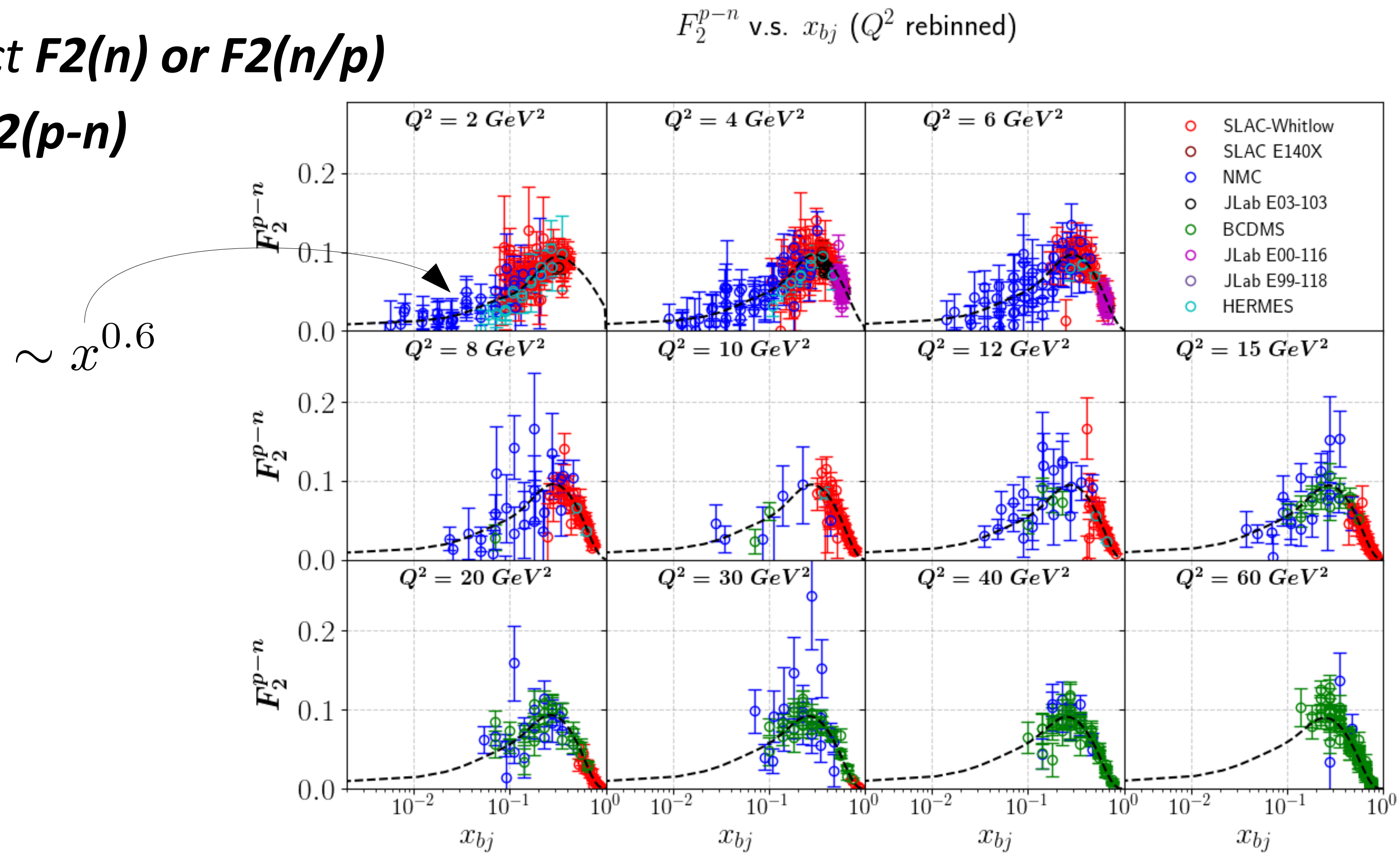
  - Apply CJ15 nuclear corrections
  - *Extract **F2(n) or F2(n/p)***
  - And ***F2(p-n)***



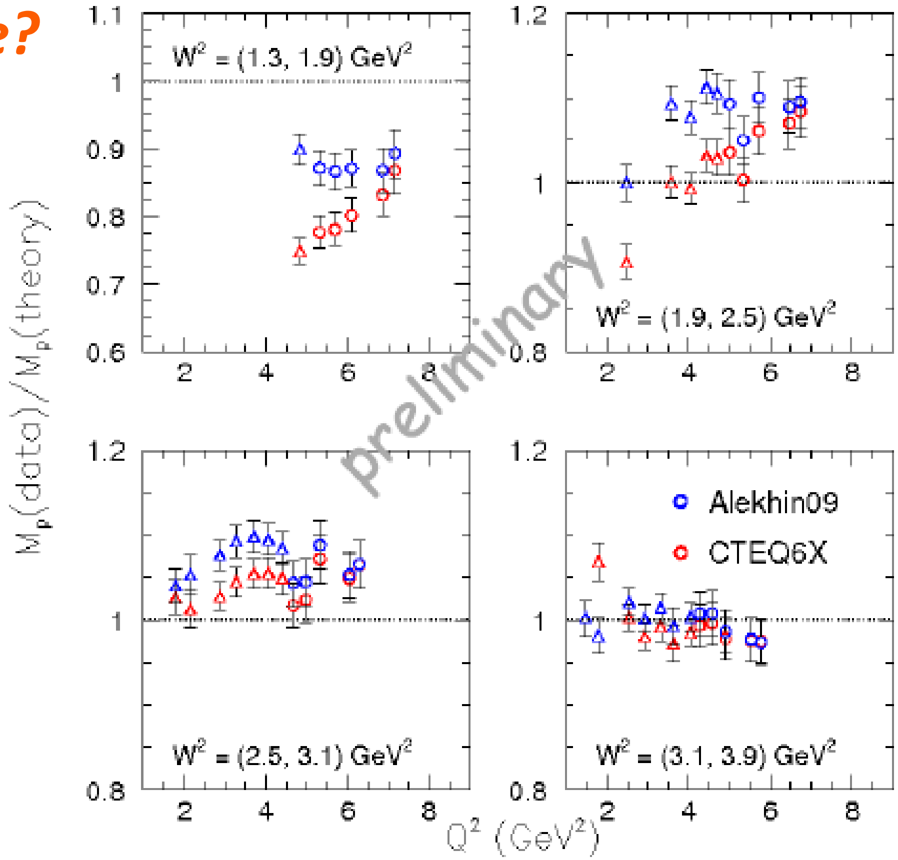
Further questions

- **Question:**

  What / how should we integrate?

