

Parton distributions from protons to nuclei

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DIS 2015

Dallas, TX, April 27 – May 1, 2015

Plan

□ Why (n)PDFs ?

- Connections of hadronic, nuclear, particle physics

□ Proton PDFs – $A = 1, 2, (3)$

- Deuteron corrections and the d/u ratio
- Threshold resummation

□ Interlude

- Strangeness and di-muon data

□ Nuclear PDFs – $A > 10$

- Neutral vs. Charged currents
- EMC effect and Short Range Correlations

□ Conclusions

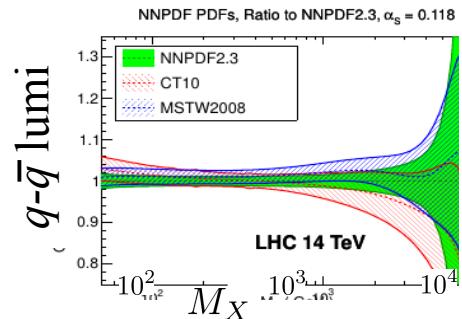
Why (n)PDFs ?

Why (n)PDFs ?

Accardi – Mod.Phys.Lett. A28 (2013) 35
Forte and Watt – Ann.Rev.Nucl.Part.Sci. 63 (2013) 291

□ High-energy (*large to small x*)

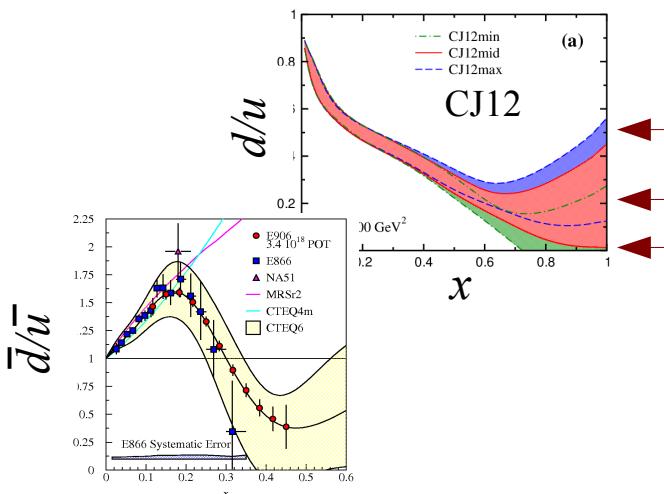
- Beyond the Standard Model searches → *A.DeRoeck [pl]*
- NuTeV weak mixing angle
- Precision (Higgs) physics → *P.Meade, F.Siegert [pl]*
- Small-x and gluonic “matter” → *T.Lappi [pl]*



□ Hadron structure (*large to medium x*)

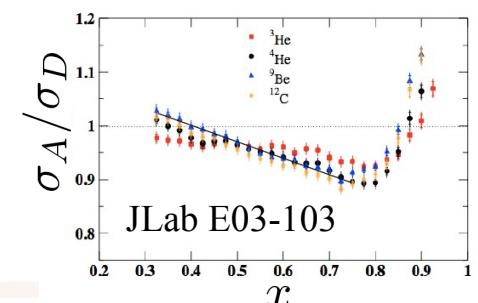
- Effects of confinement on valence quarks
- $q - \bar{q}$ asymmetries; isospin asymmetry → *C.Keppel*
- Strangeness, intrinsic charm

→ *T.Hobbs, F.Lyonnet*



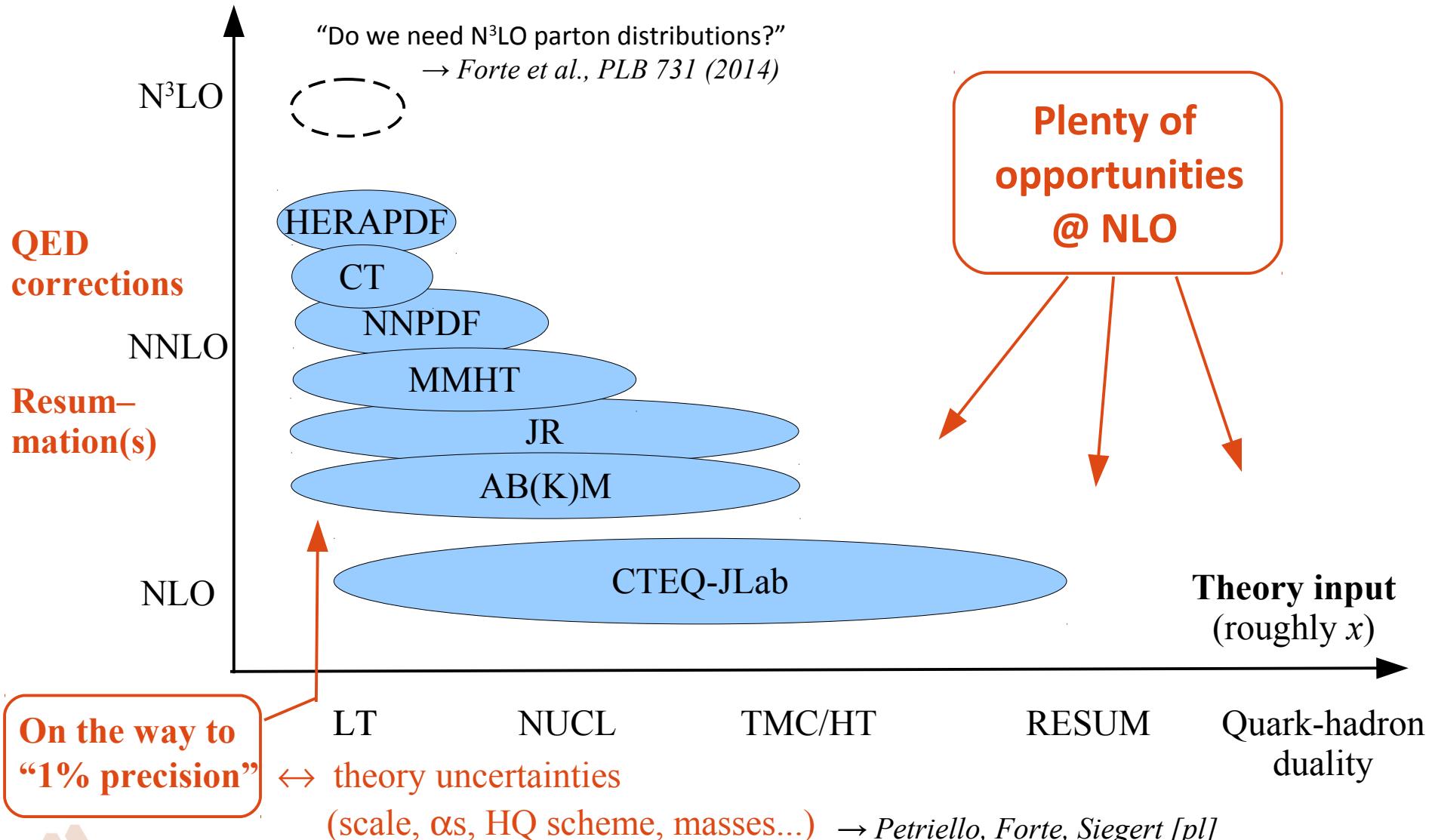
□ Nuclear Physics

- Bound nucleons, EMC effect, SRC → *N.Fomin*
- p+A and A+A collisions at RHIC / LHC
- Color propagation in nuclear matter



