CTEQ-JLab plans (and future data from JLab)

Alberto Accardi
Hampton U. and Jefferson Lab

"Parton Distributions for the LHC"

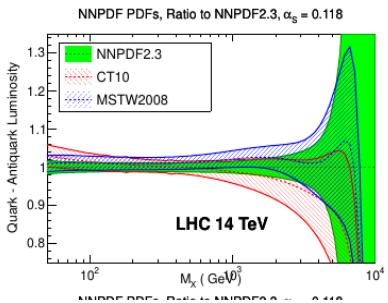
Benasque, 15–21 February 2015

The CTEQ-JLab global fits

- **Collaborators:**
  - **Theory:** A.Accardi, W.Melnitchouk, J.Owens
  - **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***
- **Public release: CJ12**
  - **Owens, Accardi, Melnitchouk, PRD87 (2013) 094012**
    - www.jlab.org/cj
    - Included in LHAPDF

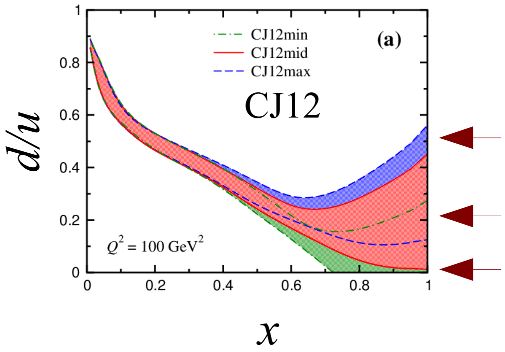
Why large x ?

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



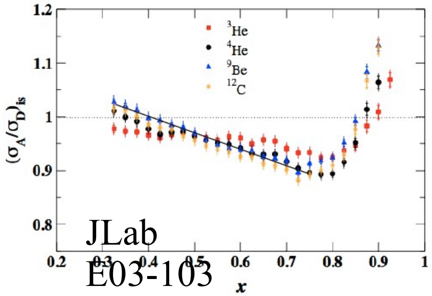
- **Reduce uncertainties**
  - Increase potential for LHC discoveries
  - Precision measurements of particle properties

- **Non-perturbative structure of the proton**
  - Effects of confinement on valence quarks
  - q – qbar asymmetries; isospin symmetry violation
  - Strangeness, intrinsic charm
  - Comparison to (lattice) QCD, …