  – Region by region?

AA, AIP Conf.Proc. 1369 (2011)
→ in collaboration with S.Malace

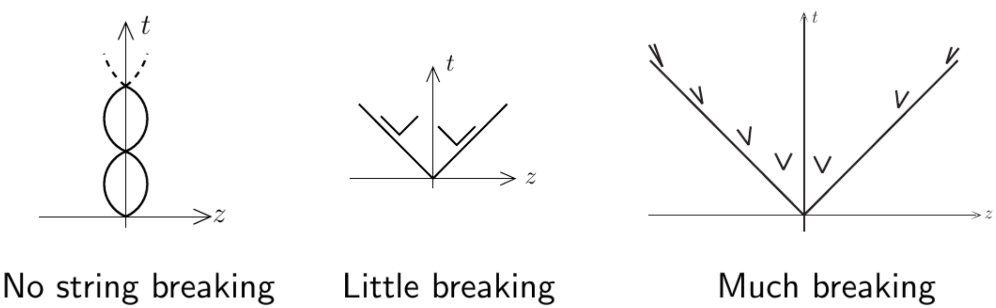


Further questions

- **Question:**

  What / how should we integrate?

  – Cut out data where struck quark "too close" to target remnant?



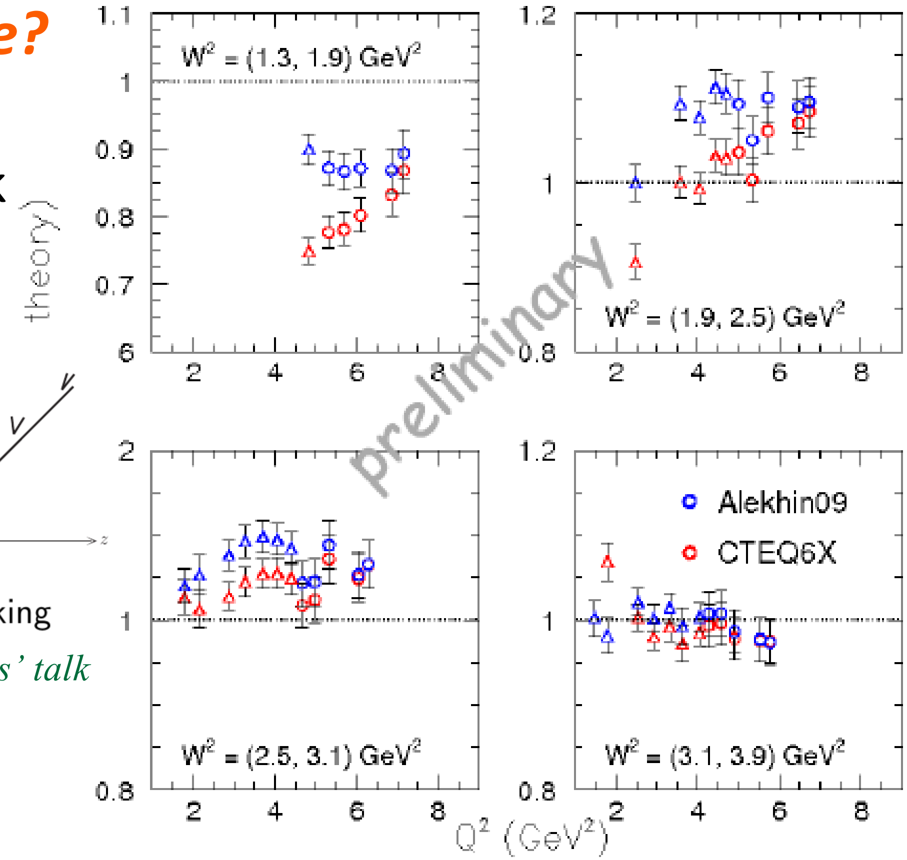
→ *Collins' talk*

  – How?

    → *e.g.*, use "Berger's criterion"

Berger, ANL-HEP-CP-87-045 (1987)
Mulders, hep-ph/0010199

AA, AIP Conf.Proc. 1369 (2011)
→ in collaboration with S.Malace



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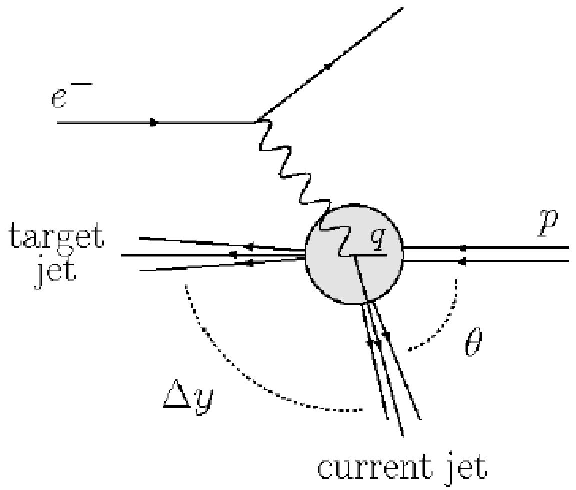