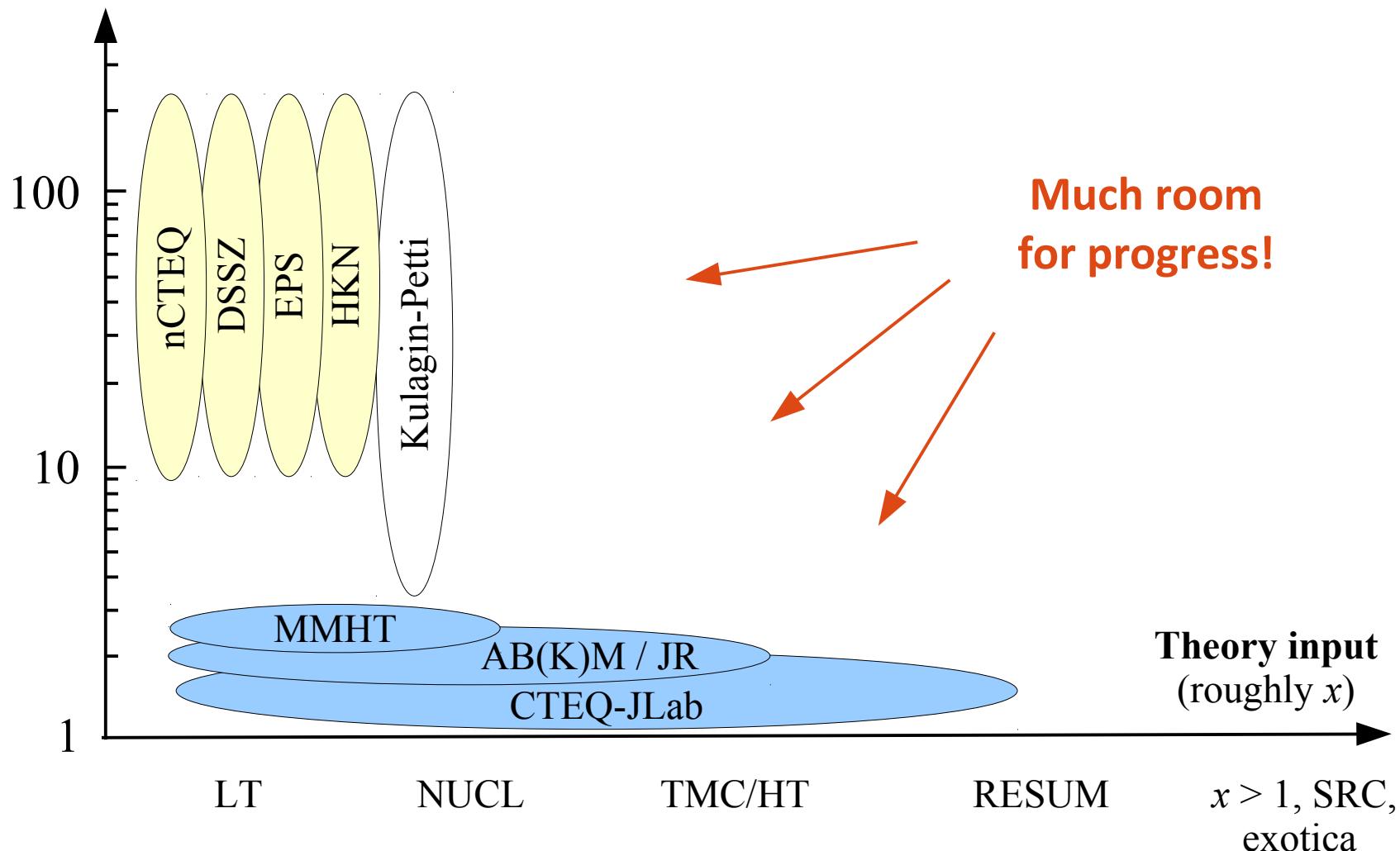
A PDF landscape

Pert. order



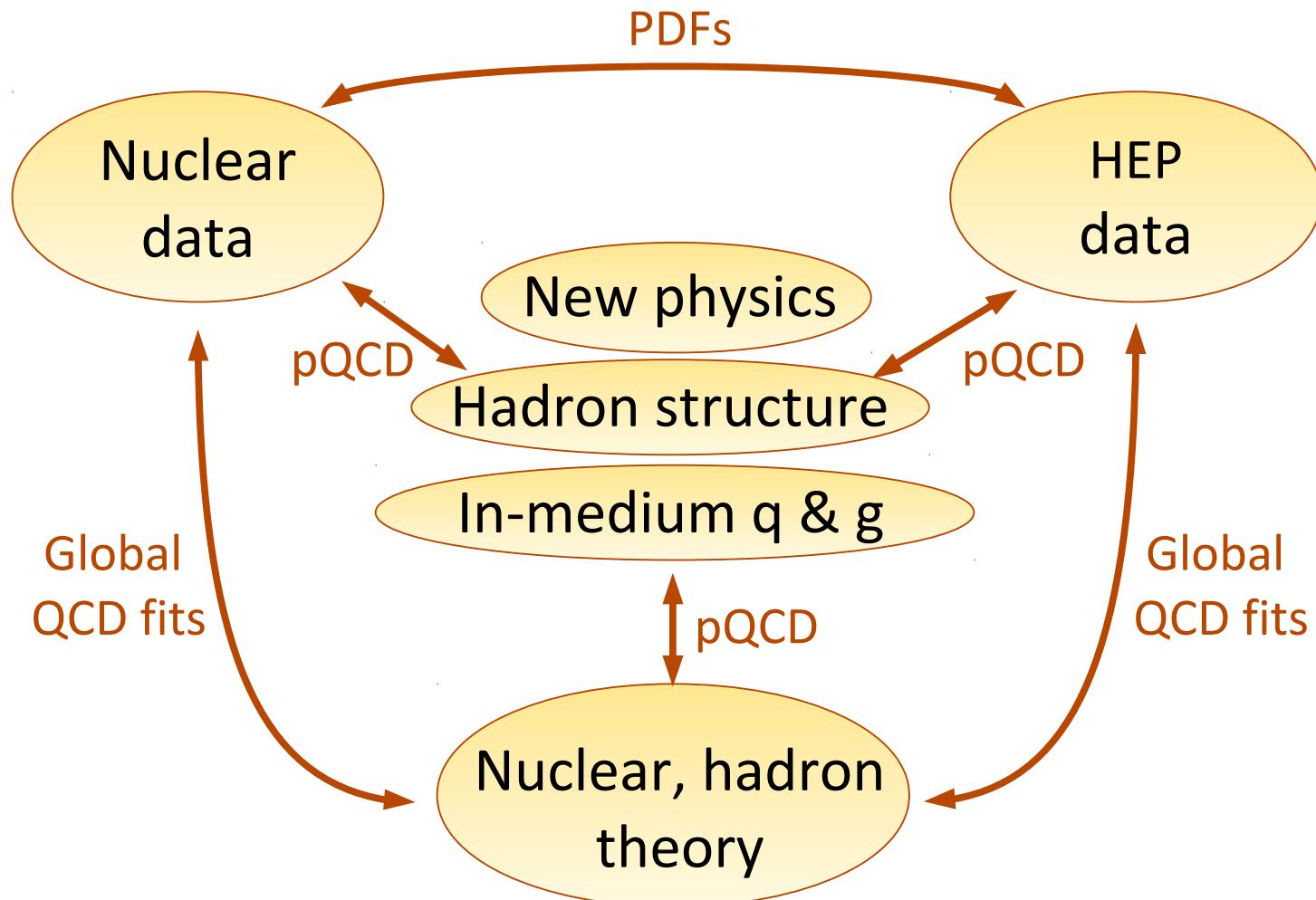
A nPDF landscape

Atomic number



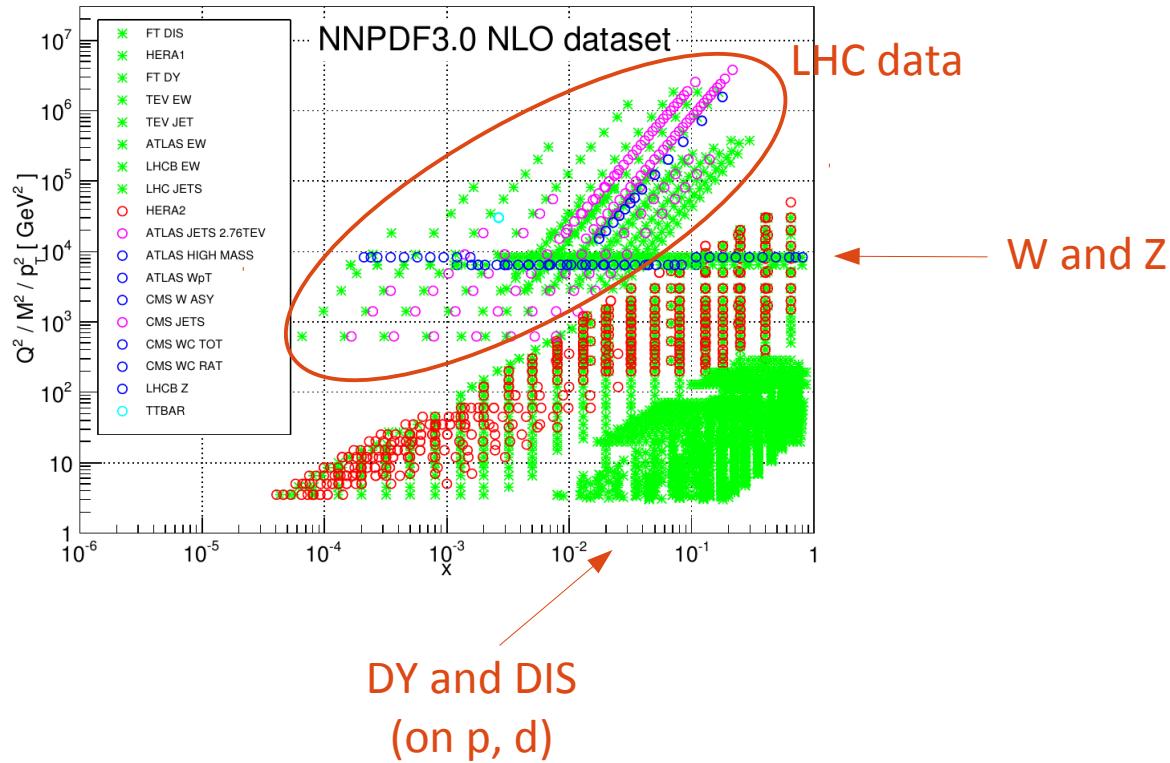
Needs the betrothal of HEP and NUCL

- A global approach across subfields

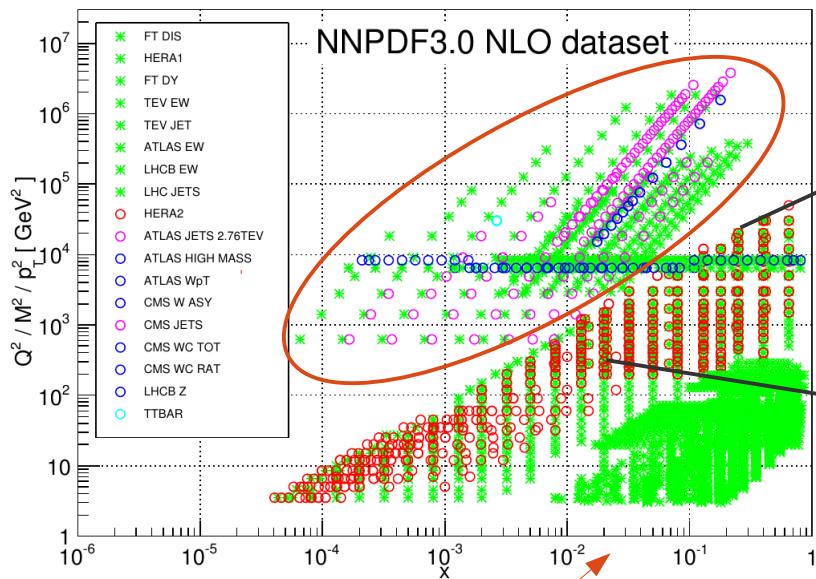


Proton PDFs

Data coverage

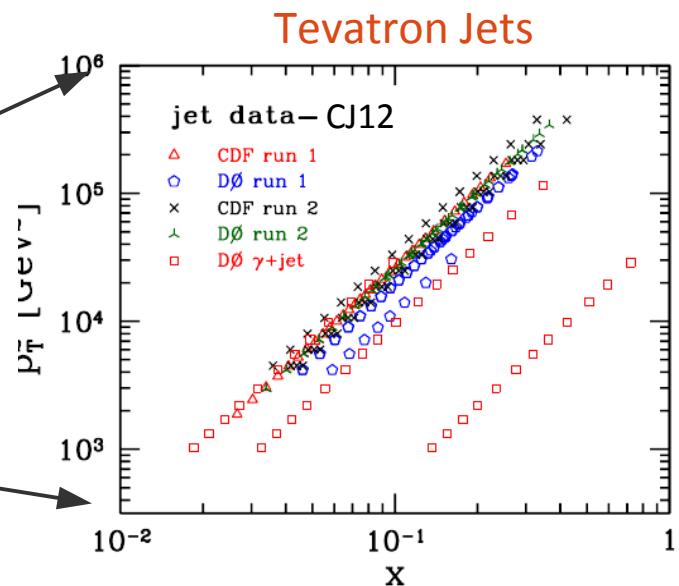


Data coverage

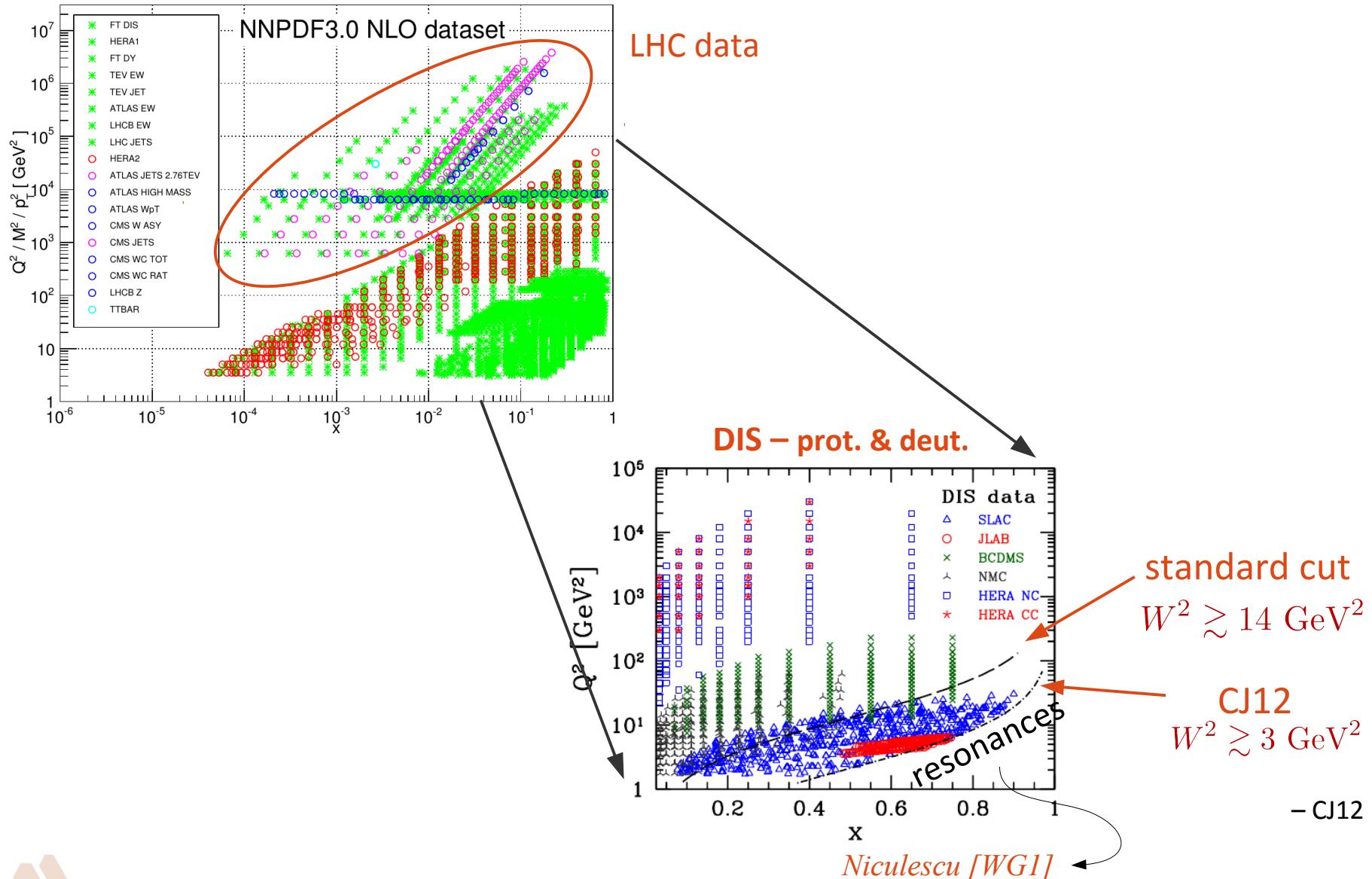


LHC data

DY and DIS
(on p, d)



Data coverage



Large- x , small- Q^2 corrections

□ $1/Q^{2n}$ suppressed:

- Higher-twists (non-pert. parton correlations)
→ in practice, fitted to low- Q^2 DIS data
- Target mass corrections
- Heavy quark masses → hot debates, *see (some) in WG1+5*
- Current jet invariant mass, ...

Under control
(extracted “HT” include residual power corrections)

Accardi et al. 2010
Alekhin et al. 2004-

□ Non-suppressed

- Nuclear corrections or deuteron targets → *Melnitchouk [WG1]; Thorne [WG1]*
- Threshold resummation → calculations available

□ Flexible d -quark parametrization

- Need to allow $d/u \rightarrow$ finite, as $x \rightarrow 1$
(as required in theoretical models)
- e.g. $d'(x) = d(x) + \alpha x^\beta u(x)$ [used in CJ12, analogous one in CT14]

alternative approach → Liuti [WG1]

Global fits overview

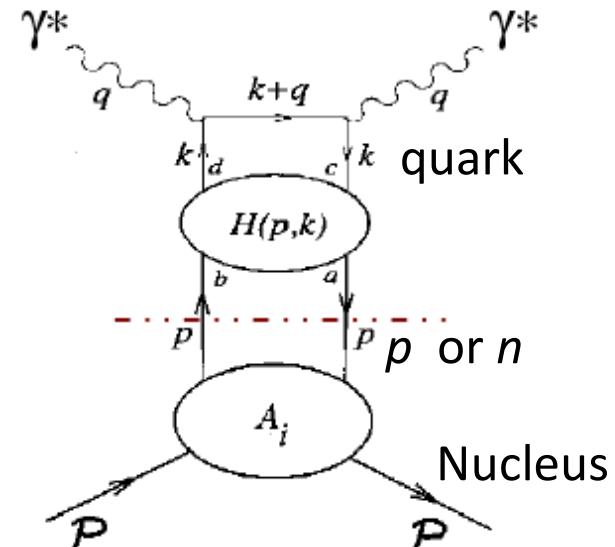
See parallel talks in WG1

	JLab	HERA I+II <i>Wichmann</i>	Tevatron new W,Z	LHC	di- μ	Nucl.	HT TMC	Flex d	closure
NEW! HERAPDF2.0 → Myronenko, Brandt		✓	✗						
NEW! CT14 → Nadolski			✓ ✗	✓	✓			✓	
NEW! MMHT14 → Thorne			✓ ✗	✓	✓	✓			
NEW! NNPDF3.0 → Deans				✓	✓				✓
[GJR14]	✓			✓	✓	✓	✓	✓	
CJ12 * (→ CJ15) → Melnitchouk	✓	(✓)	(✓)		✗	✓	✓	✓	
ABM12 **					✓	✓	✓		

* NLO only ** No jet data ✗ but see 1503.05221 ✗ no reconstructed W

Deuteron corrections

- No free neutron → use deuteron
- CJ: Nuclear modeling
 - ✓ Connects to underlying nuclear theory
 - ✓ Can reject models → verify assumptions
 - ✓ Cross check with other processes
 - DY(p+d), ${}^3\text{He}$, polarized DIS, ...
 - ✗ Continuous vs. discrete parameters
- MMHT: parametrize D/(p+n) ratio
 - ✓ Nuclear uncertainty straightforward
 - ✓ No “model bias” (beside parametrization)
 - ✗ Limited nuclear physics output
 - ✗ May be missing non-negligible Q^2 dependence
 - ✗ Needs one parametrization per process



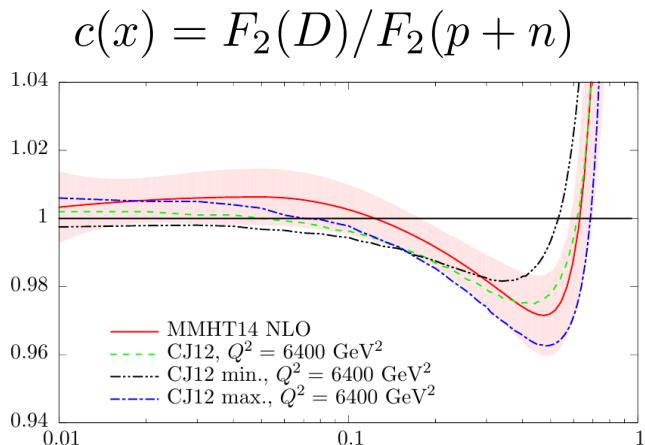
Low-energy factorization issues

Renorm. of nucl. operators, gauge inv., FSI, ...

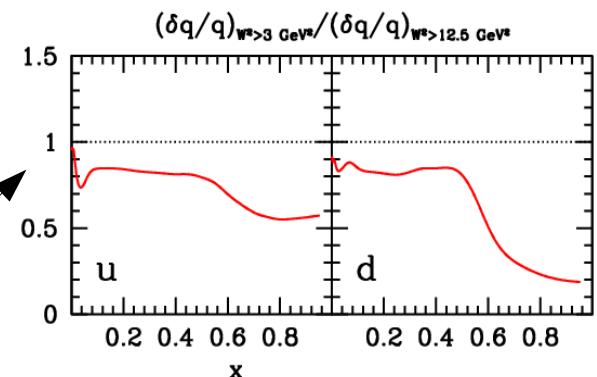
$$\begin{aligned} \mathcal{N}[1 + a_1 \ln^2(x_p/x)] & \quad x < x_p \\ \mathcal{N}[1 + a_2 \ln^2(x_p/x) \\ & + a_3 \ln^{20}(x_p/x)] \quad x > x_p \end{aligned}$$

Deuteron corrections

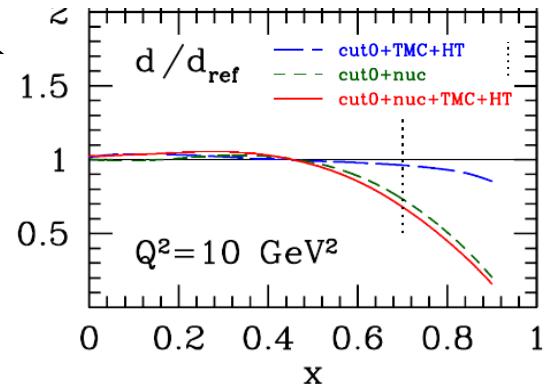
- The 2 complementray strategies agree
 - Can use reliably, extend to lower W^2



Reduced PDF uncertainty
with SLAC/JLab data



d-quark suppression



- Nucl / HEP symbiosis:

- W and Z → constrain d-quark → constrain deuteron corrections
- Abundant DIS deuteron data → precise u/d flavor separation

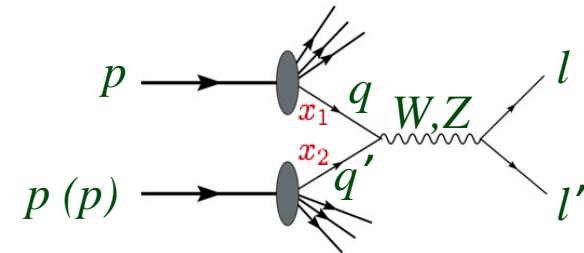
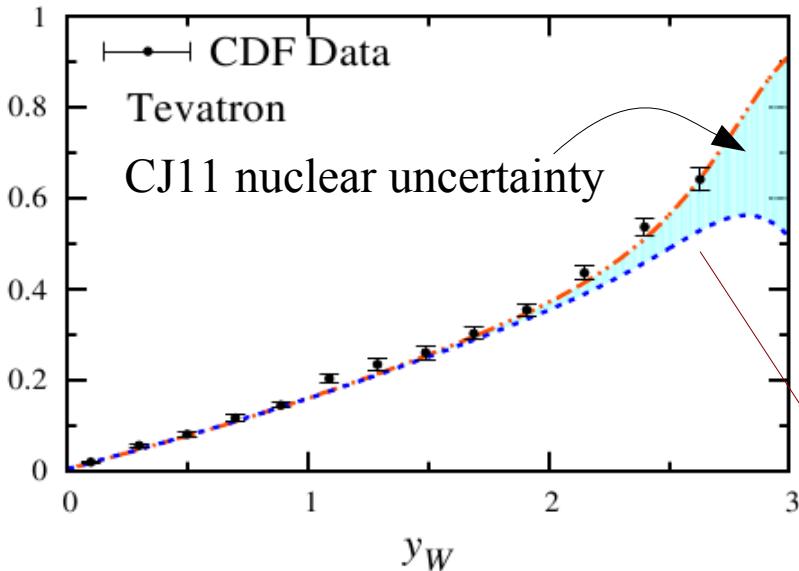
Use protons to study nuclei (!)

Accardi, Mod.Phys.Lett. A28(2013)35

Brady, A.A., Melnitchouk, Owens, JHEP 1206 (2012) 019

□ Directly reconstructed W:

- highest sensitivity to large x



$$A_W(y) \approx \frac{d/u(x_2) - d/u(x_1)}{d/u(x_2) + d/u(x_1)}$$

sensitive to
 d at high x

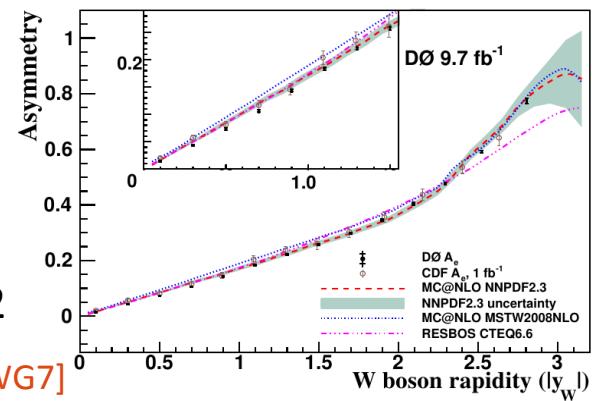
Can constrain
Deuteron models!