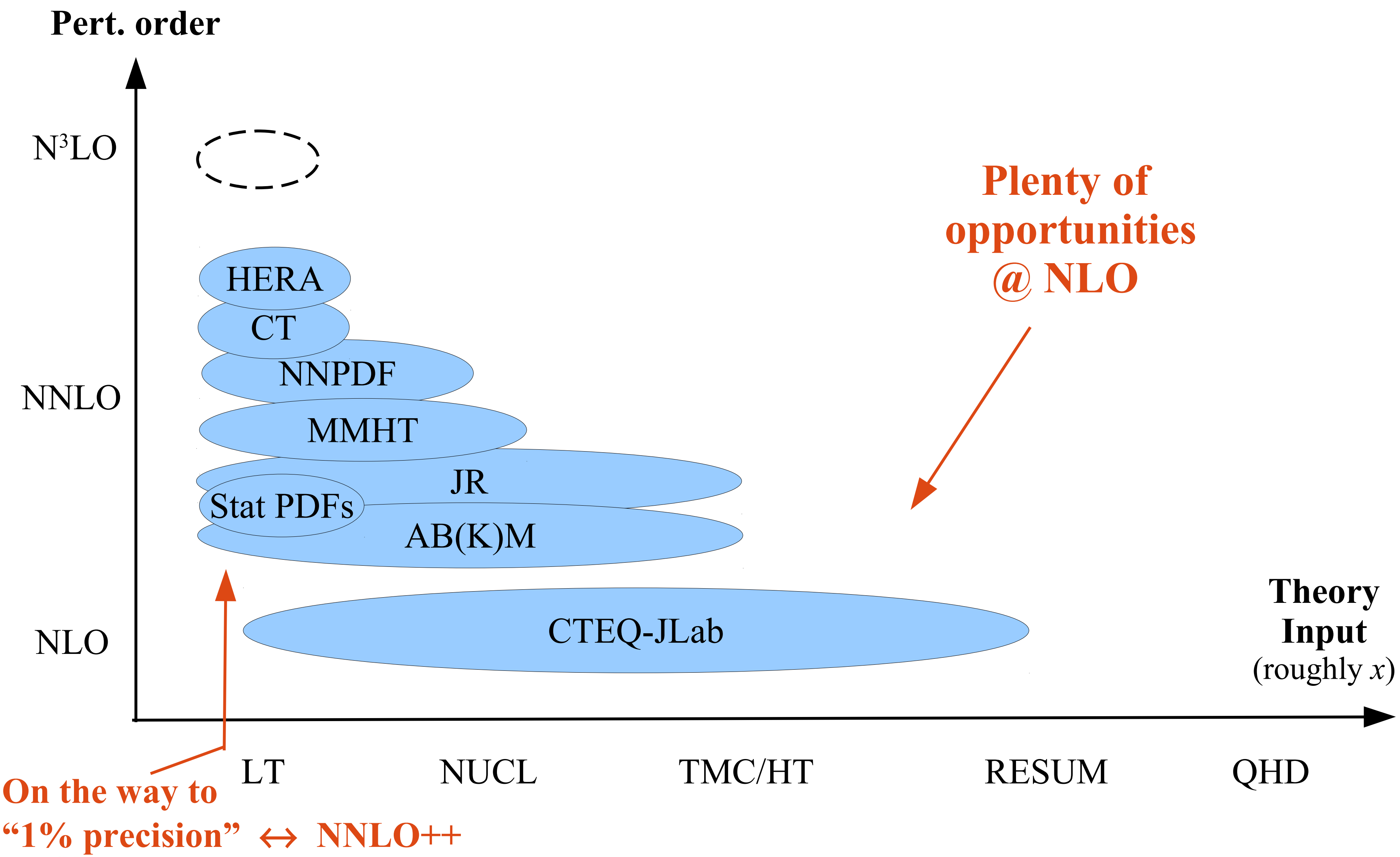


- **New handles on structure of the nucleus**
  - Nuclear targets for PDF fits (d-quark, neutrinos, ...)
  - Proton vs. nuclear targets