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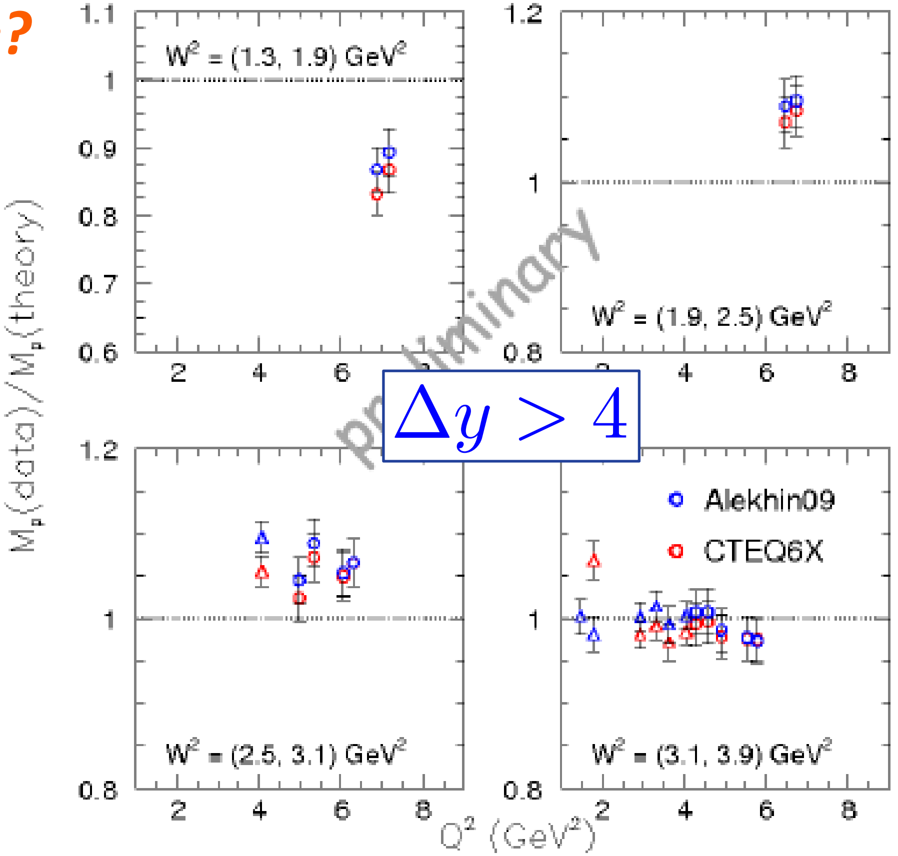

$$\Delta y \approx y_q - y_p = \ln \frac{2\sqrt{2}\nu}{Q} \frac{1}{\sqrt{1 - Q^2/(2MxE)}}$$

$$y = \frac{1}{2} \ln(p^+/p^-)$$

Further questions

- **Question:**

  To what extent does duality work?

  What does "work" mean??

- **Global QCD analysis can help:**
  - Extensive old/recent/upcoming data in resonance region
  - **Average the way you want**
  - **Calculate in pQCD (+TMC+HT+…) the same way**
  - **Put in CJ15 fits:**
    - Tension with higher Q2 DIS data?
    - Tension wit non-DIS data?
    - Do we need more theory input?
  - **Find what "works" and what does not**

Concluding thoughts

A question (or two) to rule them all

- ***What do we need in order to use duality as a tool for large x ?***
  - **A reliable extrapolation from DIS to resonance region**
    - Well constrained PDFs
    - Evaluation of theoretical systematics
    - Theory corrections to structure functions

    → **CJ15 fits the bill !**
  - **Tests of duality**
    - averaging procedures, regions of integrations
    - Right theory corrections, additional cuts (e.g., Berger criterion)

    → **QCD global analysis as a tool**
- ***What other questions do we need to ask to "understand" duality ?***

Backup

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

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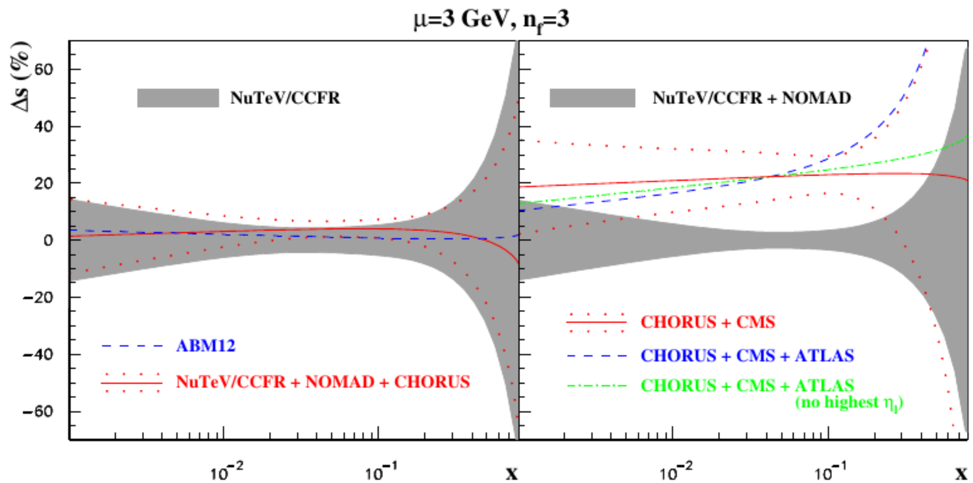
	DØ (W) [19]	14	39	**14**	15	82
Z rapidity	CDF (Z) [90]	28	100	**27**	27	26