□ New precise DØ data:

- W ; also $W \rightarrow l + \nu$ and Z (but less sensitive)

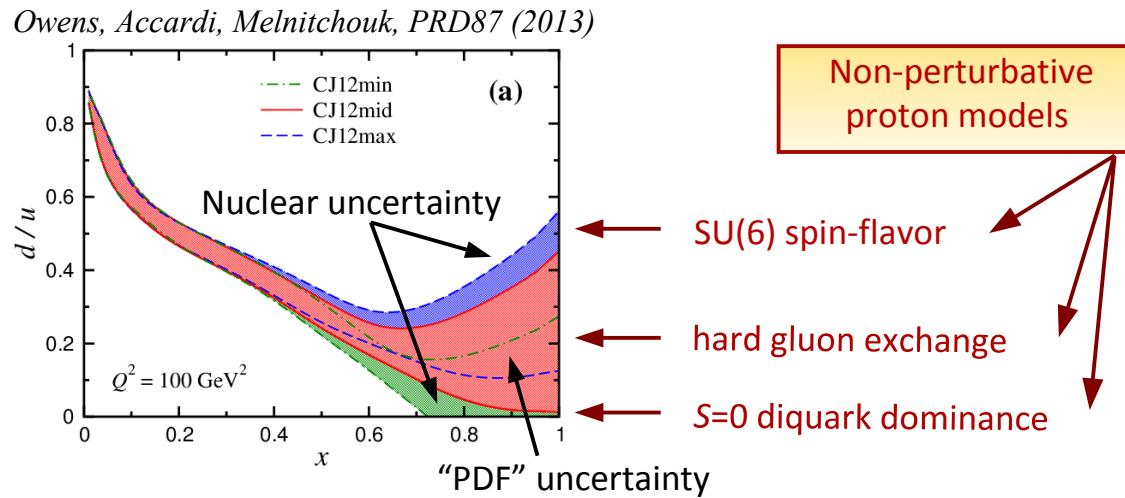
□ And also:

- W, Z at RHIC / LHC [WG1], $W+jet$ at LHCb,
- BONUS [WG1], MARATHON, PVDIS [WG3+7] at JLab 6/12
- CC, e^+e^- @ HERA [WG1] (limited x reach); EIC / LHeC [WG7]



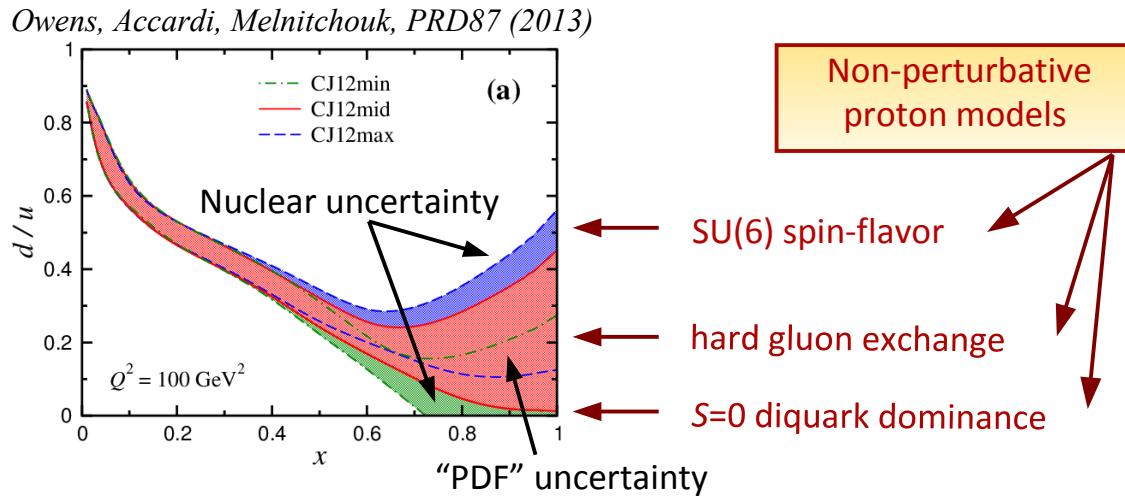
And nuclei to study protons

- For example d/u ratio at large x

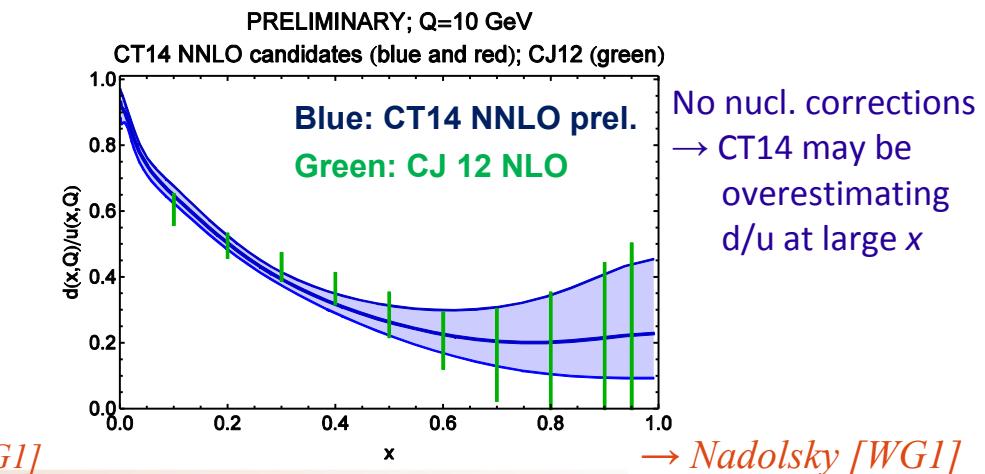
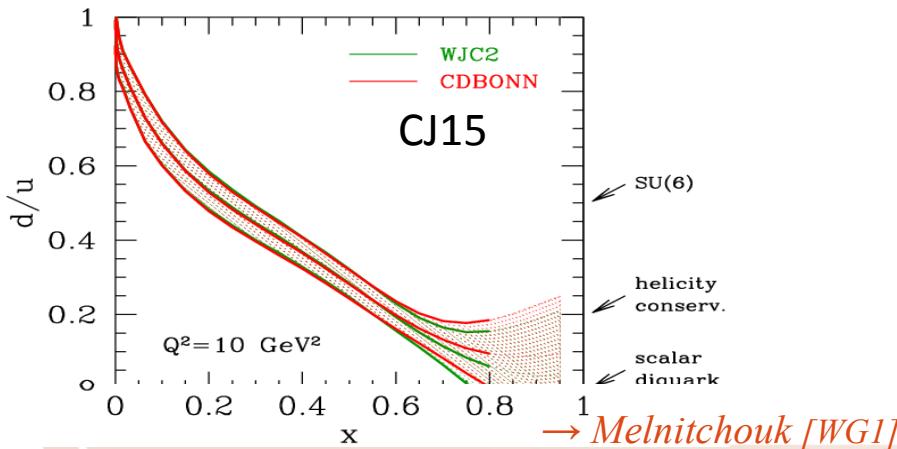


And nuclei to study protons

- For example d/u ratio at large x



- New data, new theory → stronger constraints:



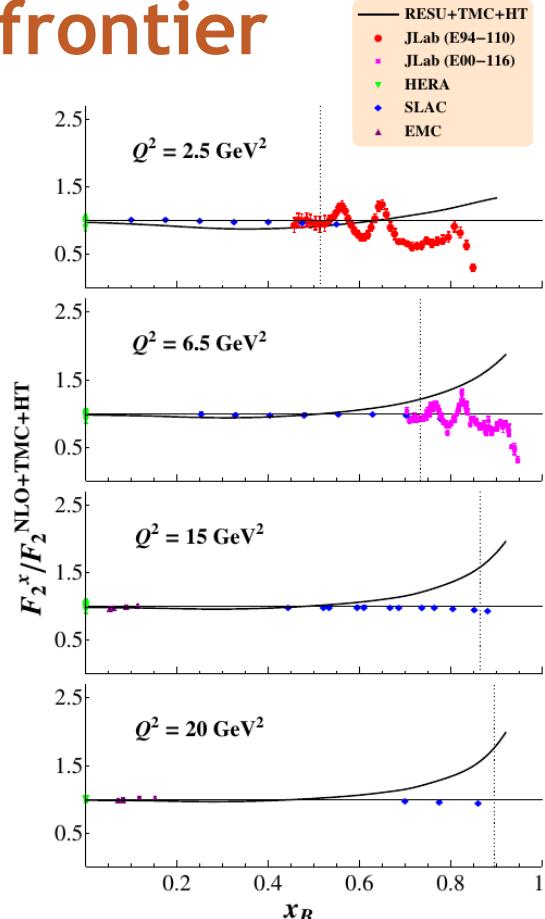
Threshold resummation - the new frontier

□ DIS: *Accardi, Anderle, Ringer – arXiv:1411.3649*

- Can be combined with TMC w/o threshold problems
- Large corrections, will affect PDFs

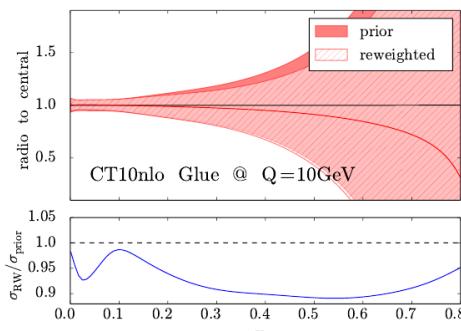
□ Drell-Yan *Alekhin et al., PRD74 (2006)*

- At NNLO, tension with DIS, vector bosons
- Resummation effects are large
 - Need to be evaluated



□ Direct photons → *Sato [WG1]*

- Resummation allows use in global fits
- 10% reduction in large- x gluon errors



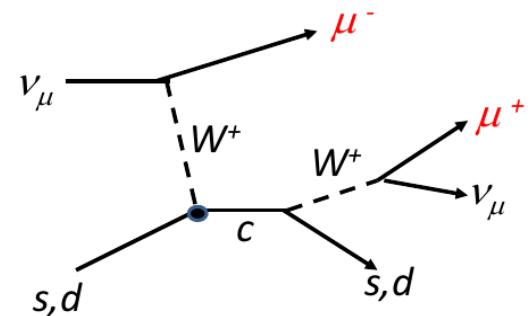
Interlude: strangeness fits

Strangeness and strangeness asymmetry

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

- In pre-LHC fits, mostly constrained by ν+A data

- CCFR inclusive DIS
- NuTeV muon pair production
- NOMAD and CHORUS

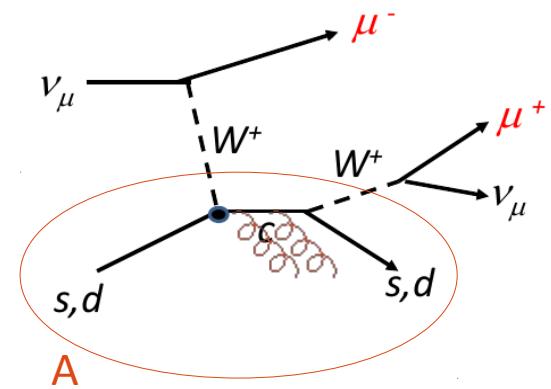


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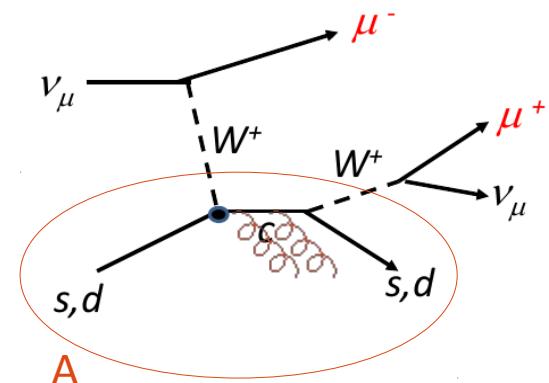
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 - NOMAD and CHORUS

- Nuclear corrections again...

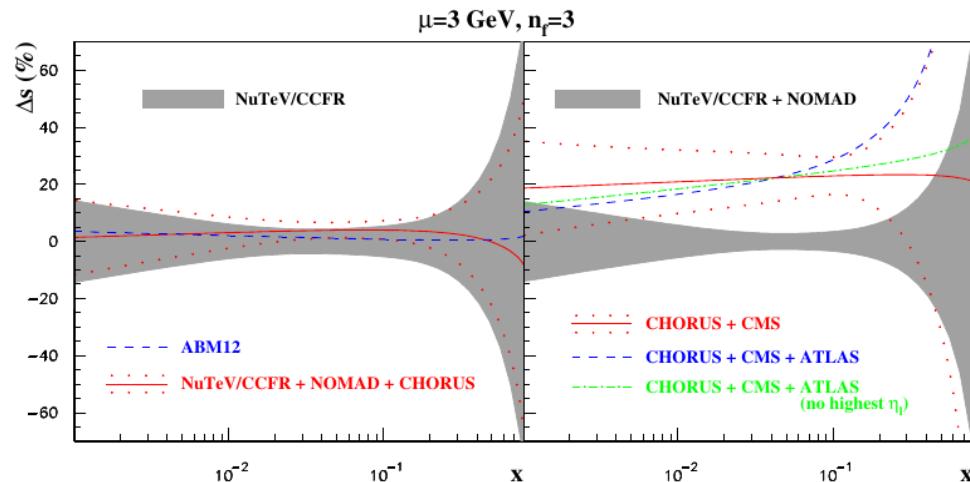
- Initial state nuclear wave-function mods
 - Partly under control using nPDFs
 - But: double counting!!
 - Final state propagation of the charm quark / D meson
 - Not under theoretical / phenomenological control
(cf. heavy quark “puzzle” in A+A at RHIC, LHC)



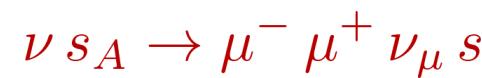
Strange tensions

- ☐ $\nu+A \rightarrow \text{dimuons}$ vs. $p+p \rightarrow W+c$ at LHC

Alekhin et al., arXiv:1404.6469

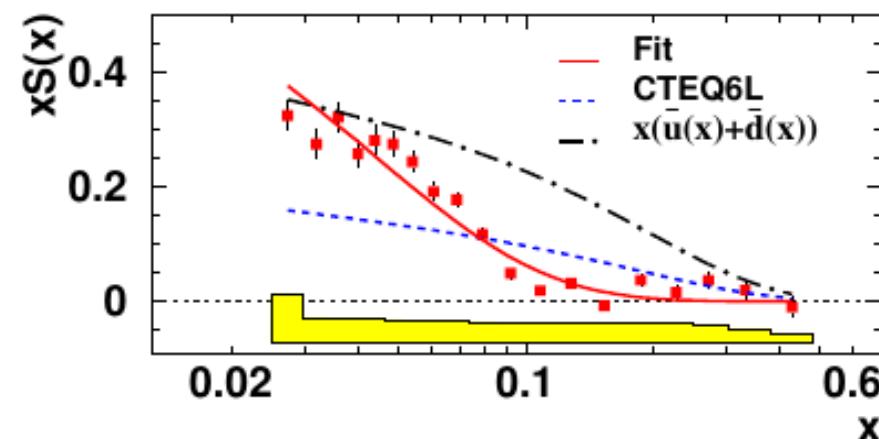


↓
FSI ?



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

HERMES, PLB 666 (2008) 446



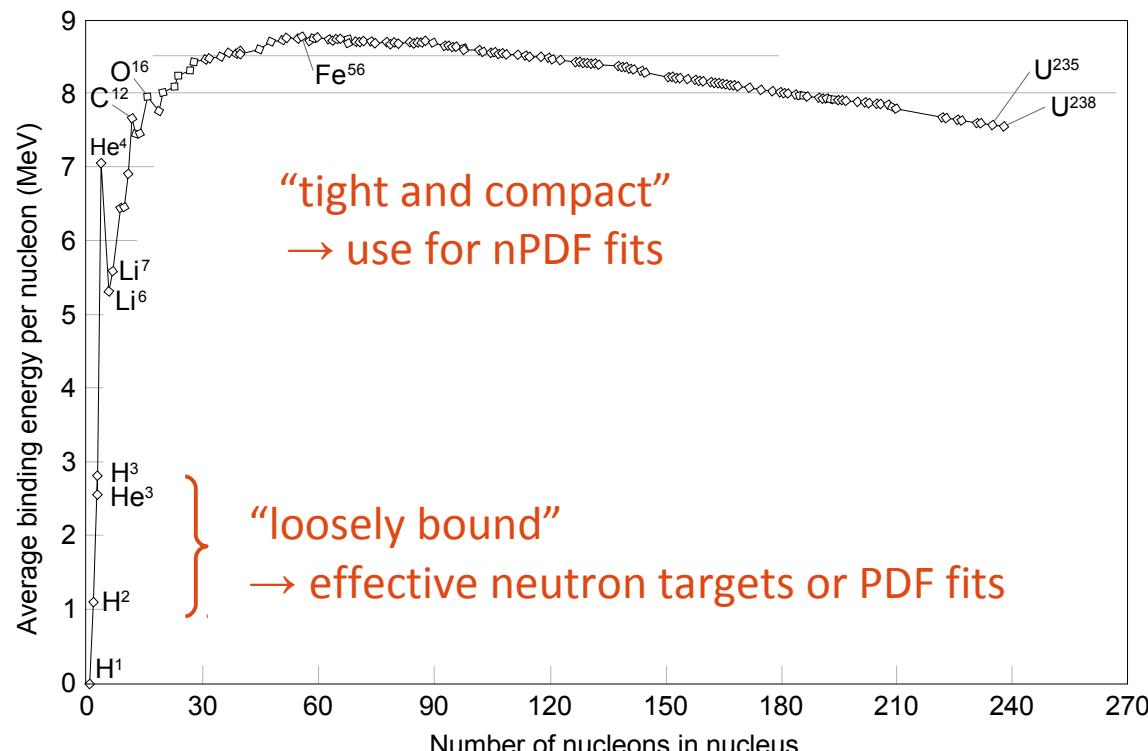
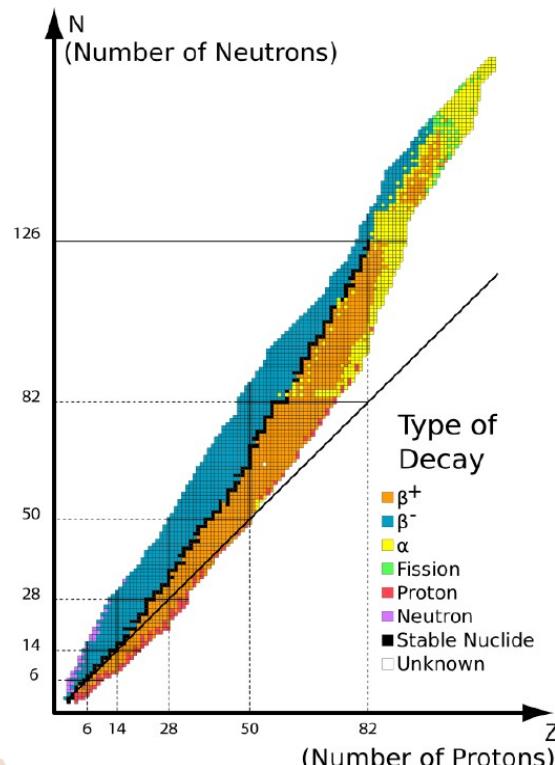
Strangeness and strangeness asymmetry

- In my opinion: **Don't use $\nu+A$ data in proton PDF analysis!!**
 - **Use neutrino data only for nPDFs**
 - combine with W/Z in $p+A \rightarrow$ nuclear strange
 - fit proton's strange PDF with, say, LHC/RHIC $W(+c)$, Z
 - **Anchor nPDFs to proton PDFs, use nuclear data:**
 - Detect deviations from free proton strangeness
 - W and Z from RHIC, LHC \rightarrow fit IS nuclear strangeness
 - Dimuons in $\nu+A$ \rightarrow fit charm's FS “energy loss”
(rather than subsuming in proton's s-quark)