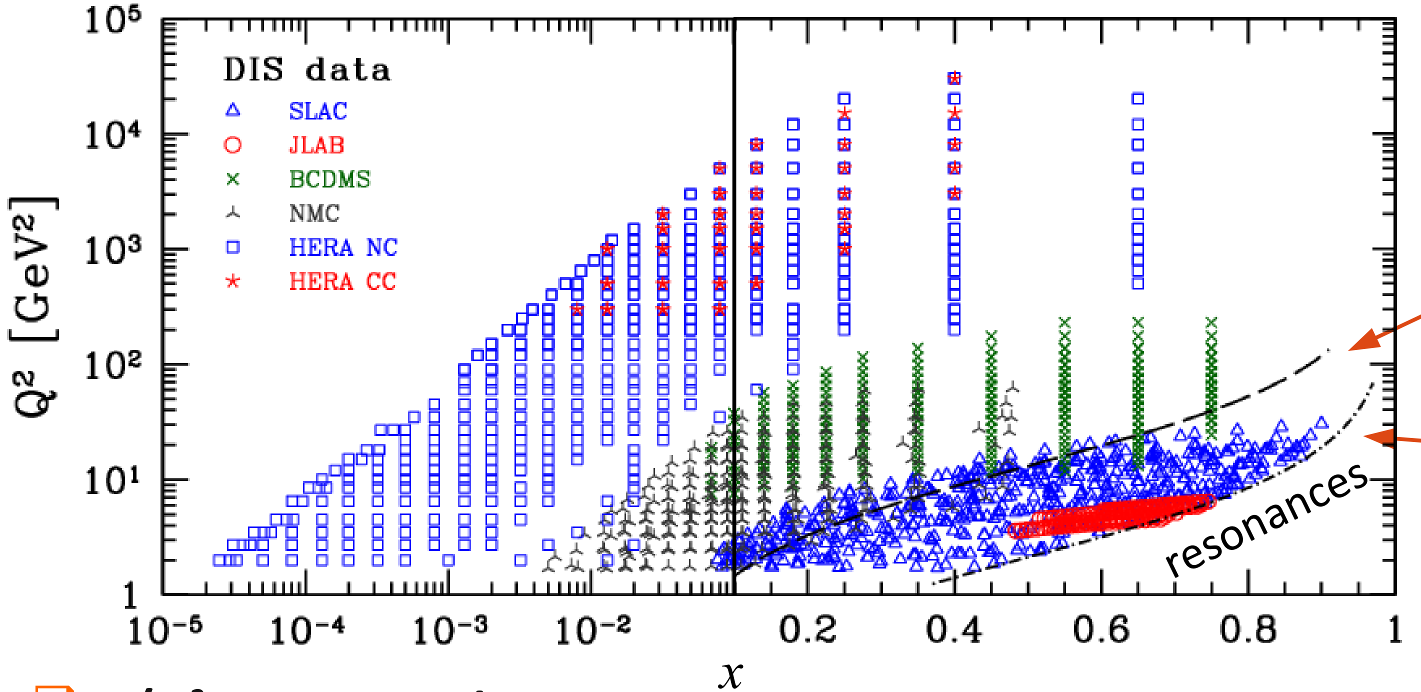
    → constraints on nuclear effects
  - A=1,2 anchor for nuclear PDFs / new light on EMC effect



A theory PDF landscape



Large-x, small-Q^2 corrections



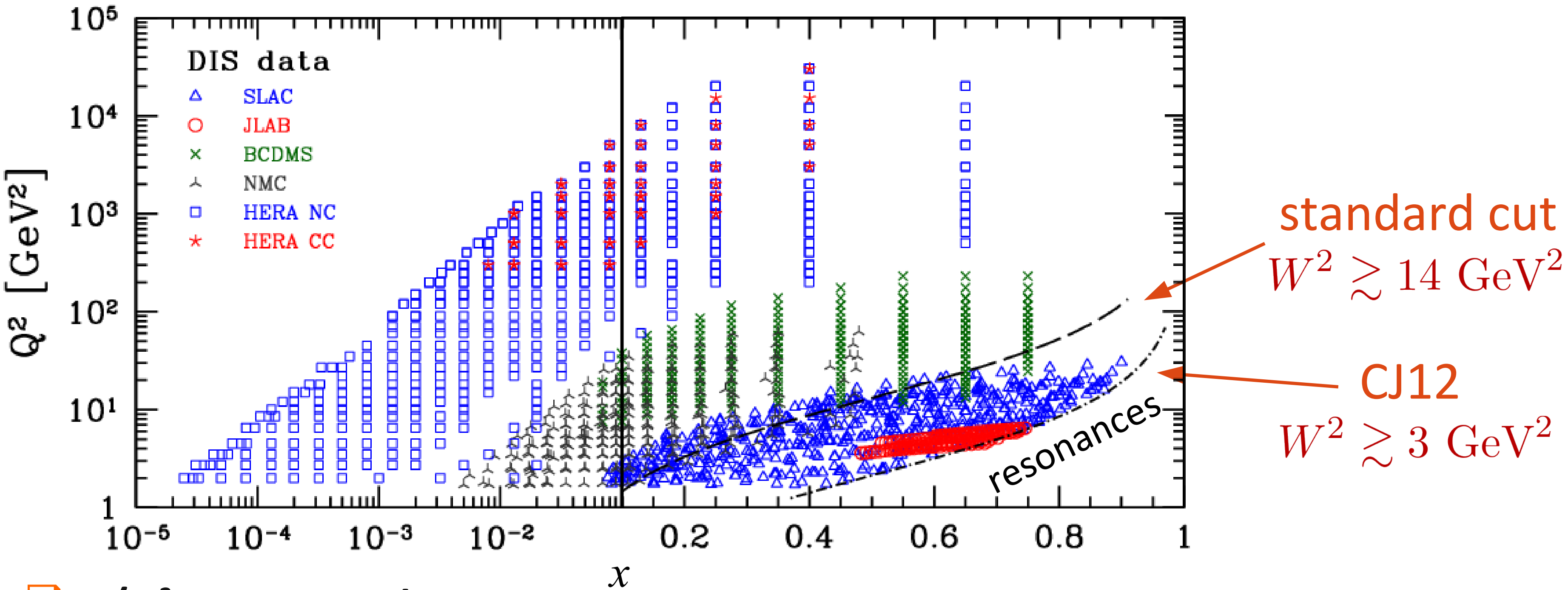
standard cut
$W^2 \gtrsim 14\ \text{GeV}^2$