- 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**

Example 2: strange strange quarks

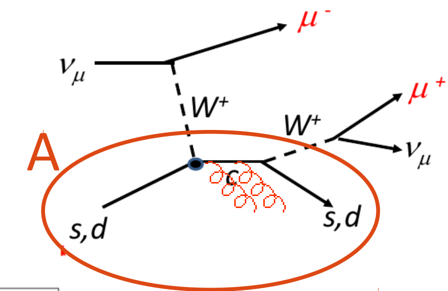
- **ν+*A* → dimuons** *vs.* ***p+p* → *W+c* at LHC** *Alekhin et al., arXiv:1404.6469*



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

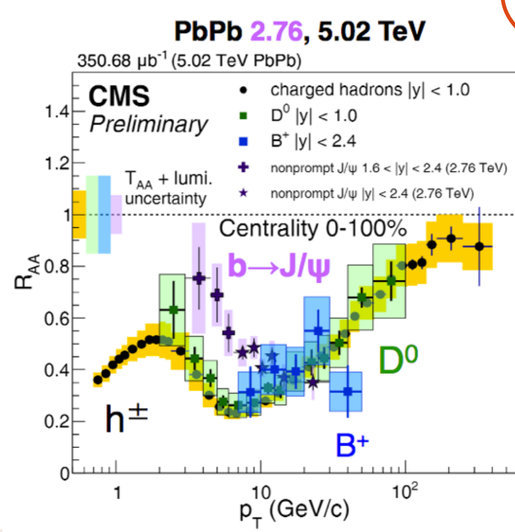
$$\nu\, s_A \to \mu^- \mu^+ \nu_\mu\, s$$

FSI ?



- **Heavy quark puzzle at RHIC / LHC:**
  - Color propagation in QCD matter not under theoretical control!

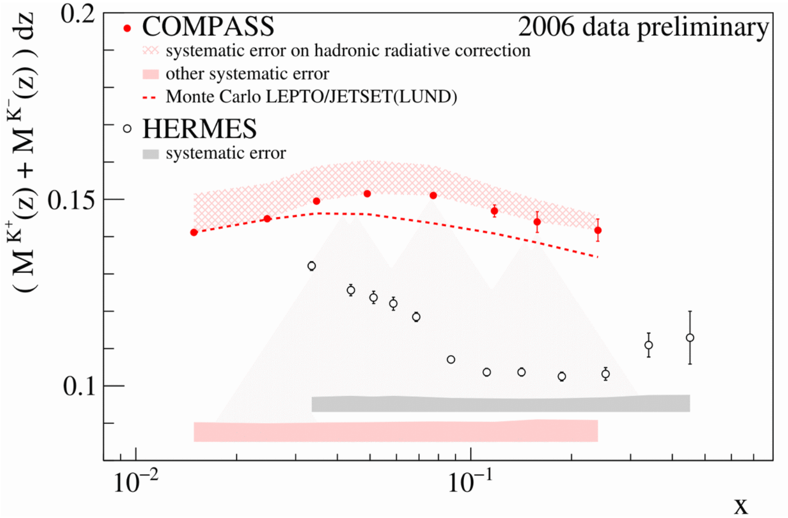
$$R^h_{AA} = \frac{\left(dN^h/d^2p_T\right)_{AA}}{N_{col} \times \left(dN^h/d^2p_T\right)_{pp}}$$



Yen-Jie , Quark Matter 2017

Example 2: strange strange quarks

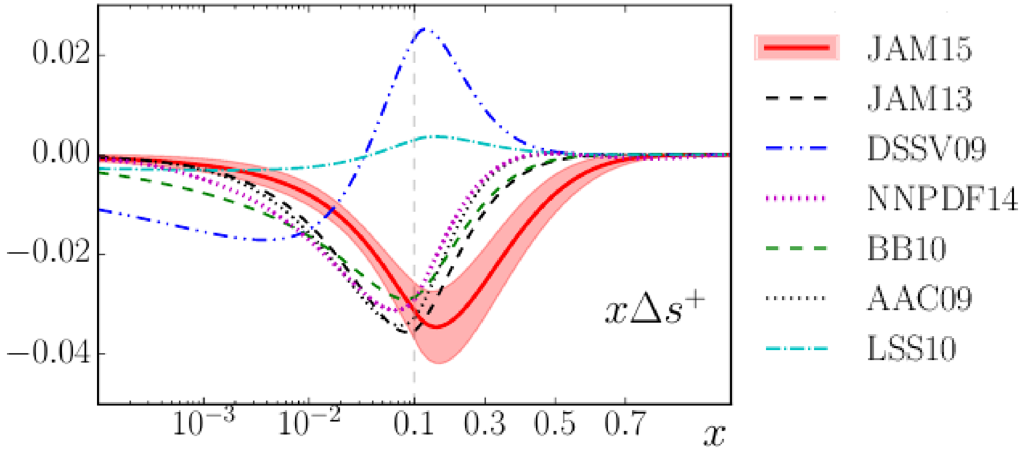
- **s : large or small?**
  - Possibly, large Hadron Mass effects
    Guerrero, Accardi, in preparation
  - Extraction of s(x) strongly affected by **kaon <u>systematic</u> uncertainty**



- **Δs : positive or negative?**
  - Depends on **kaon FF used in SIDIS calculations!**
    LSS, PRD 84&91

$$A_1^h(x,z,Q^2) = \frac{g_1^h(x,z,Q^2)}{F_1(x,z,Q^2)}$$

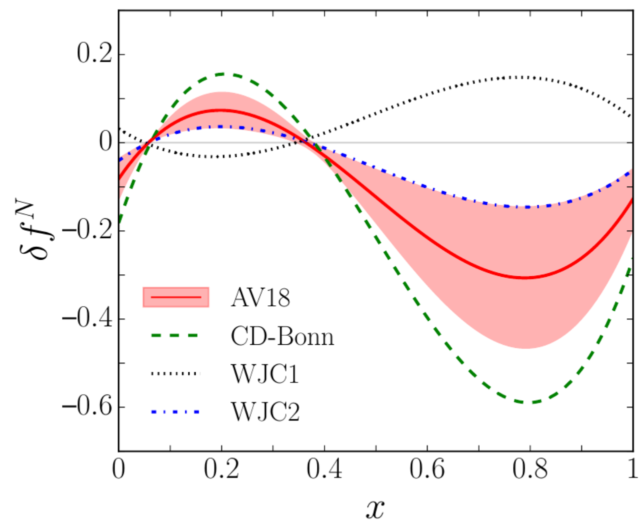
  - What about the unpol s ?