Nuclear PDFs

Binding of nucleon in nuclei

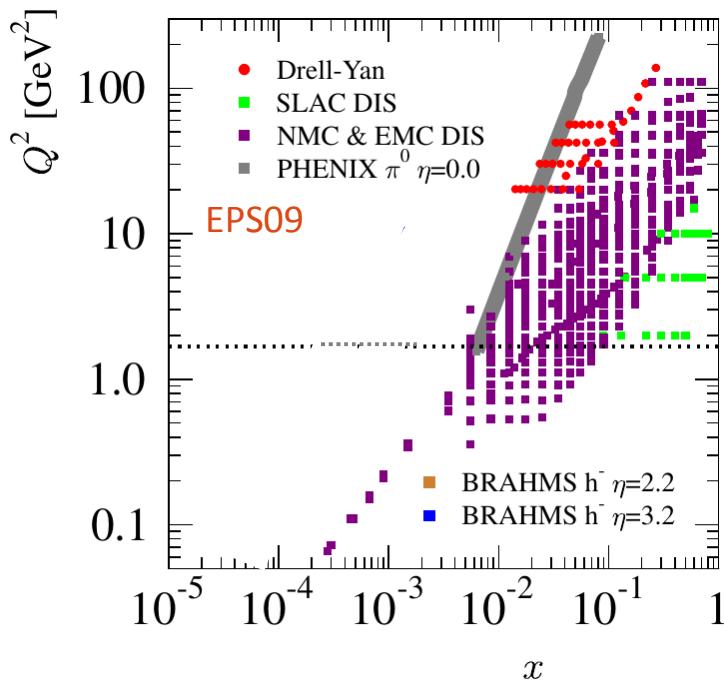
		Binding energy per nucleon	Radius
Deuteron	$p\ n$	1.1 MeV	2.14 fm
Triton	$p\ n\ n$	2.8 MeV	
Helium-4	$p\ p\ n\ n$	7.1 MeV	1.9 fm



Kinematic coverage of data

□ Global dataset

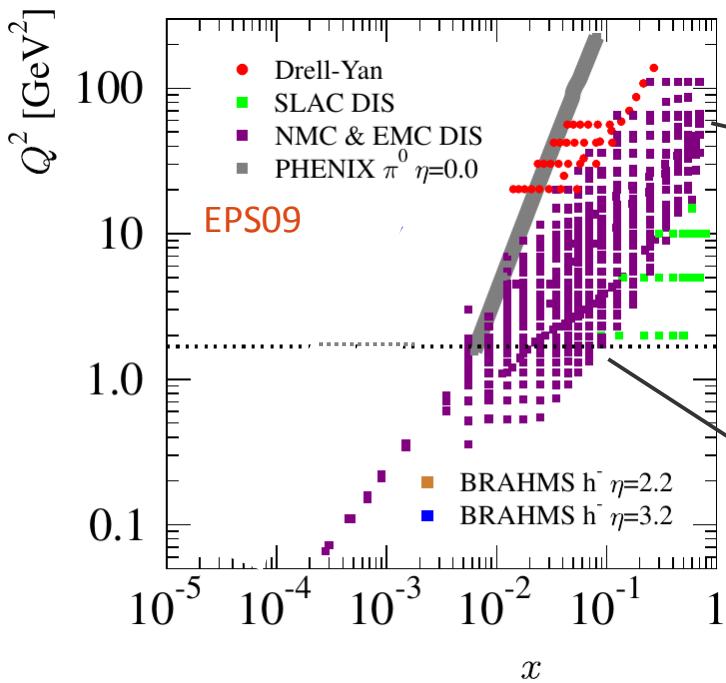
- DIS ; $p+A \rightarrow l^+l^-$; $p+A \rightarrow \text{hadron}, \gamma$
- Large choice of nuclei: $A = 10-208$



Kinematic coverage of data

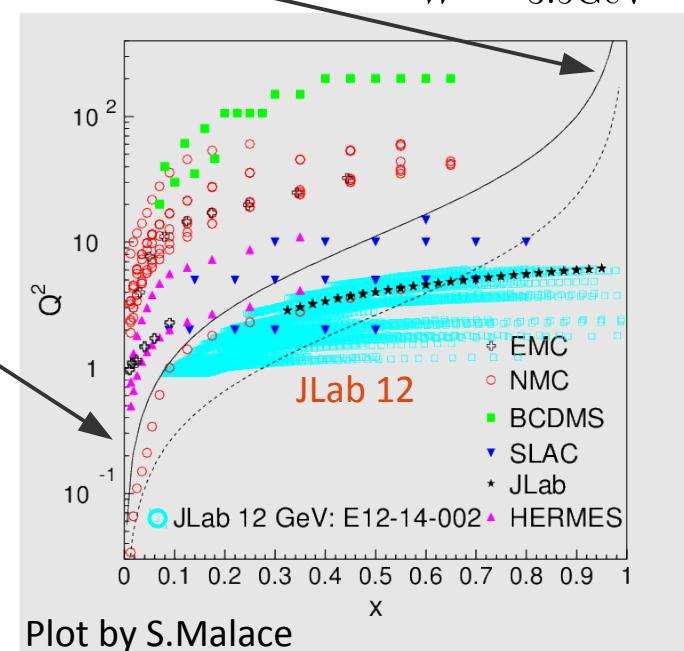
□ Global dataset

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- Large choice of nuclei: $A = 10-208$



Much data from JLab & soon JLab 12:

- wide A range; LT separation $\rightarrow S.\text{Malace}$
- low Q^2 , large x (also $x > 1$)



Plot by S.Malace

Nuclear partons - 2 approaches

□ Global fits of nuclear PDFs

- Partons belong to the whole nucleus
- Assume collinear factorization holds, fit the nPDFs
- Easy to extend to any hard scattering observable

→ **nCTEQ, EPS, DSSZ, HKN**

□ Modeling of nuclear dynamics

- Nuclear PDFs as convolution of
 - bound nucleons dynamics
 - Nucleon PDFs

→ “**Kulagin-Petti” model** → *S.Kulagin, R.Petti*
(similar to CJ for deuteron)

Global nuclear fits overview

See parallel talks in WG1

	F_{2A}/F_{2B}	F_2^{VA}	DY σ_A/σ_B	RHIC π	LHC π / γ	NLO	Native PDFs	PDF Ratios	Hess. errors
nCTEQ15 → Kovarik	✓		✓	✓		✓	✓		✓
EPS09 → Helenius	✓		✓	✓	See talk	✓		✓	✓
DSSZ ('12)	✓	✓	✓	✓		✓		✓	✓
HKN07	✓		✓			✓		✓	✓

Need Frag. Fns.

□ To keep in mind:

- How well are p FFs known? $g \rightarrow \pi$ seems to hard *cf.* LHC data
- IS quark energy loss in DY, FS effects in p+A

d'Enterria et al. NPB 883 (2014)

Accardi et al., Riv.Nuovo Cim. 32 (2010)

Multiplicative vs. Native parametrization

□ Multiplicative nuclear correction factor

$$f_i^A(x_N, Q_0^2) = R_i(x_N, Q_0, A, Z) f_i(x_N, Q_0^2)$$

bound parton density free parton density

Hirai, Kumano, Nagai [PRC76(2007)065207] arXiv: 0709.0338

Eskola, Paukkunen, Salgado [JHEP0904(2009)065] arXiv: 0902.4154

de Florian, Sassot, Stratmann, Zurita [PRD85(2012)074028] arXiv: 1112.6324

Parametrize and fit, e.g.,

$$R_i(x, A, Z) = 1 + \left(1 - \frac{1}{A^\alpha}\right) \frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^{\beta_i}}$$

(HKN07)

(DSSZ and EPS09 have more complex parametrizations)

Multiplicative vs. Native parametrization

□ Native nuclear PDF

$$f_i^A(x_N, Q_0^2) = f_i(x_N, A, Q_0^2) \quad \begin{matrix} \nearrow \\ \text{bound parton density} \end{matrix} \quad f_i(x_N, Q_0^2) = f_i(x_N, A = 1, Q_0^2) \quad \begin{matrix} \nwarrow \\ \text{free parton density} \end{matrix}$$

nCTEQ [PRD80(2009)094004] arXiv: 0907.2357

□ Select existing proton PDF set; make parametrization A dependent

$$x f_k(x, Q_0) = c_0 x^{c_1} (1 - x)^{c_2} e^{c_3 x} (1 + e^{c_4 x})^{c_5}$$

$$c_k \rightarrow c_k(A) \equiv c_{k,0} + c_{k,1} (1 - A^{-c_{k,2}})$$

CTEQ6.1

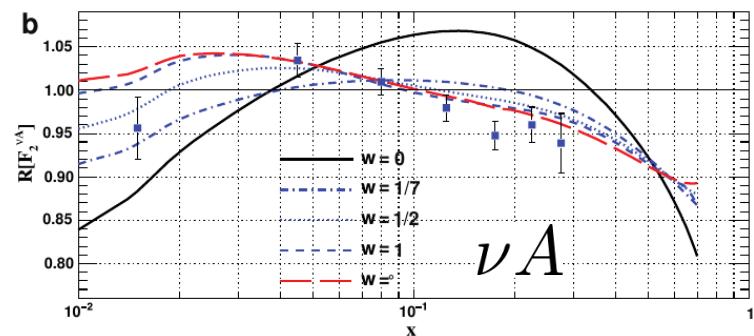
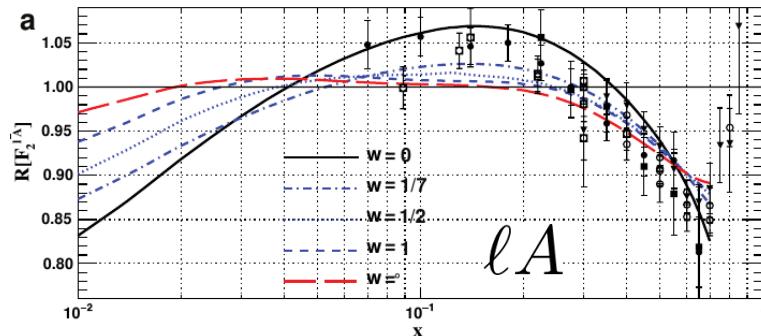
□ Advantages:

- Can verify scaling for light nuclei ($A=2,3$) vs., say, CTEQ-JLab PDFs
- Can be generalized study “superfast partons” at $x > 1$

Neutral vs. Charged Currents

- nCTEQ: NuTeV νA data cannot be simultaneously fitted with $eA + DY$

Kovarik et al., PRL 106 (2011)



- EPS, DSSZ disagree
 - But role of NuTeV data statistically less relevant in their analysis

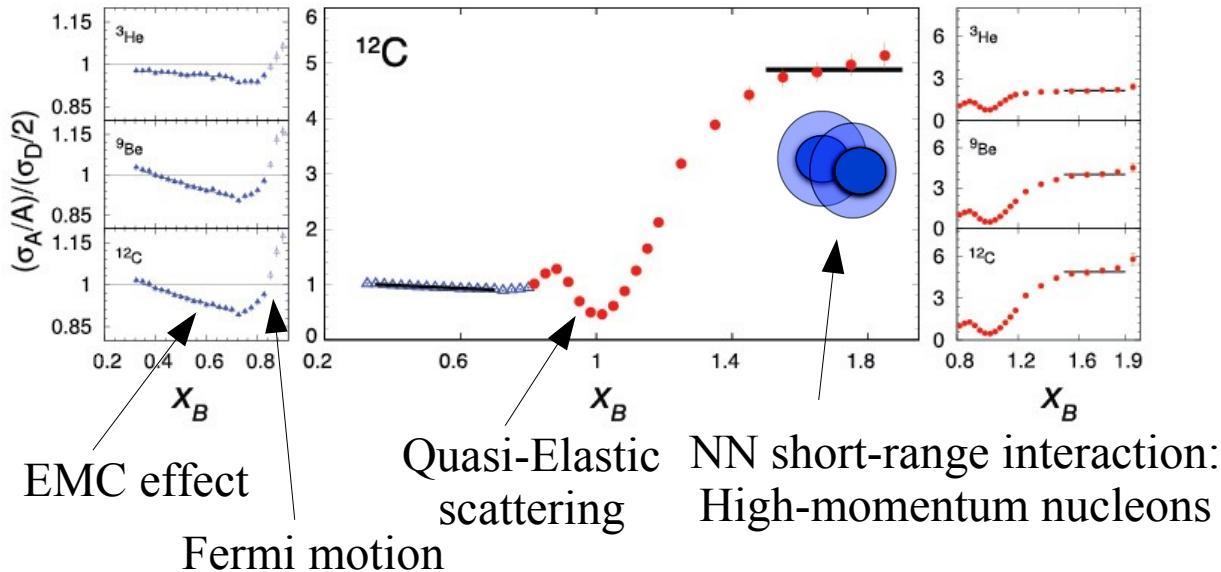
Paukkunen, Salgado, PRL110 (2013)

Paukkunen, NPA926 (2014)

- New data from NOMAD, MINERvA
 - Can these help out?

EMC effect vs. Short-range Correlations

- EMC effect: quark nuclear modifications, a puzzle since 30+ years
 - revitalized by recent Jefferson Lab experiments

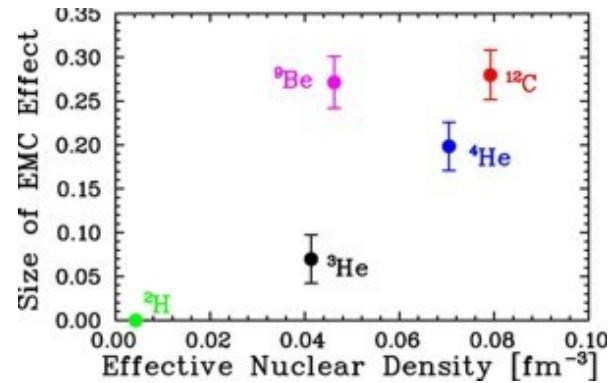
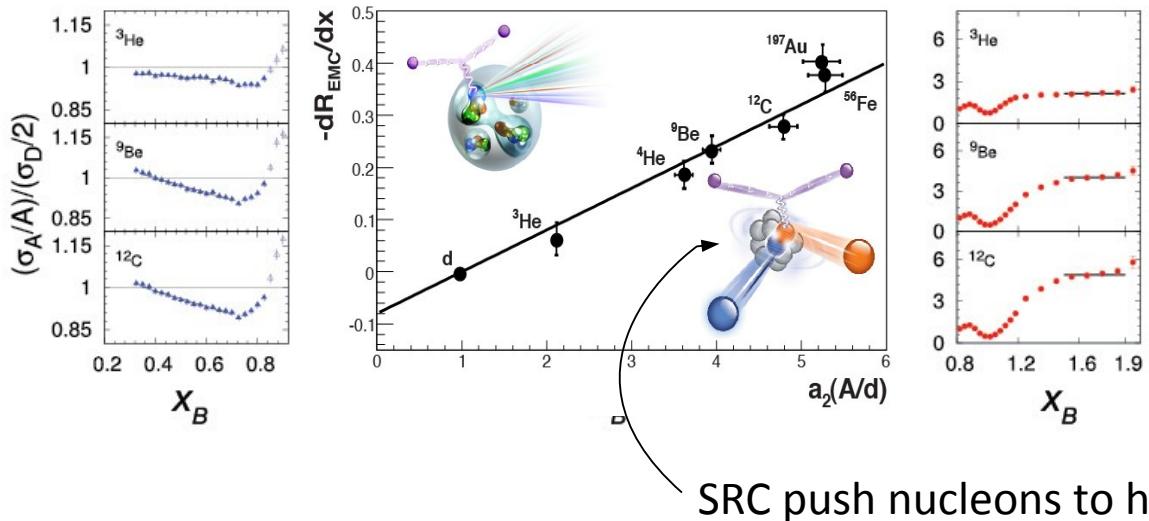


- At JLab 12 GeV, SRC will be in DIS regime:
 - A new exciting arena for nPDFs!

EMC effect vs. Short-Range Correlations

- EMC effect: revitalized by recent Jefferson Lab experiments:

- Light ion “outlier”
- Correlation with “scaling” at $x > 1$



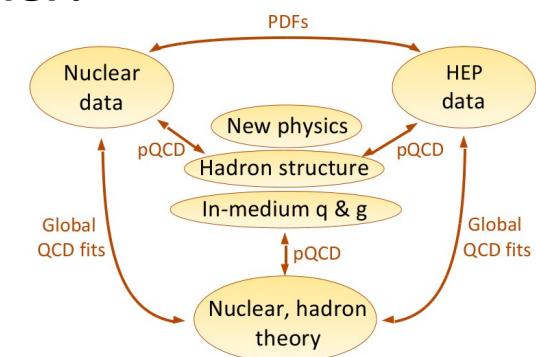
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Conclusions

Conclusions

- **PDFs and pQCD theory on the way to “1% precision”**
at medium/small x
 - New data from LHC; quantification of “theory errors”
- **Entering a new precision era in large- x PDFs**
 - New data (now and in the future), new fitting approaches
 - Conquering nuclear corrections
 - Time for threshold resummation
- **High-energy and nucl. physics need to work together!**
 - Progress in hadron / nuclear structure
 - Precision PDFs for BSM searches
- **Next step: the betrothal of PDFs and nPDFs!**

P.S. other betrothals also possible: PDFs+pol PDFs; (n)PDF + FF; ...



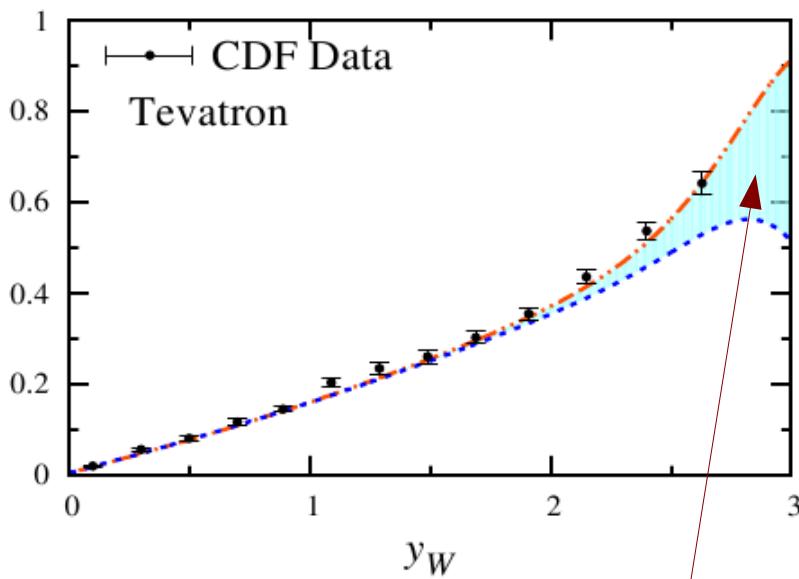
Appendix: Very large x at Tevatron and LHC

W charge asymmetry at Tevatron

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

Directly reconstructed W :

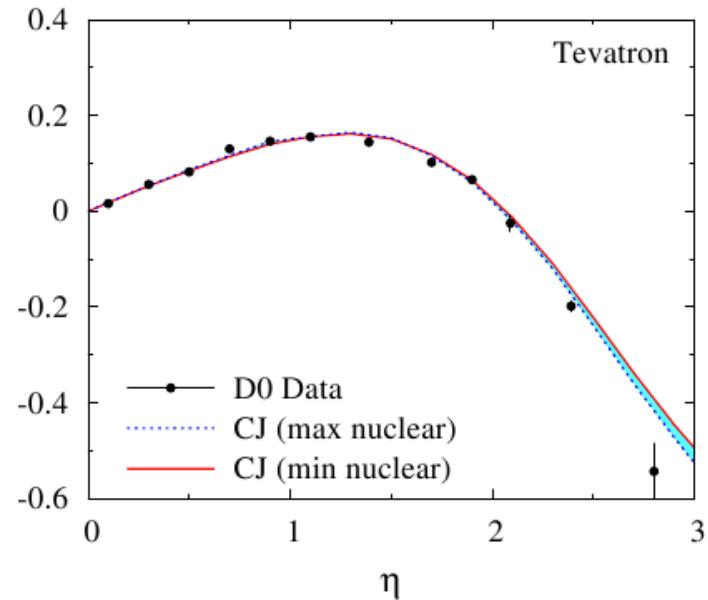
- highest sensitivity to large x



sensitive to
 d at high x

From decay lepton $W \rightarrow l + \nu$:

- smearing in x



Can constrain
Nuclear models!