CJ12
$W^2 \gtrsim 3\ \text{GeV}^2$

Accardi et al.
PRD ***D81*** *(2010)*

- **$1/Q^{2n}$ suppressed:**
  - Target mass corrections (TMC), higher-twists (HT)
  - Current jet mass, heavy quark masses
- **Non-suppressed**
  - Nuclear corrections, threshold resum., ...
- **New d-quark parametrization:** $d'(x) = d(x) + \alpha x^\beta u(x)$

Large-x, small-Q^2 corrections



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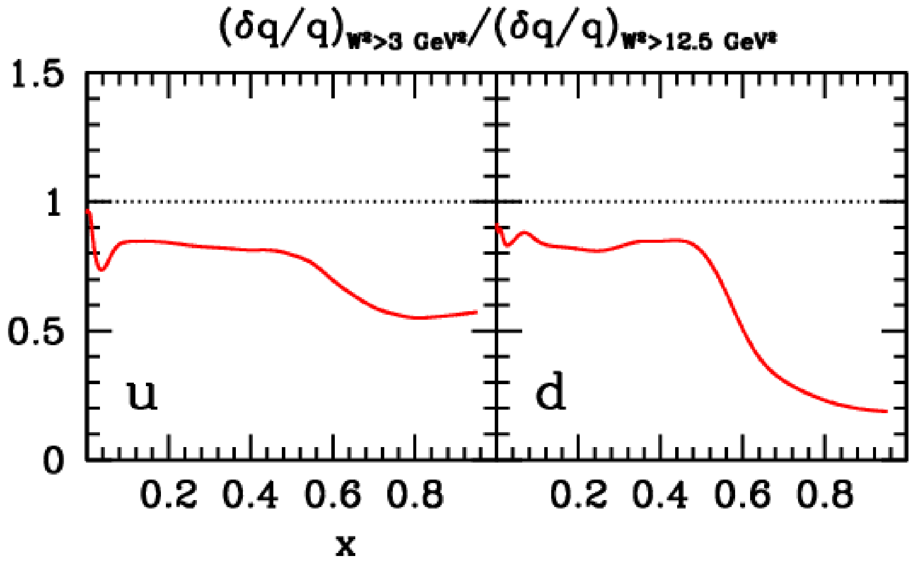
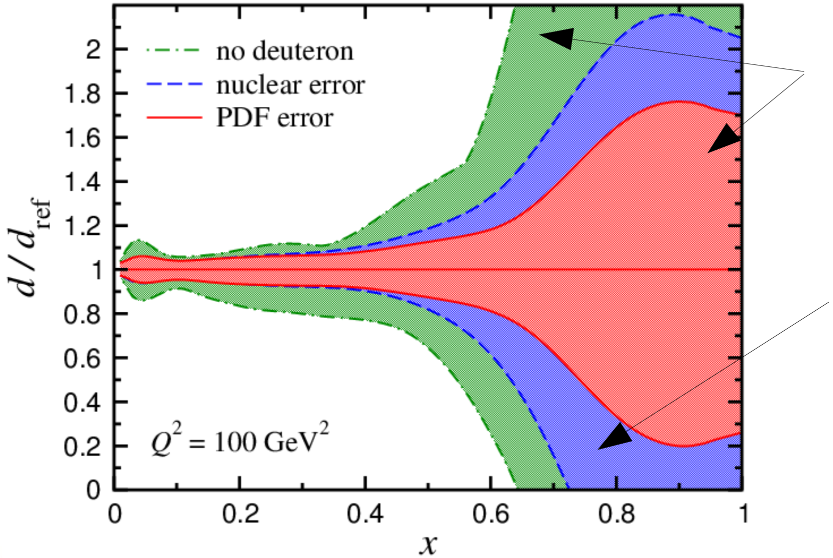
included in CJ fits