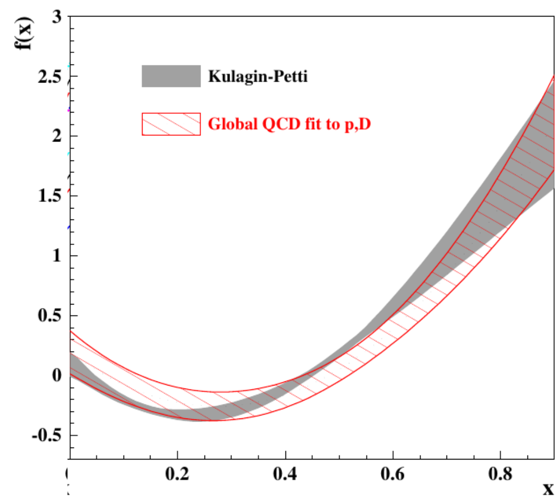


Appendix:
Nuclear corrections

Nuclear physics output

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





Kulagin, Petti,
NPA 765 (2006) 126

Alekhin + KP
PRD96 (2017) 054005

- Different shape and size

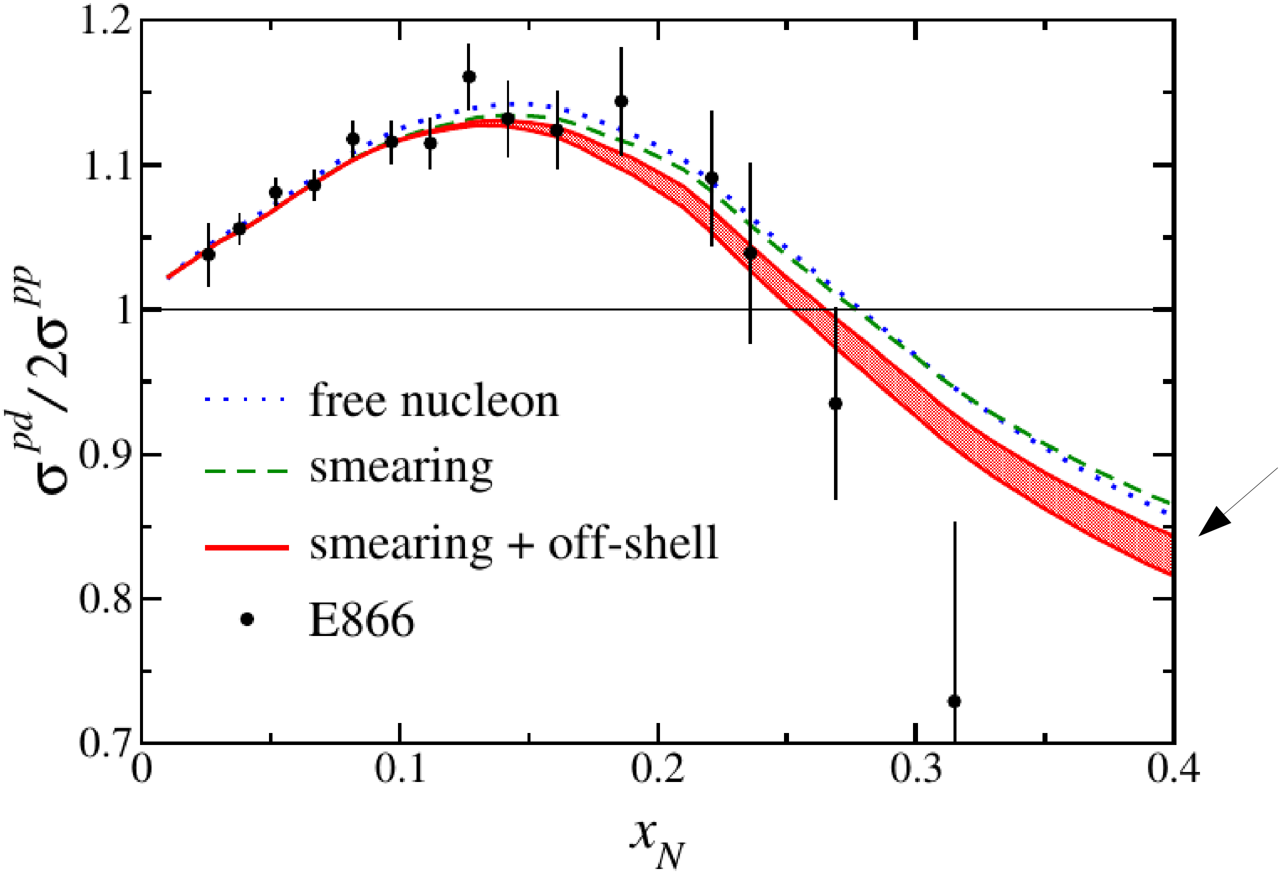
  → no nuclear universality ?? δf_N

  → too hard nuclear spectral function at large momentum ??

  → ???