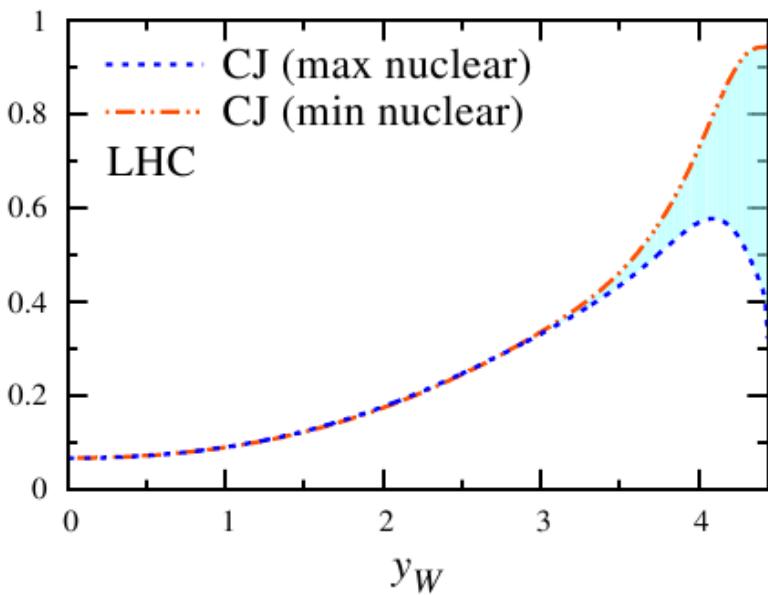
- Too little large- x sensitivity in lepton asymmetry:
 - need reconstructed W

W charge asymmetry at LHC

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

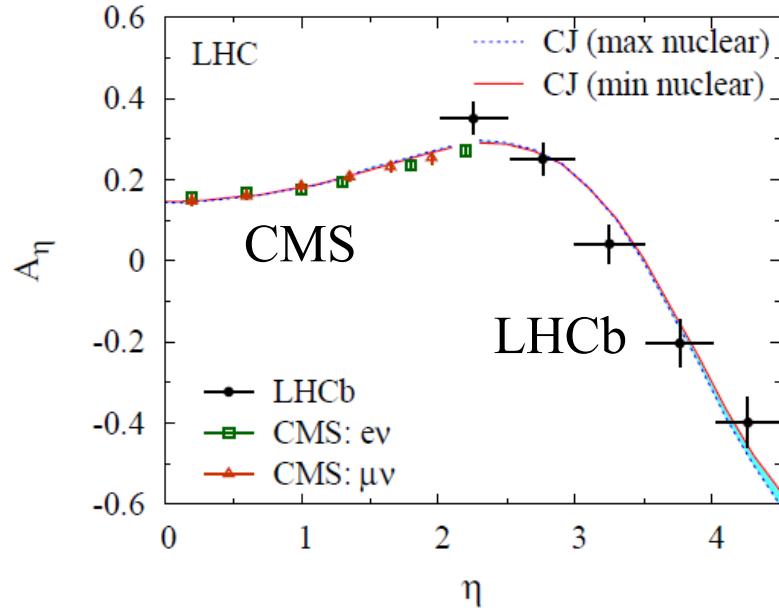
Directly reconstructed W :

- highest sensitivity to large x



From decay lepton $W \rightarrow l + \nu$:

- smearing in x

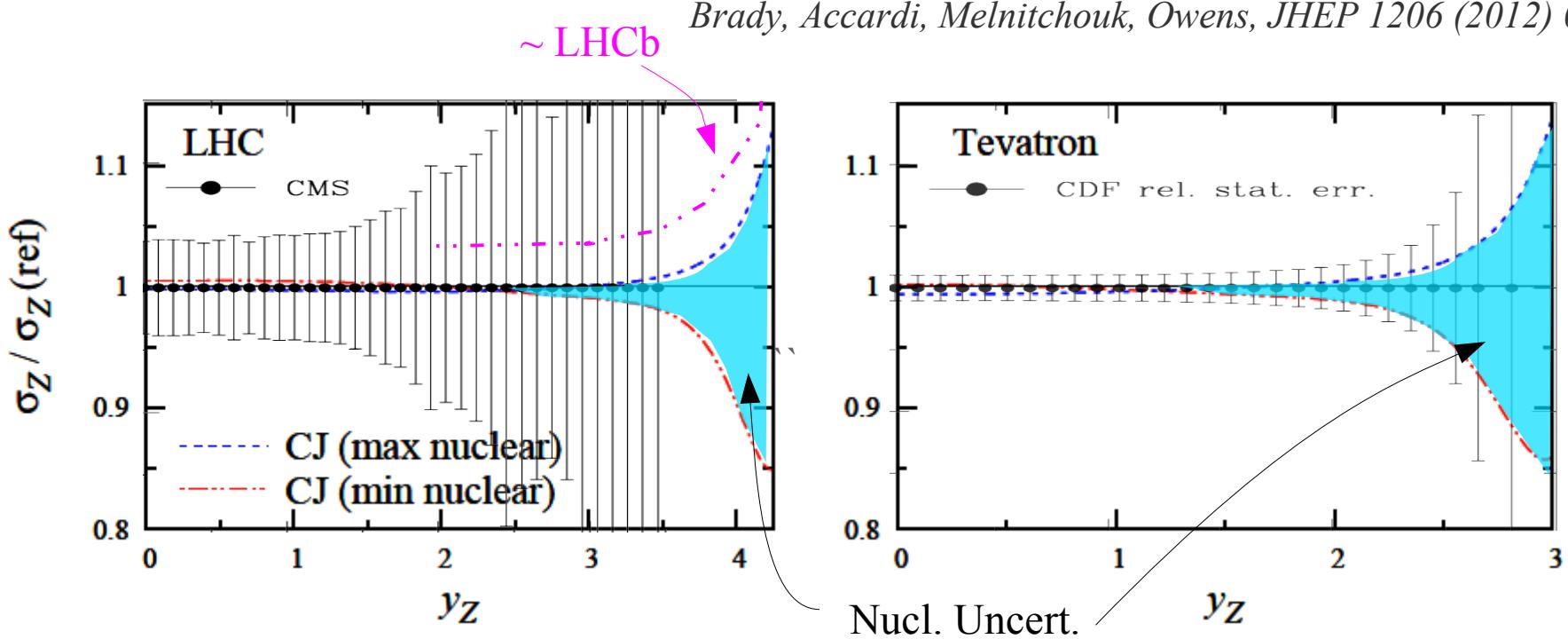


❑ Would be nice to reconstruct W at LHCb

- Definitely needs more statistics
- Is it at all possible?? (too many holes in detector?)
- Systematics in W reconstruction?
- **What about RHIC, AFTER@LHC?**

Z rapidity distribution

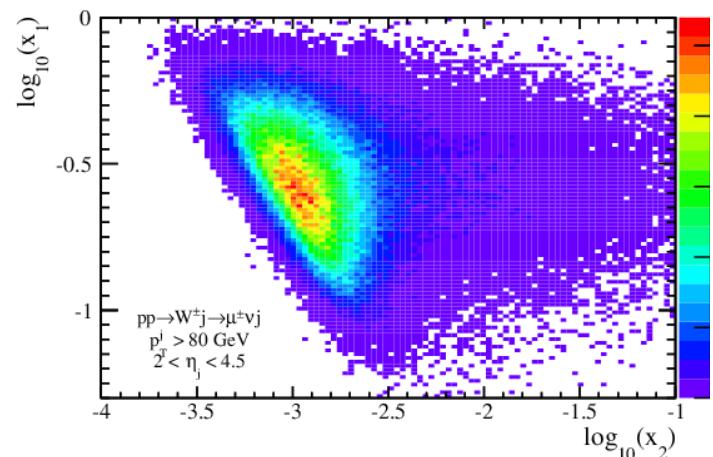
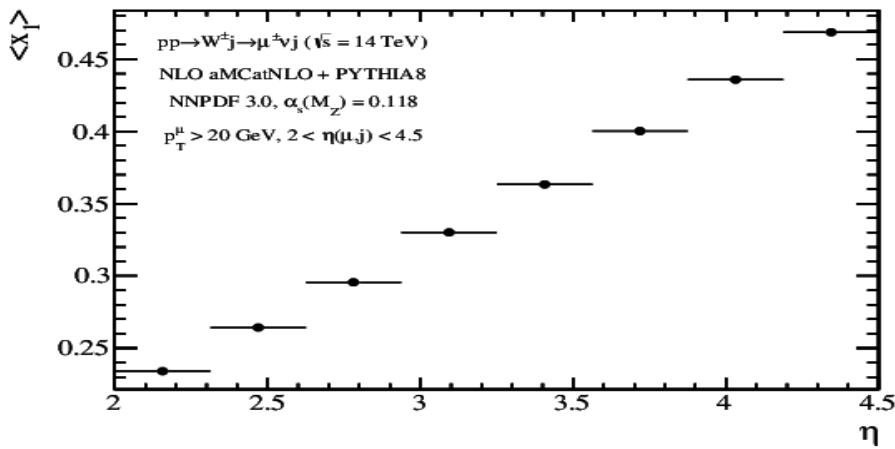
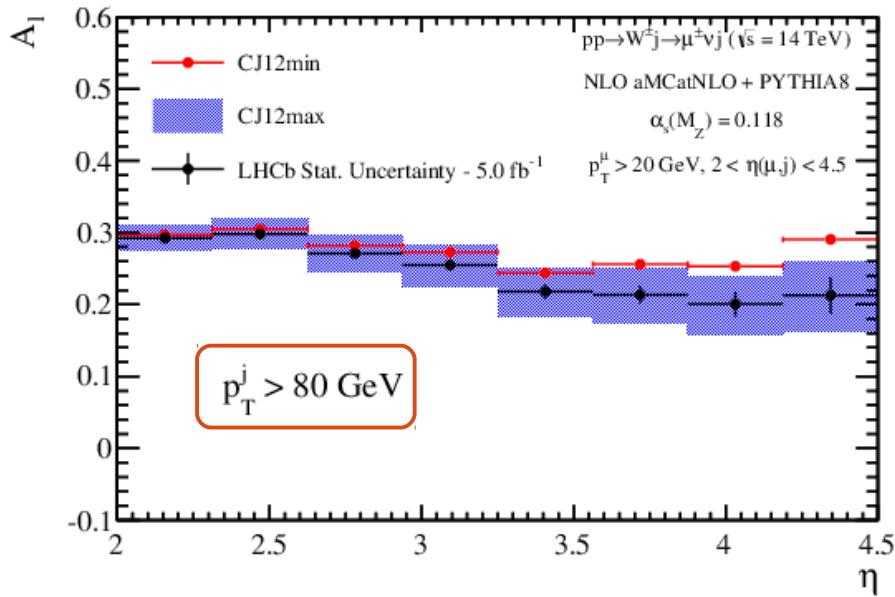
Brady, Accardi, Melnitchouk, Owens, JHEP 1206 (2012) 019



- ❑ 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?

$W+c$ at LHCb

S.Farry and R.Gauld, Benasque workshop, Feb 2015



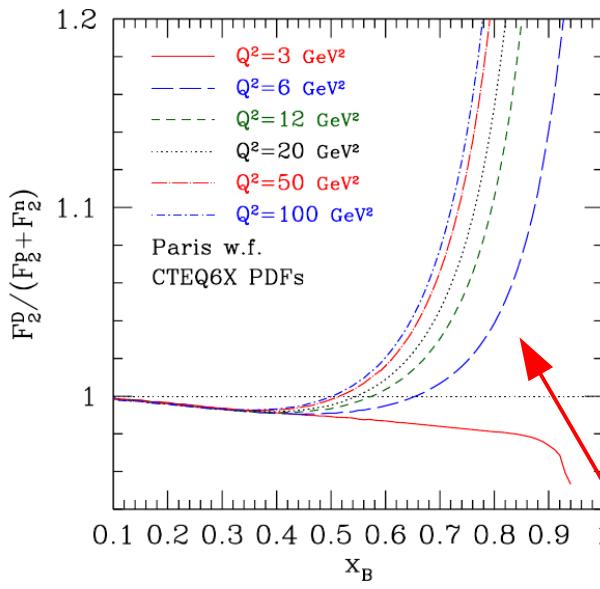
Appendix: Nuclear corrections

CJ12 Deuteron corrections

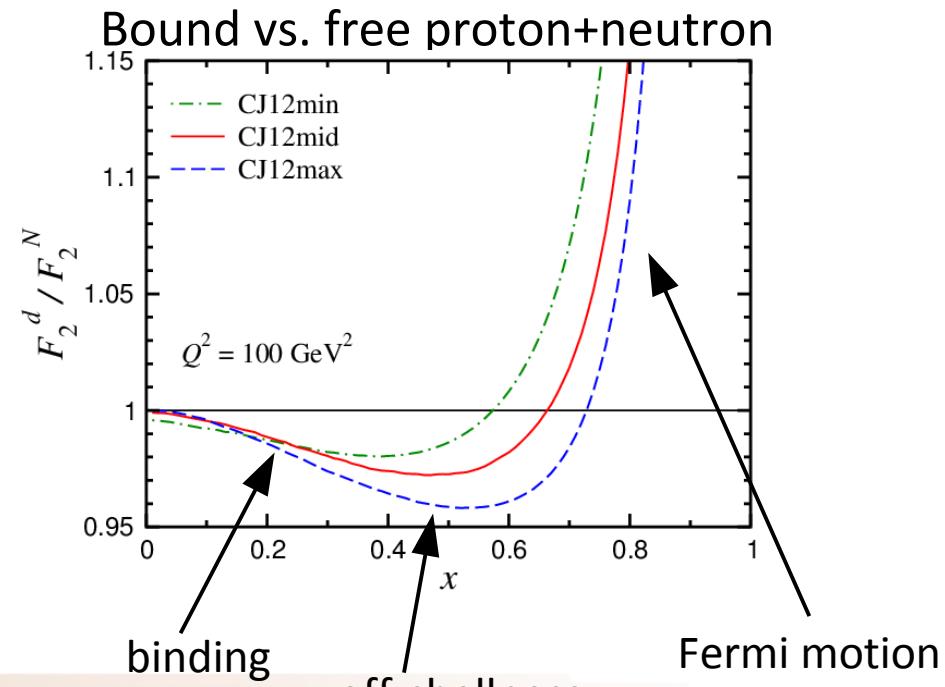
- No free neutron! Best proxy: Deuteron

- Parton distributions (to be fitted)
 - nuclear wave function (AV18, CD-Bonn, WJC1, ...)
 - Off-shell nucleon modification (model dependent)
- Theoretical uncertainty

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



Strong Q^2 dependence at large x !



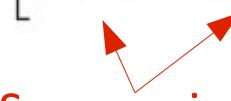
Nuclear corrections for p+d DY

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

- Same nuclear model for DY cross sections

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

Same as in DIS
(in Bj. limit)



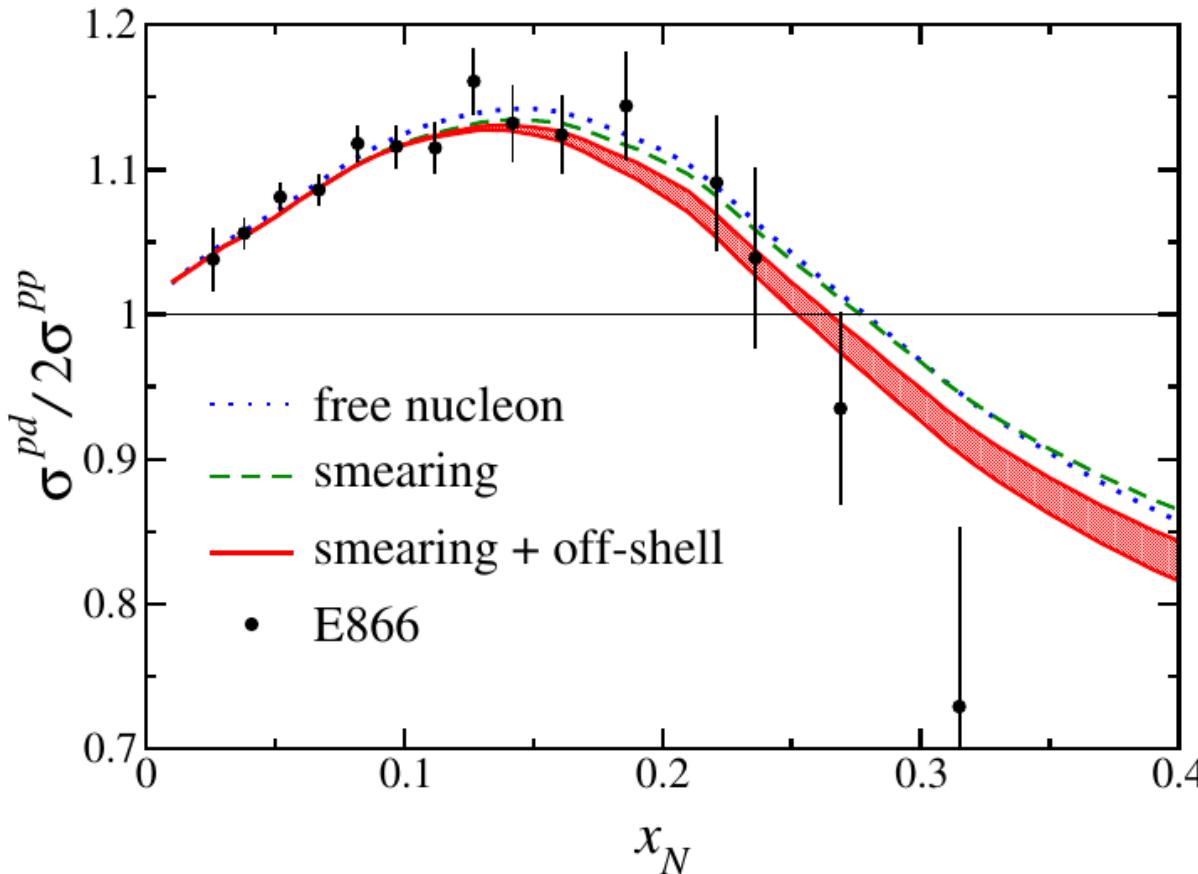
- Off-shell model extended to sea quarks and gluons
 - Spectral function in suitable spectator model

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

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

Nuclear corrections...