Nuclear corrections…

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

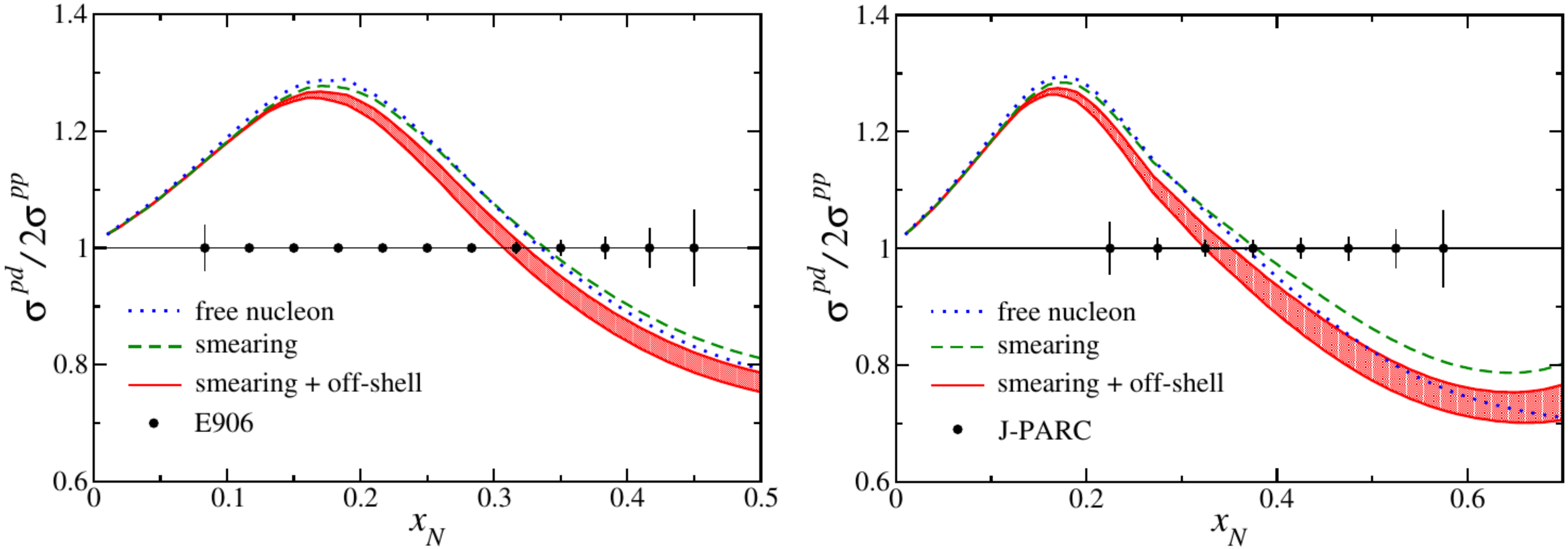


Red band: combined wave fn. & off-shell model uncertainty

- 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***

Jlab

  - ν+*p*, ν+*p* : **ShiP, ELBNF Near Detector, MINERvA**
  - *p+p, p+p* at large positive rapidity
    - *W* charge asymmetry, *Z* rapidity distribution

LHCb(?) RHIC !!
AFTER@LHC

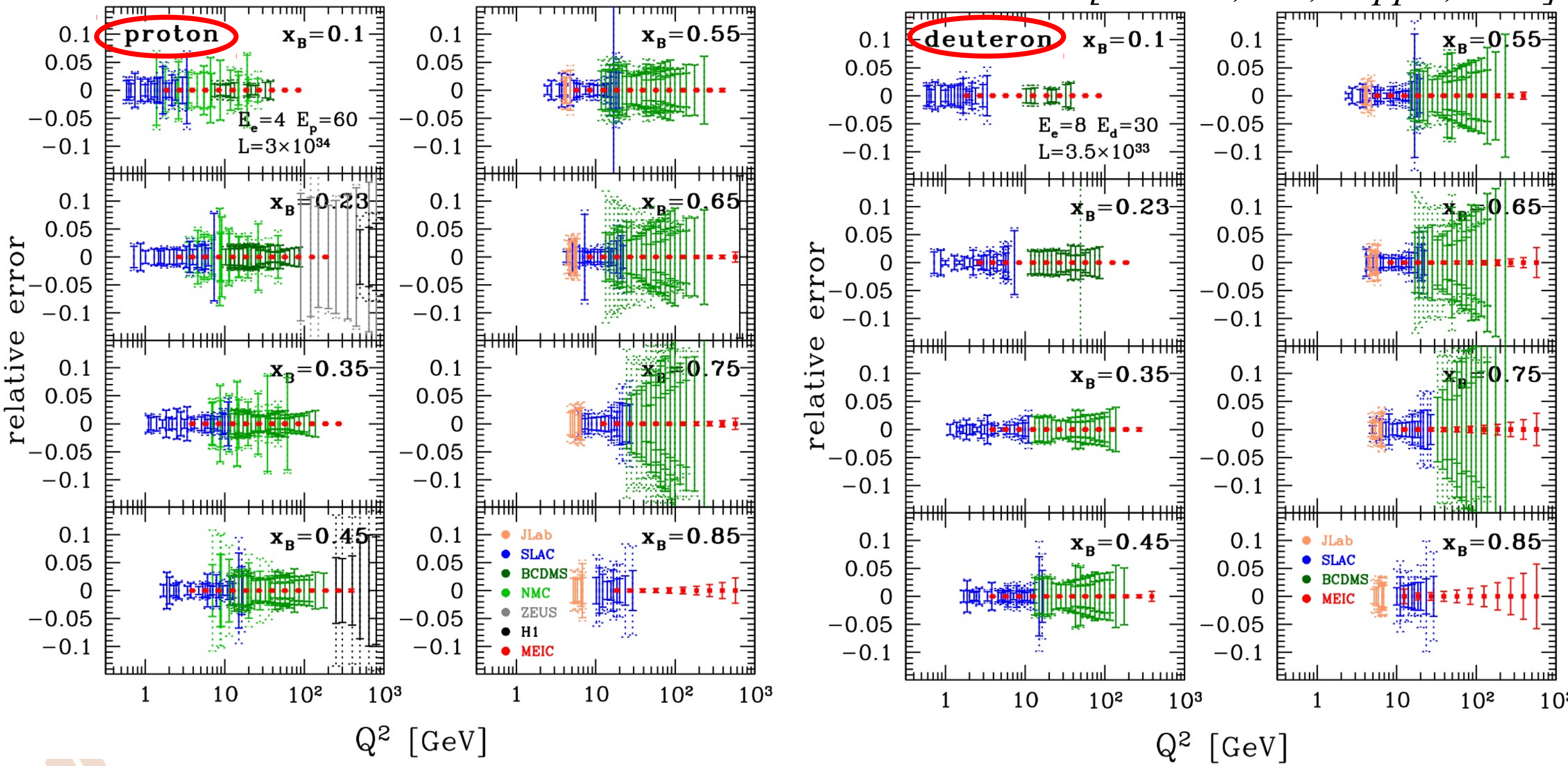
- **"Drell-Yan" data**
  - *Dimuons:* **E906, J-PARC (?)**
  - *p+d* at large negative rapidity – dileptons; *W, Z*
    - Sensitive to nuclear corrections, cross-checks *e+d*