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

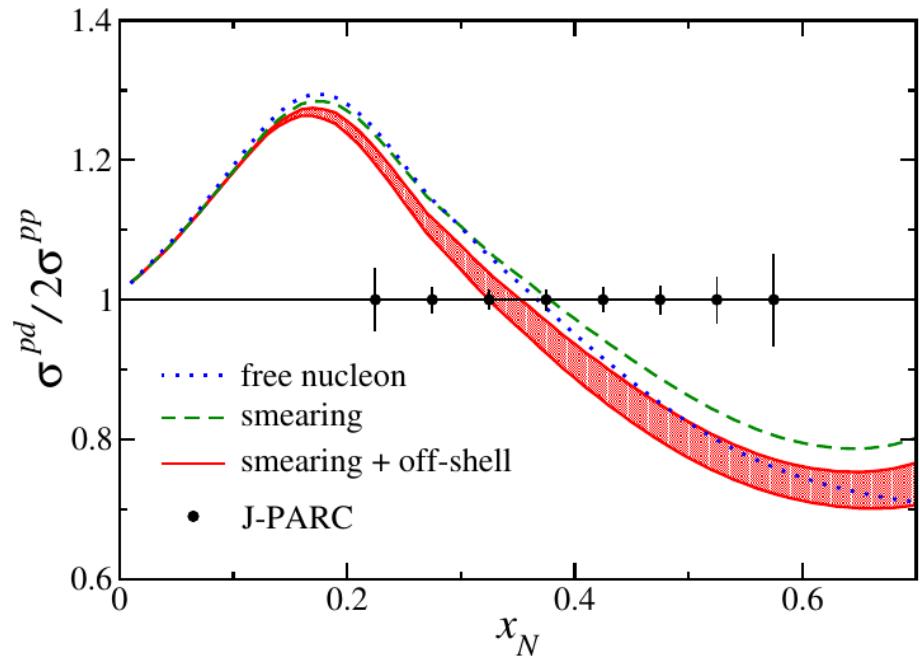
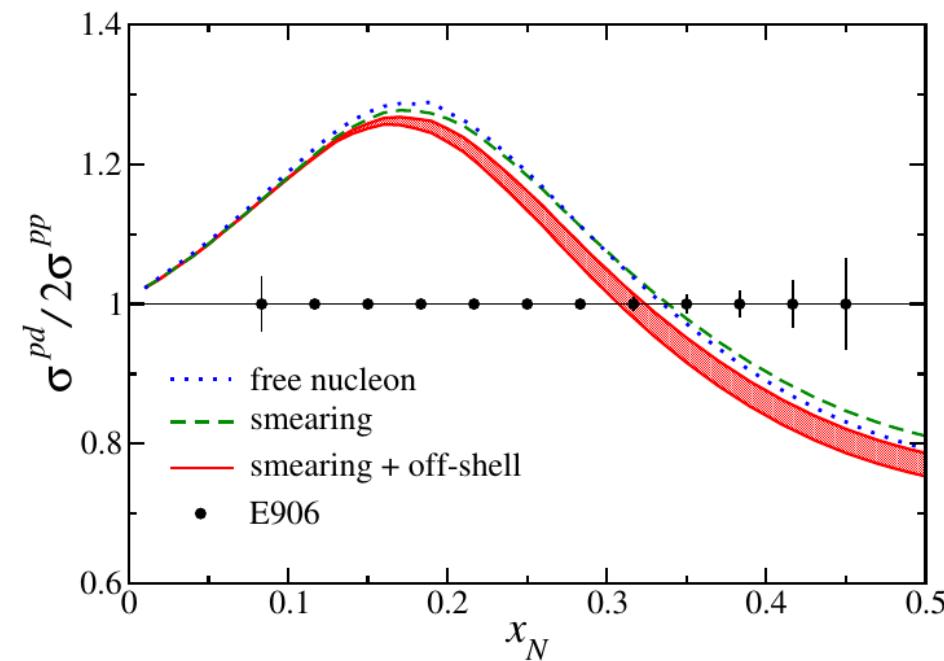


Red band:
combined wave fn.
& off-shell model
uncertainty

- Off-shell corrections help makes $\bar{d} - \bar{u}$ 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

Sea quarks

Charge symmetry breaking

□ E866 lepton pairs:

$$\bar{d}(x) - \bar{u}(x) \neq 0 \text{ at } x > 0.1$$

- Maybe even negative
(a theory challenge...)

□ E906 / SeaQuest

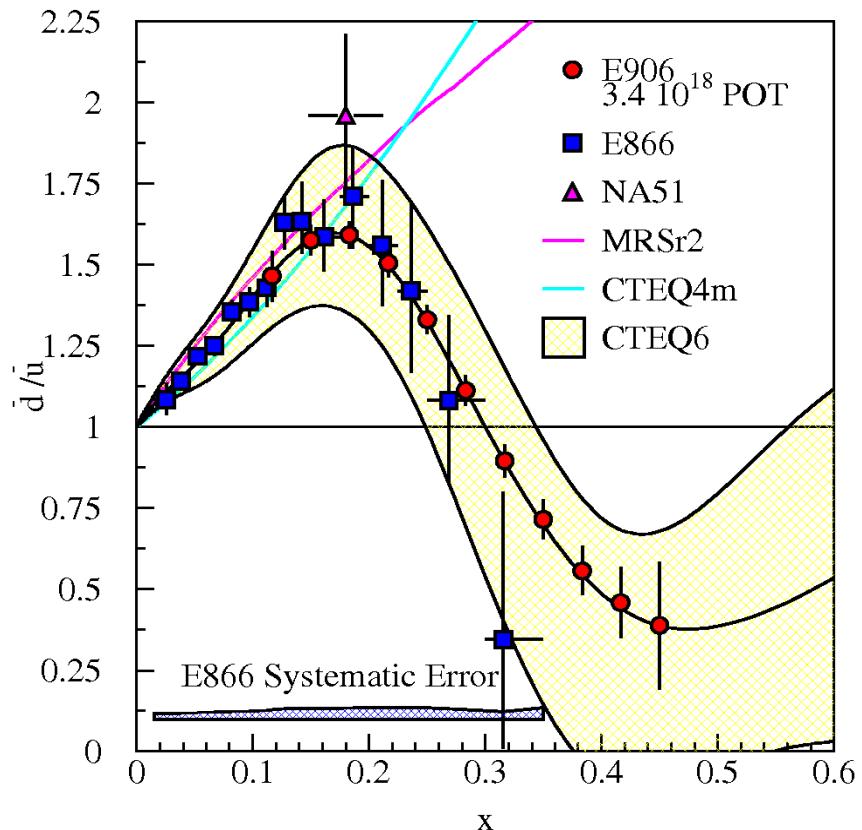
- Will focus on large x

□ LHC W/Z production:

- Access to $x \sim 0.01$ range

□ **But** $\frac{\bar{d}}{\bar{u}} \neq \frac{\sigma_{pp}}{\sigma_{pd}} - 1$

**Theory corrections needed
for few % level accuracy**



Appendix: Large-x data

New Large-x data: a partial list

□ DIS data minimally sensitive to nuclear corrections

- DIS with slow spectator proton (**BONUS**)
 - Quasi-free neutrons
- ${}^3\text{He}/{}^3\text{H}$ ratios (**Marathon**)

Jlab

□ Data on free (anti)protons, sensitive to d

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

**Tevatron: CDF, D0
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 $e+d$

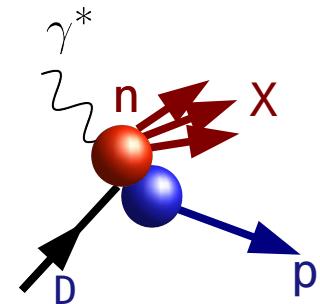
**RHIC ??
AFTER@LHC**

...

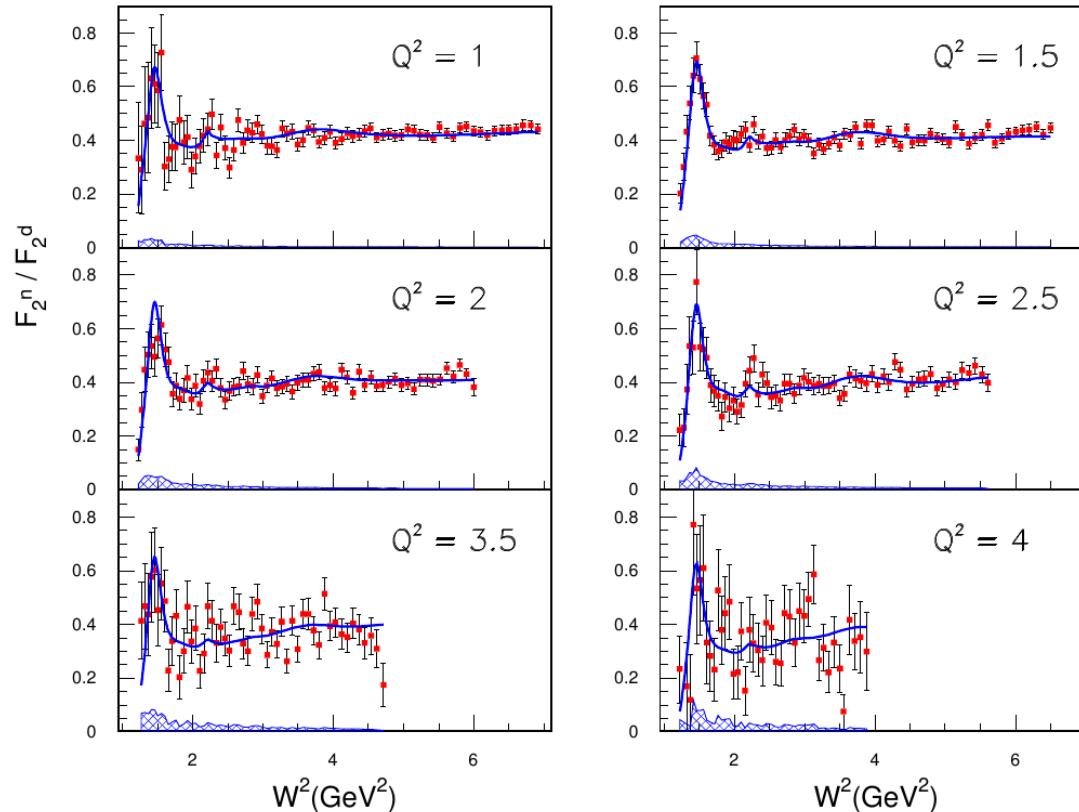
JLab 6 GeV: Quasi-free neutrons for today

□ Spectator proton tagging

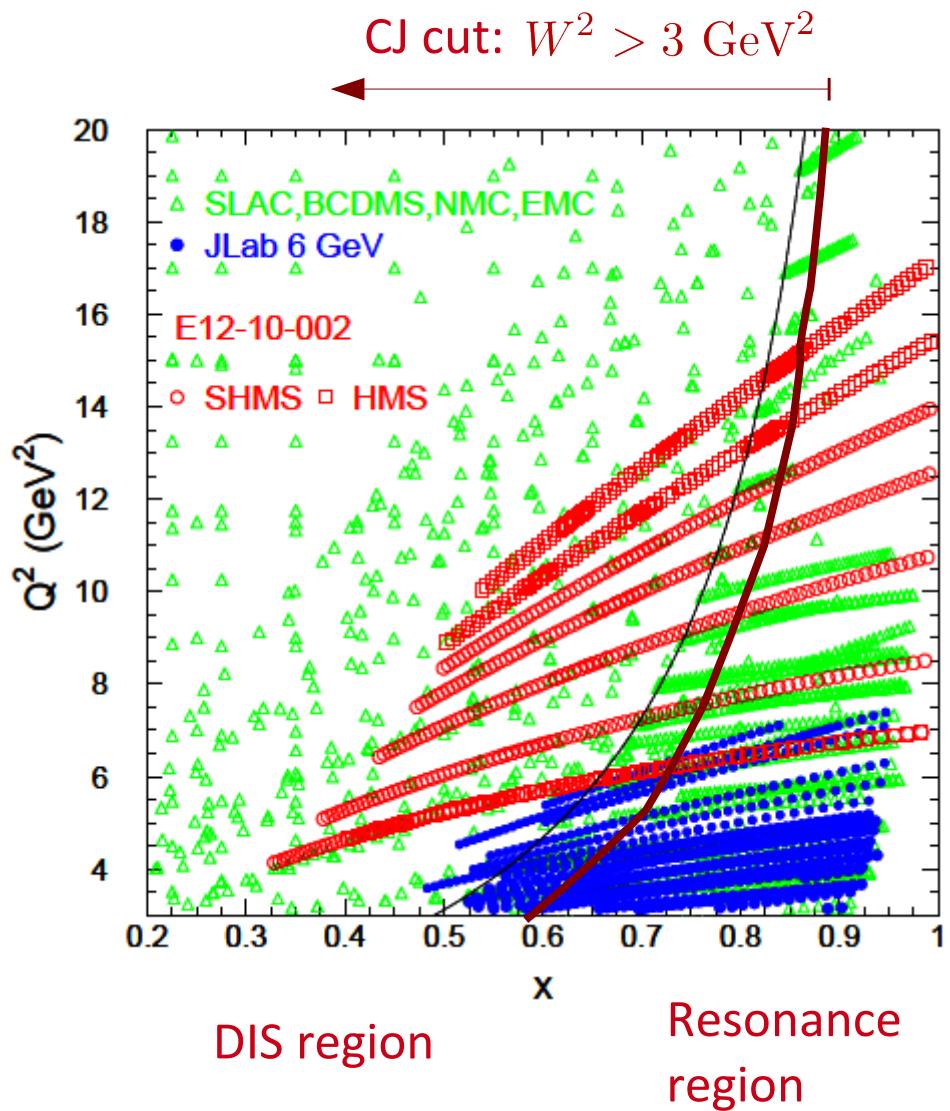
- Nuclear corrections minimized experimentally



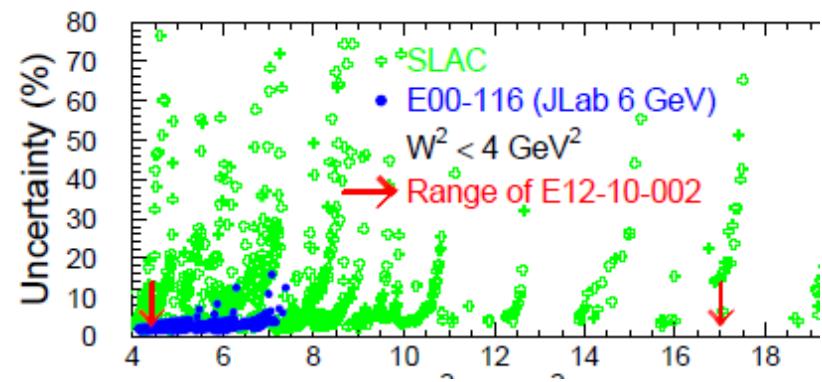
BONUS coll.,, Tkachenko et al. arXiv:1402.2477



JLab 12 - proton, deuteron structure functions



Jlab12 experiment E12-10-002

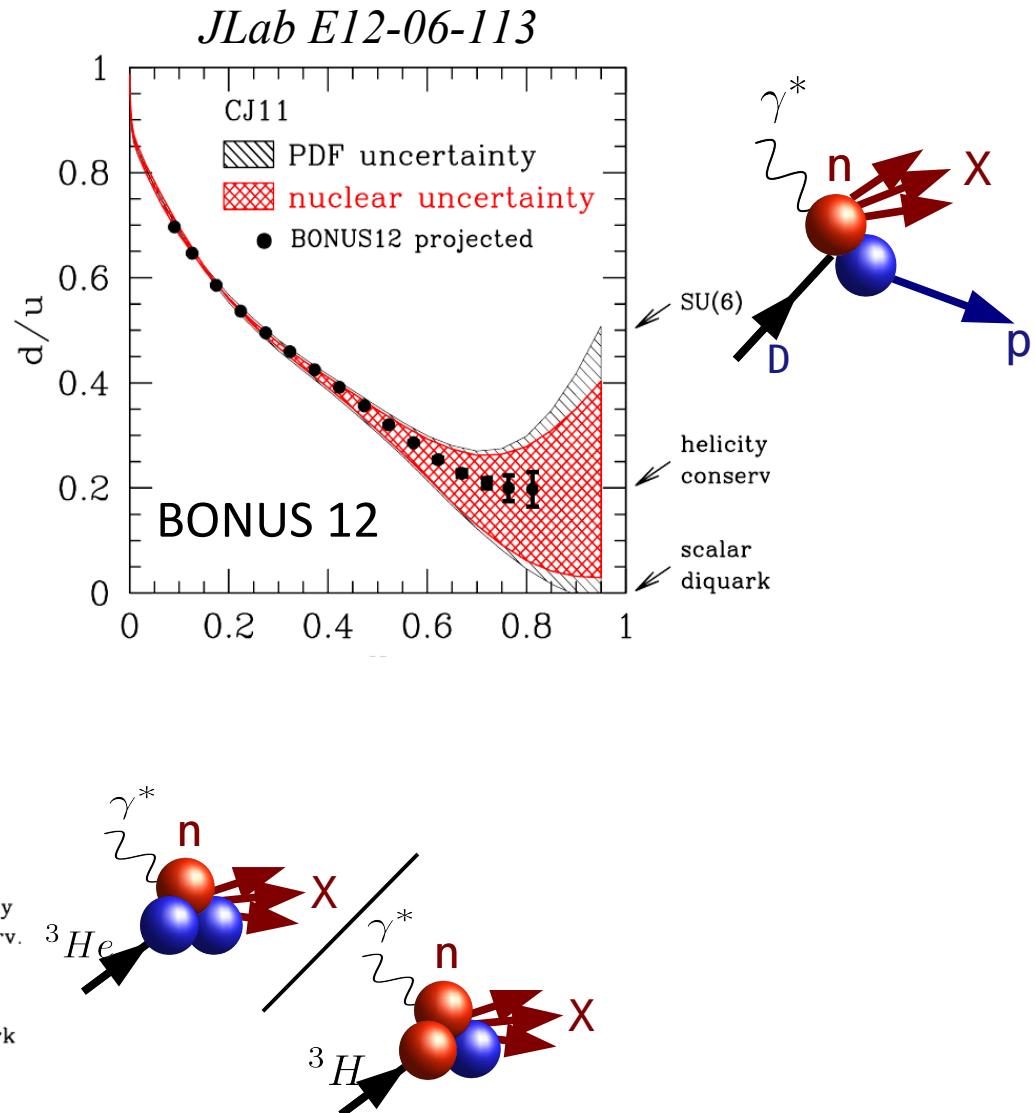
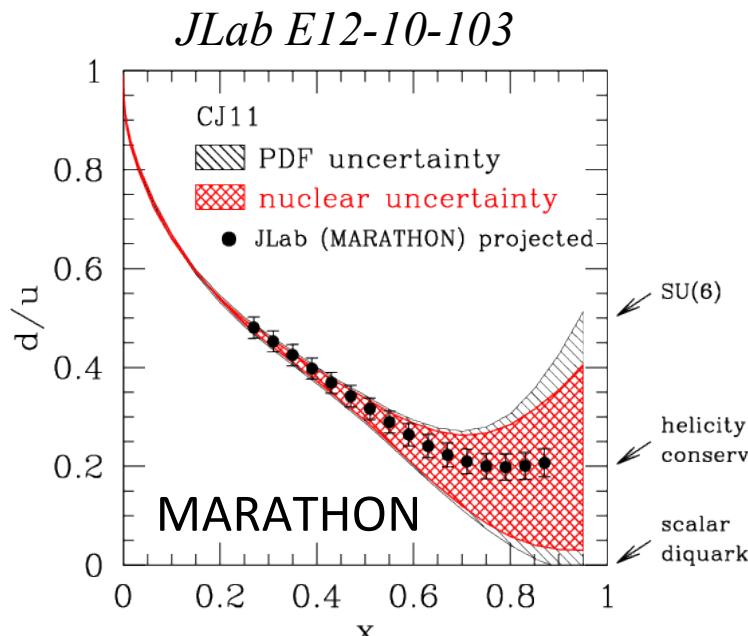


☐ JLab 12 GeV

- 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
 - ${}^3\text{He}/{}^3\text{H}$ cross sec. ratio

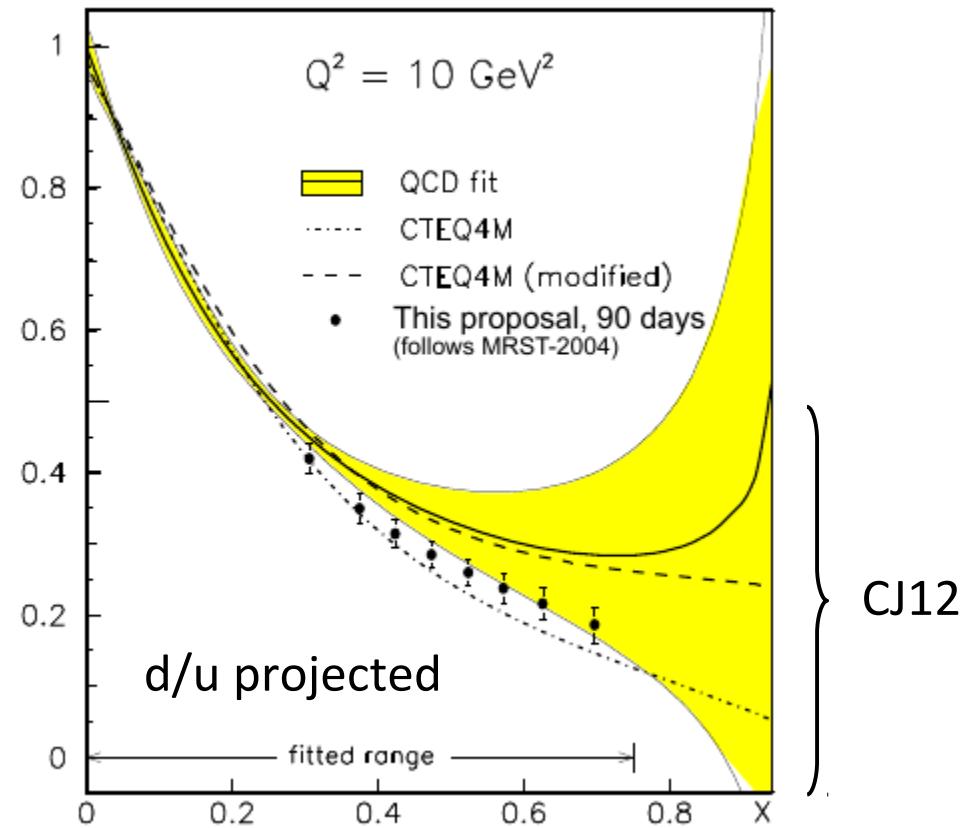
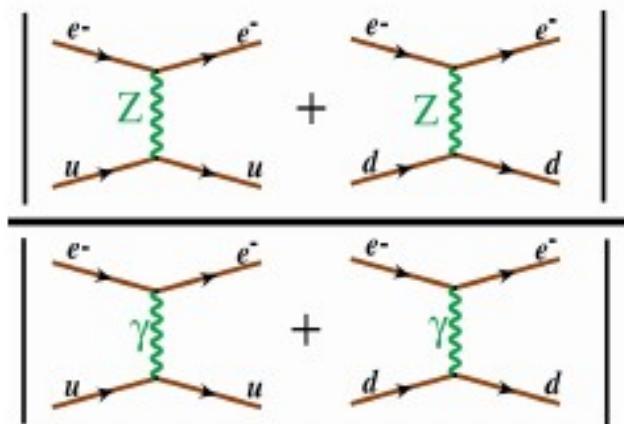


JLab 12: Parity-Violating DIS

Jlab12 experiment E12-10-007

- Longitudinally polarized electrons → PV asymmetry

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



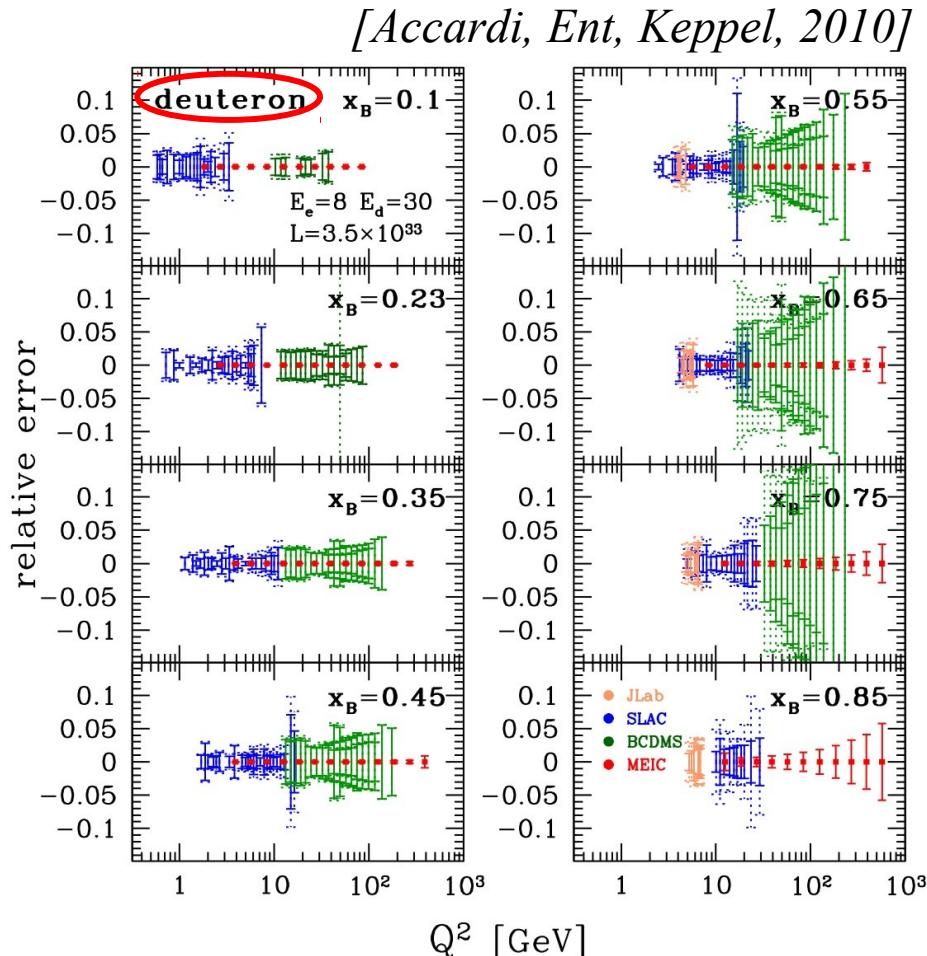
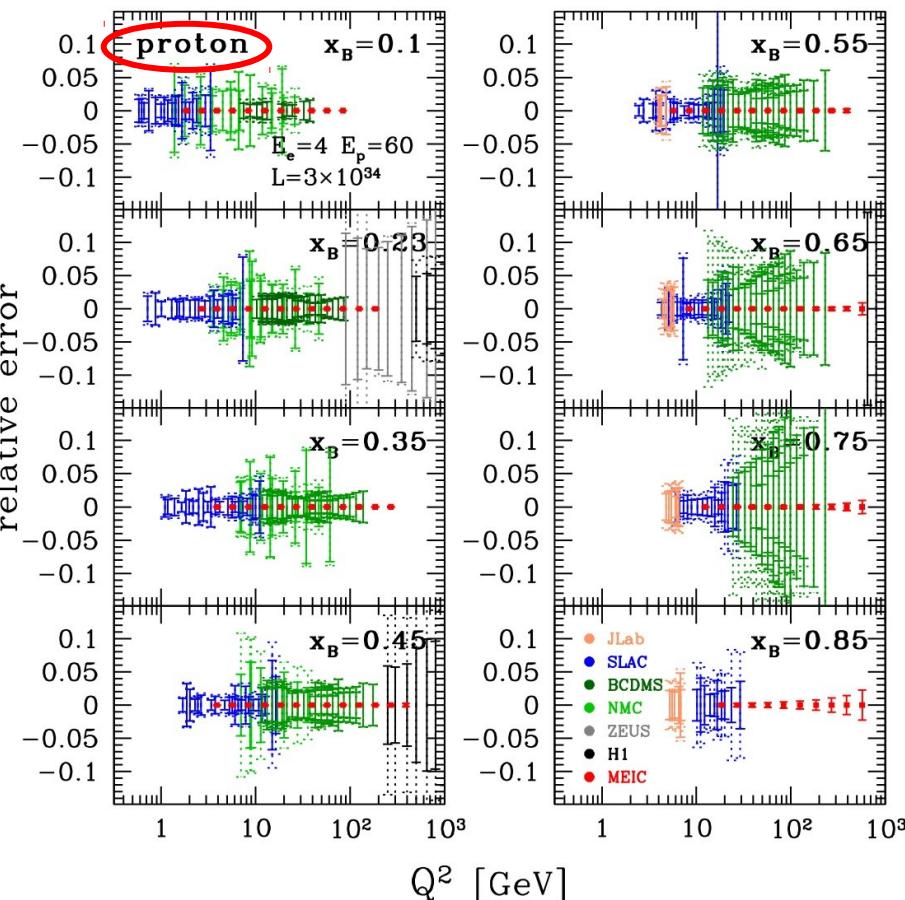
CJ12

Appendix: old and new experiments - examples -

At the EIC

□ Neutral current DIS

- MEIC $\nu s = 31 \text{ GeV}$ (ca. 2010)
- Pseudo data using “CTEQ6X” fits, $L=230 (35) \text{ fb}^{-1}$

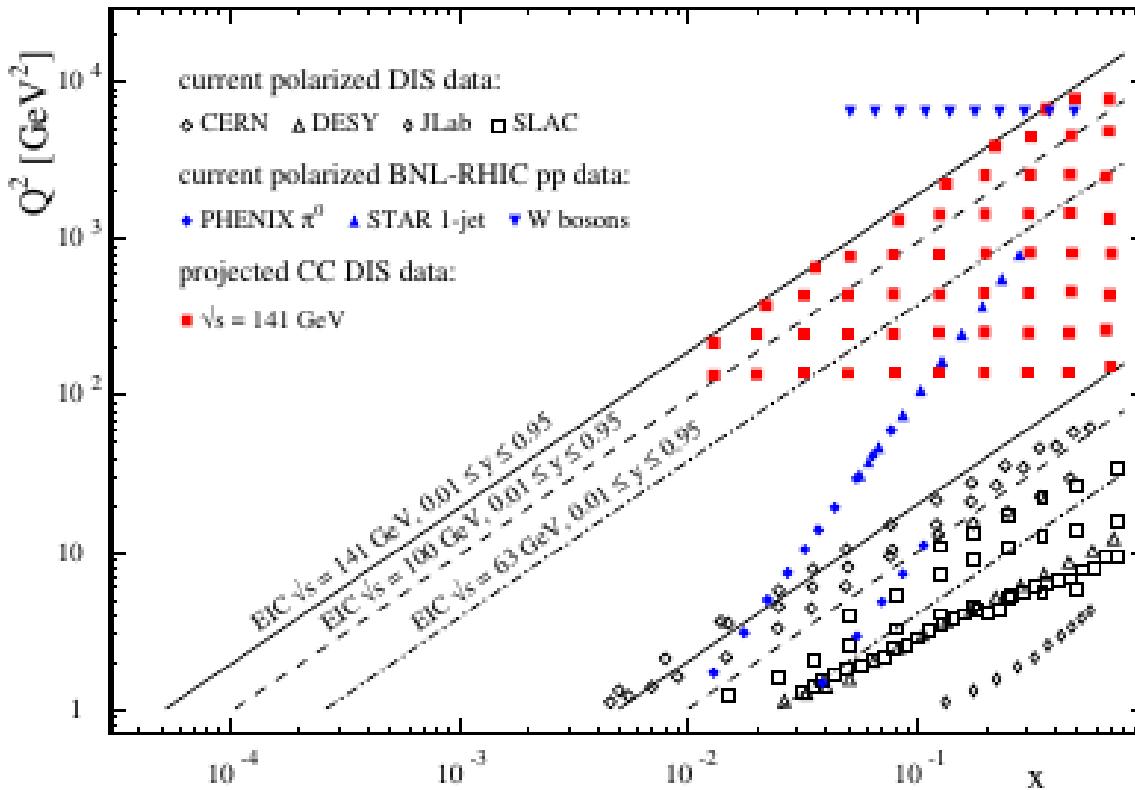


At the EIC

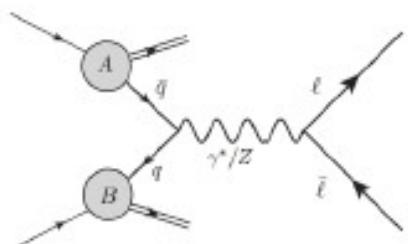
□ Charged current DIS

- 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]