RHIC ??
AFTER@LHC
…

At the EIC

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

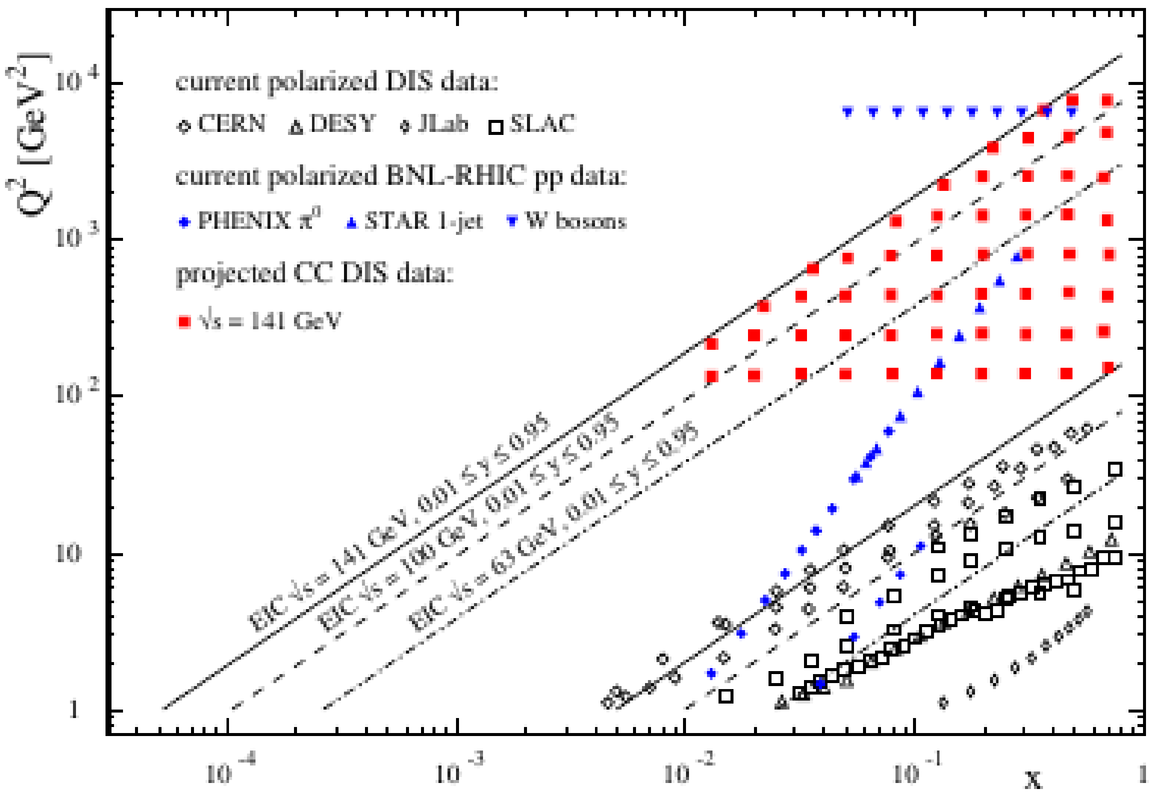
[Accardi, Ent, Keppel, 2010]



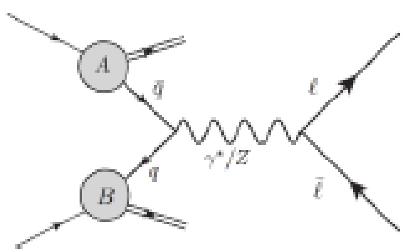
At the EIC

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

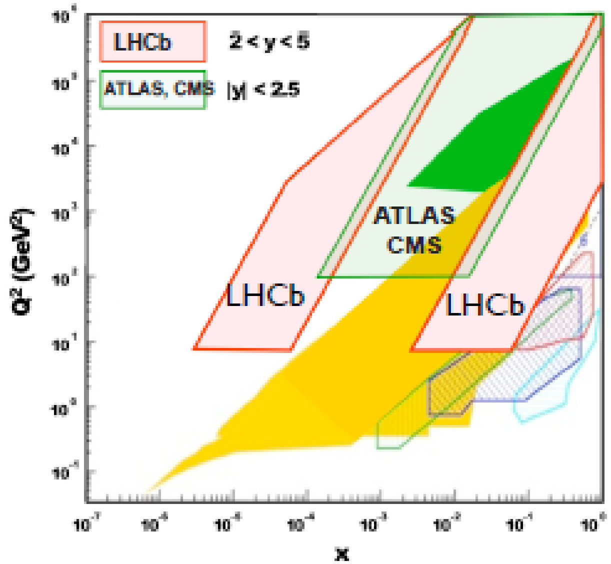
[Aschenauer et al, 2013]

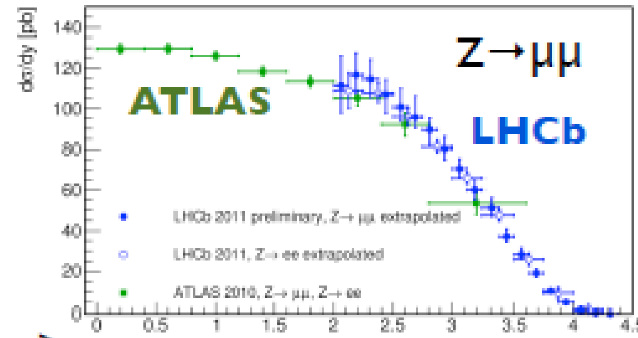


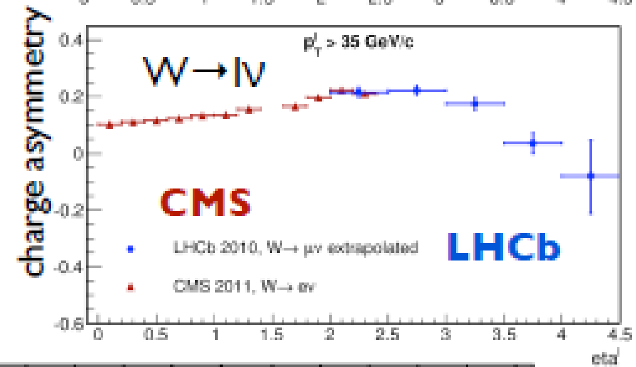
Constraints from the LHC: Electroweak Boson Production



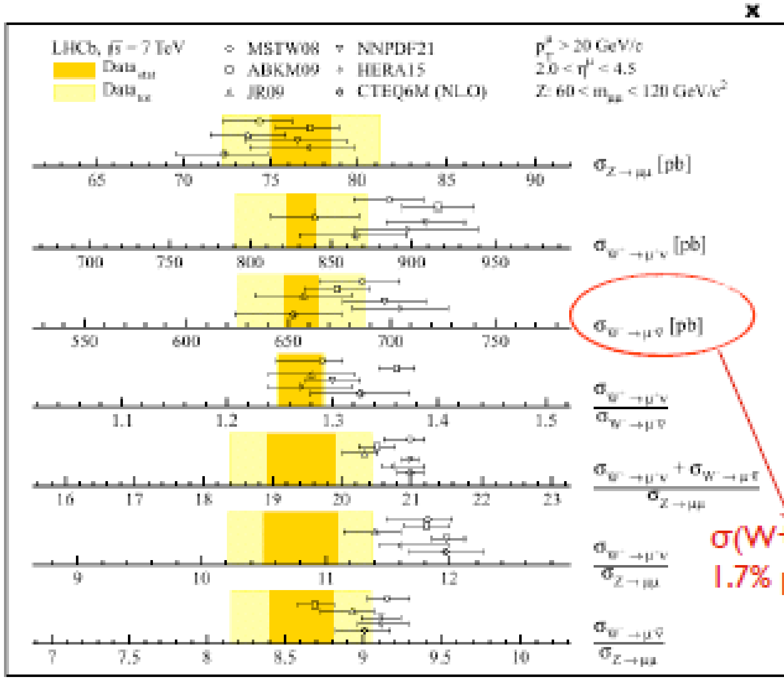
probe light quarks at low and high x



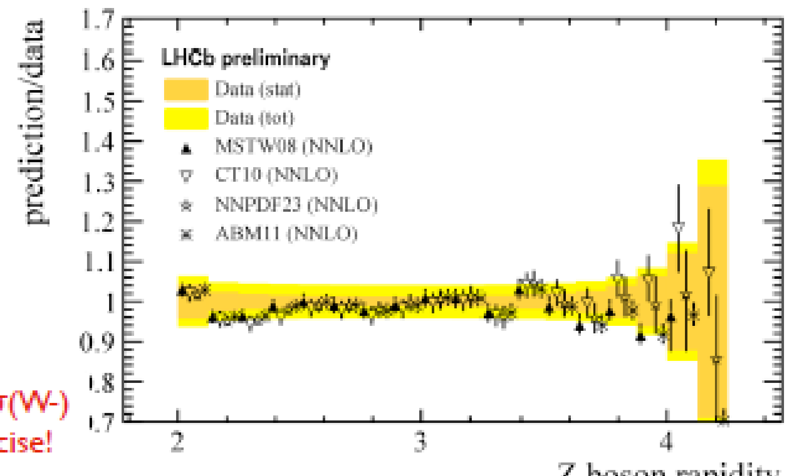




LHCb (S.Tourneur)



σ(W+)/σ(W-)
1.7% precise!



Systematic error comparable with PDF error
Benchmarking different PDF sets

K. Lipka, DIS'13 WG1 summary

Structure functions for QHD studies

- **Question:**

  "What DIS → resonance extrapolation curve should we use?"

  - *CJ15, of course!*
  - Provides a controlled extrapolation from pQCD regime
  - Includes the best available theory corrections: nuclear, HT, TMCs

- **CJ15 structure functions soon publicly available**
  - I can give you **F2 p, d, and n** right now
    - 3 sets: LT, with TMC+HT, fully corrected
  - F2 uncertainties need some debugging
  - FL, F3, PVDIS in "near future"
    - Help is very welcome!