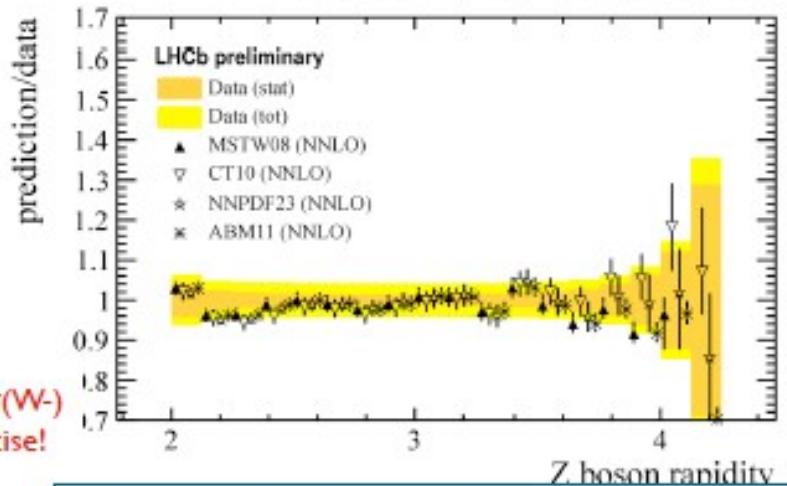
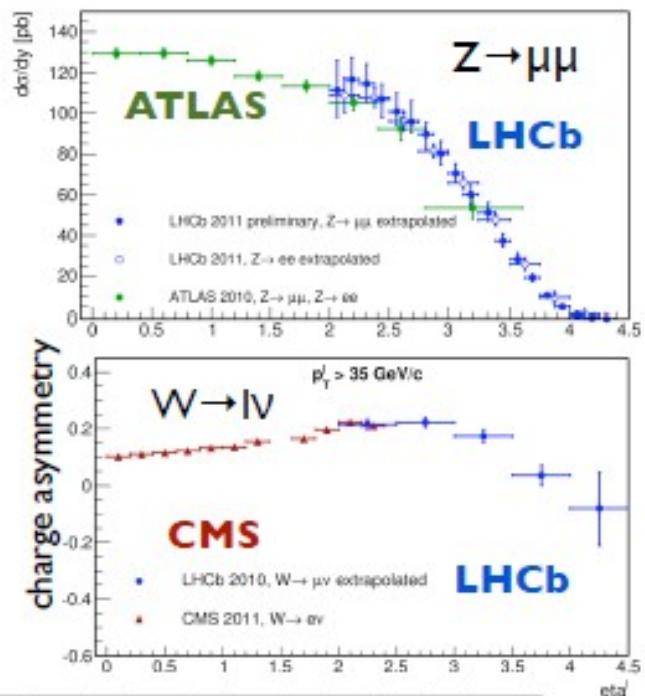
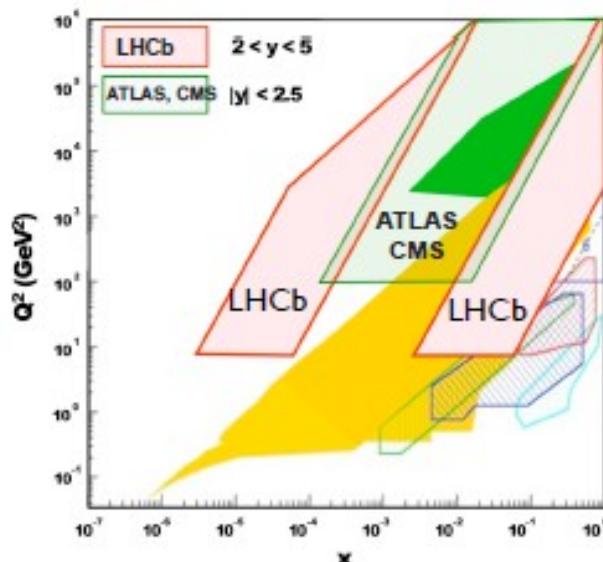
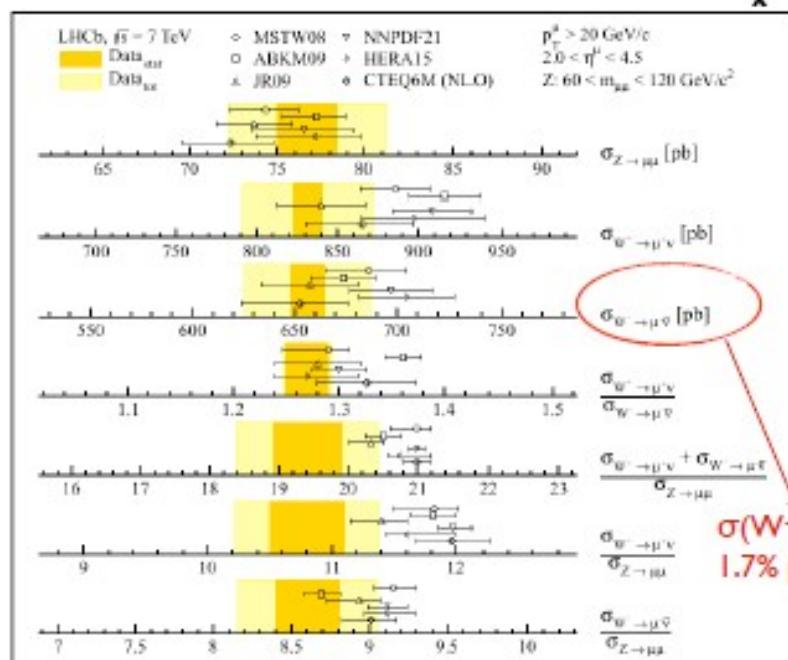


Constraints from the LHC: Electroweak Boson Production



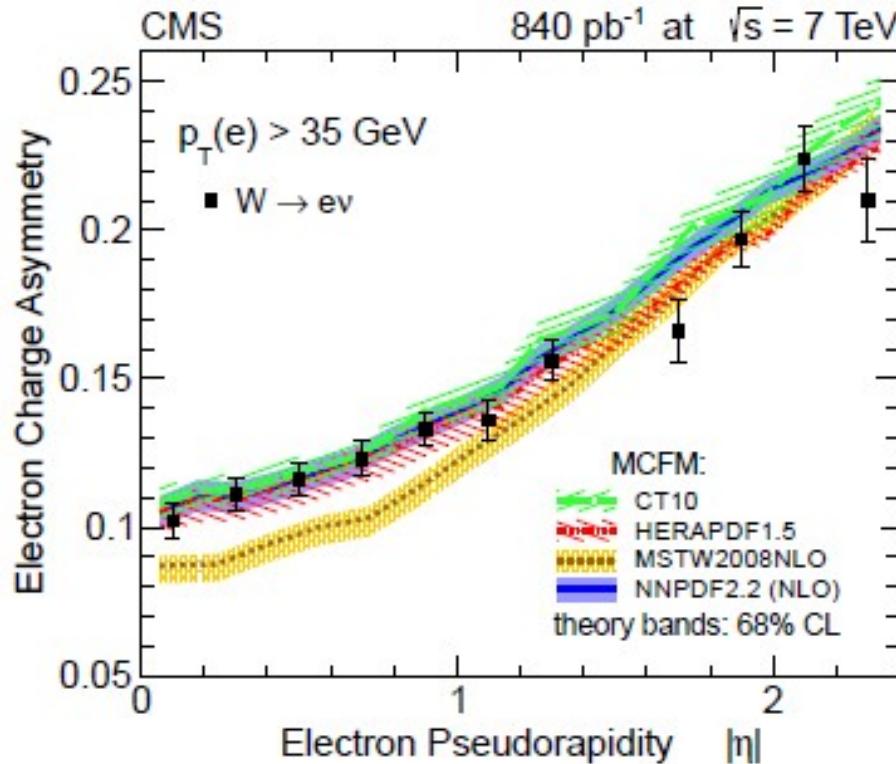
**probe light quarks
at low and high x**

LHCb (S.Tourneur)



Systematic error comparable with PDF error
Benchmarking different PDF sets

W lepton asymmetry at LHC



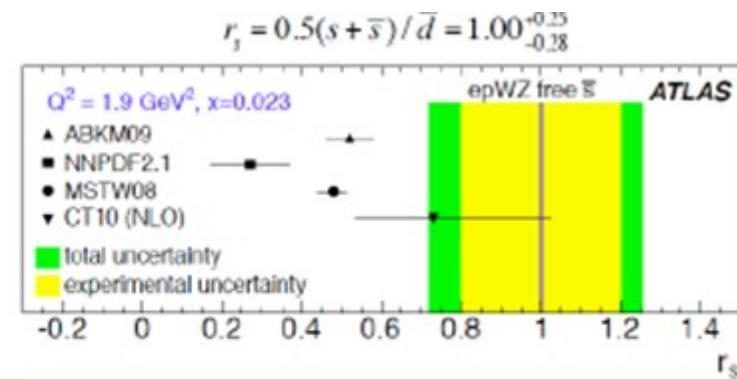
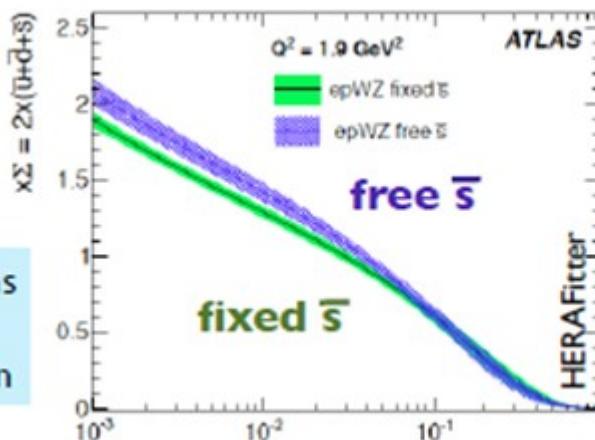
Sensitive both to d/u at $x > 0.1$ and \bar{u}/\bar{d} at $x \sim 0.01$ (not constrained well by other experiments)

Constraints on strangeness: $W, Z, W+c$

ATLAS (K. Nikolic)

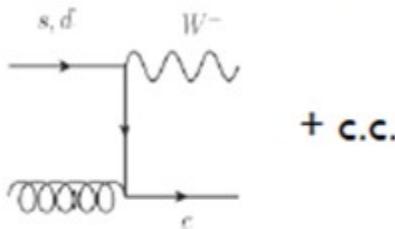
$\sqrt{s}=7 \text{ TeV}, L=35 \text{ pb}^{-1}$

Z,W rapidity distributions
sensitive to
strangeness in the proton



data disfavors strangeness suppression

$W+c$ probe strangeness



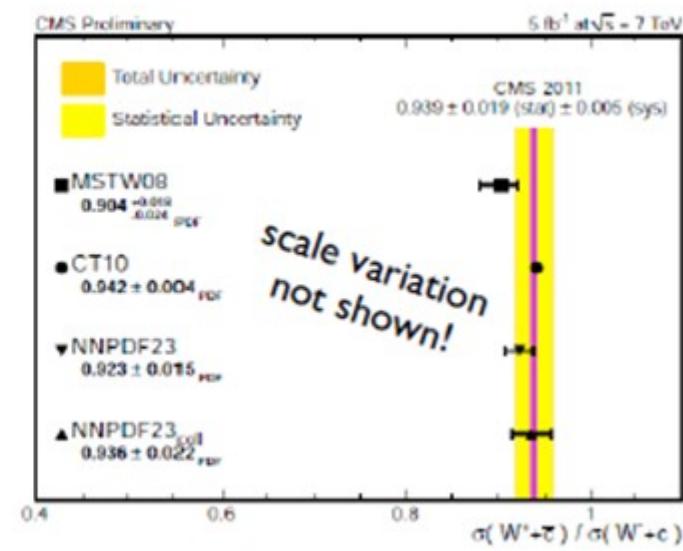
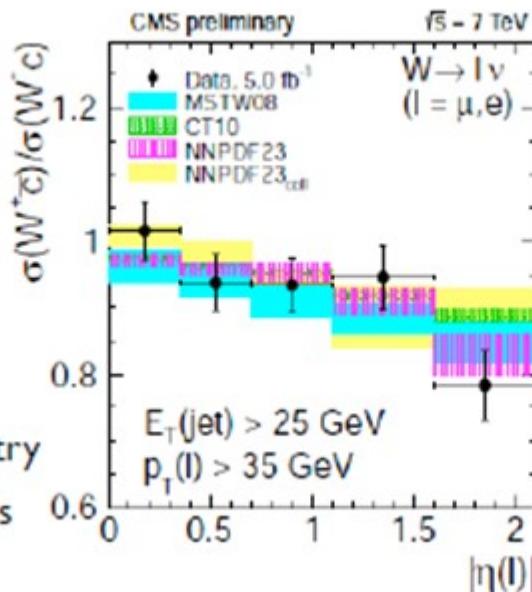
(E. Vryonidou)

Ratios: $\frac{W^+ + \bar{c}}{W^- + c}$, $\frac{W + c}{W + \text{jets}}$

Strangeness and strange asymmetry

Precise data could constrain PDFs

W+ charm & jets



K. Lipka, DIS'13 WG1 summary

Constraints on strangeness: K^\pm at the EIC

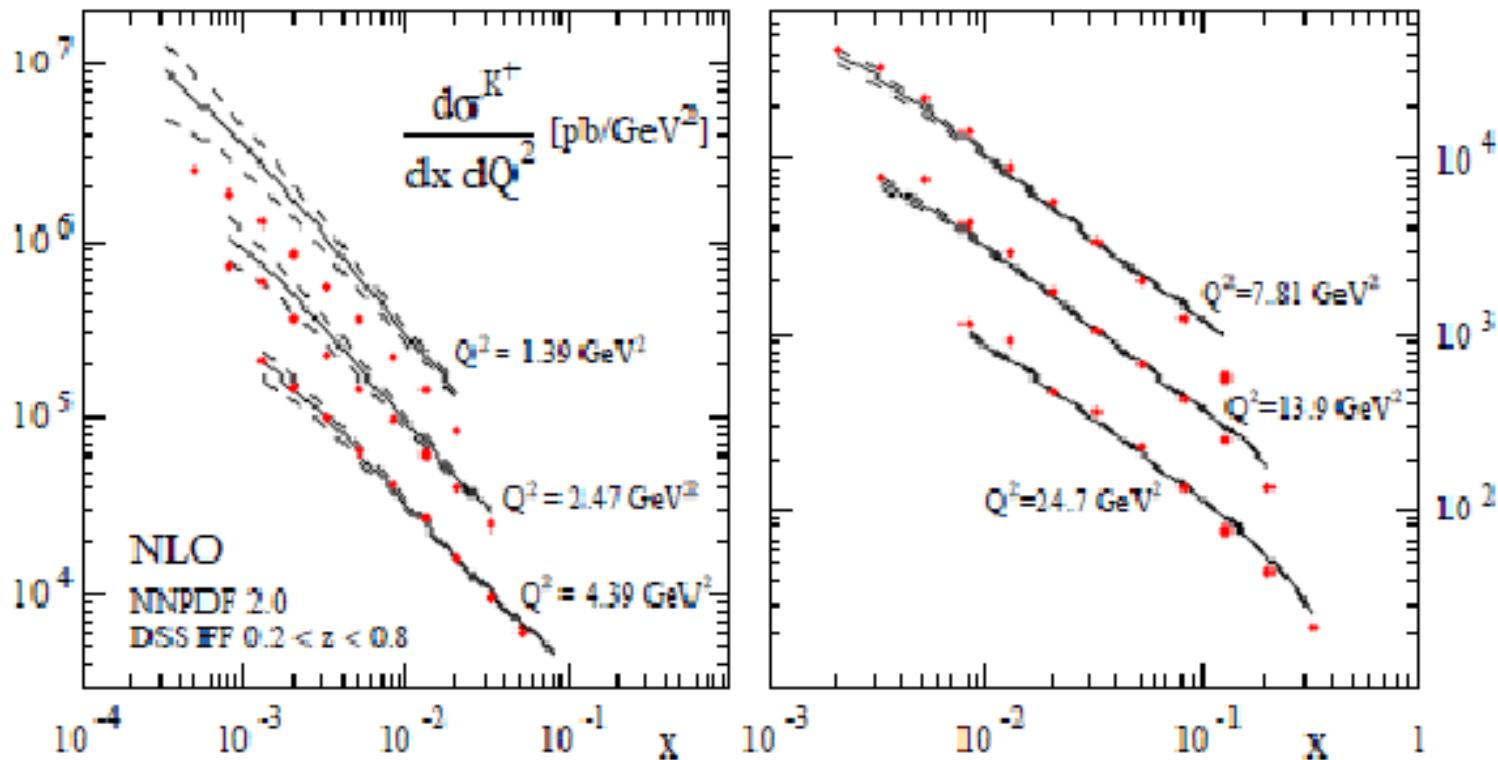


Figure 1.10. SIDIS cross section for K^+ production at NLO accuracy using NNPDF2.0 PDFs [47]. The dashed lines denote the PDF uncertainties. Also shown (points) are the results from a PYTHIA simulation (see text).

Aschenauer, Stratmann, in 1108.1713

Intrinsic charm at the EIC

The ultimate test of the intrinsic charm mechanism is possible in charm SIDIS at the EIC with modest luminosities

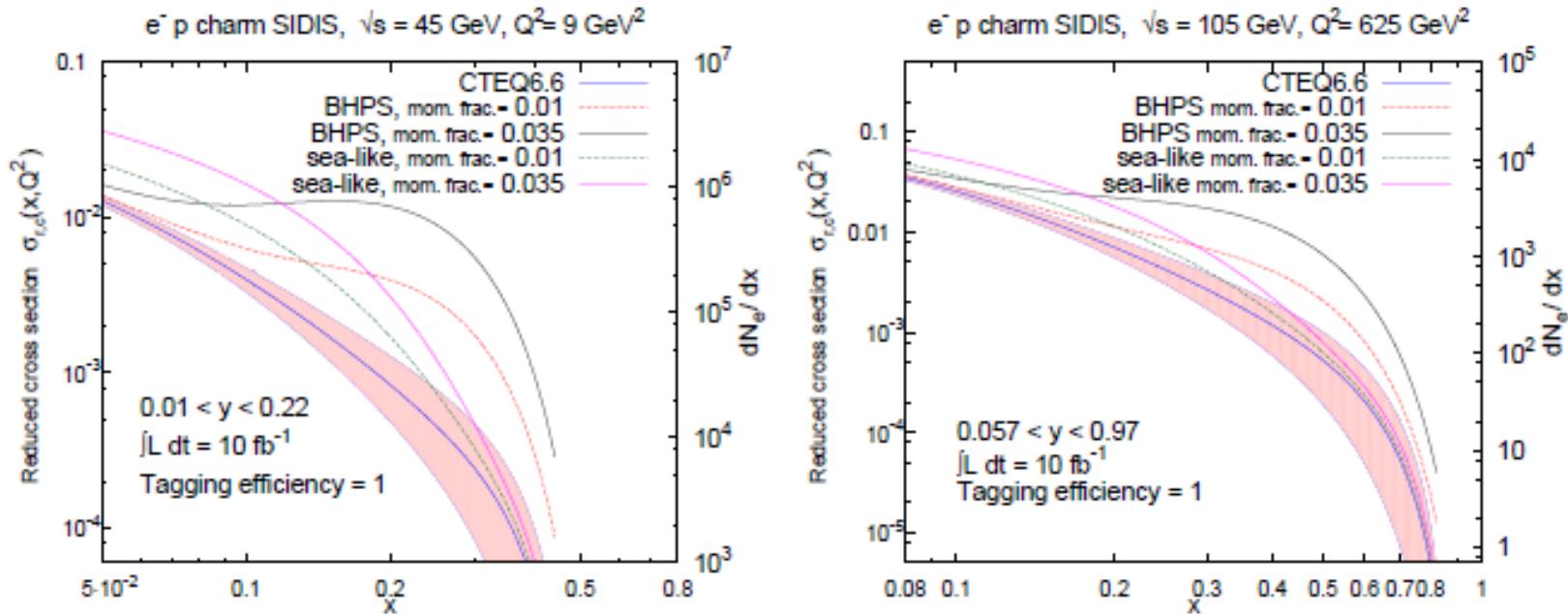


Figure 1.20. Charm contribution to the reduced NC e^-p DIS cross section at $\sqrt{s} = 45$ and 105 GeV. For each IC model, curves for charm momentum fractions of 1% and 3.5% are shown. For comparison we display the number of events dN_e/dx for 10 fb^{-1} , assuming perfect charm tagging efficiency.

Guzzi, Nadolsky, Olness, Sec. 1.9 in 1108.1713