CJ12 – statistical improvement





Largely reduced PDF errors
(increased statistics)

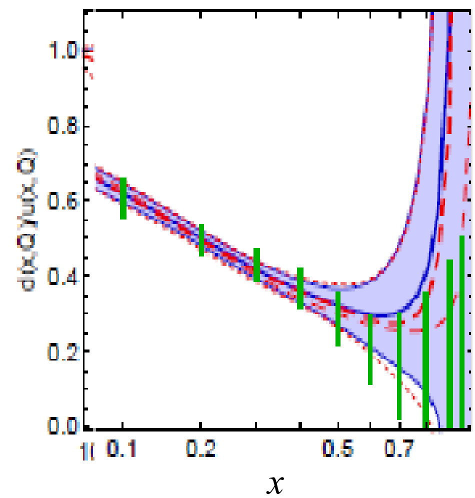
Nuclear uncertainties (systematic):
- choice of nuclear w.fn.
- size, type of off-shell correction

Large-x *d/u* quark ratio: state-of-the-art

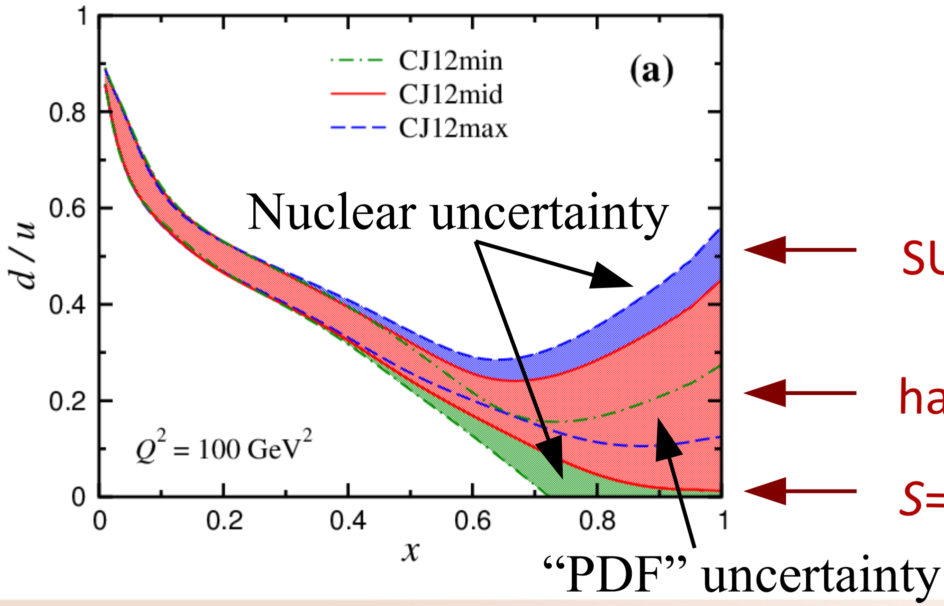
- **CJ12 results**
  - Large reduction in *d*-quark error
  - Large *d*-quark suppression
  - Meaningful extrapolation to x → 1
    d/u(*x*=1) ∈ [0.0.5] instead of [0,∞] !!
  - Almost constrains proton models

Nucl. Corr.

Extended d-quark parametr.



Owens, Accardi, Melnitchouk, PRD87 (2013) 094012



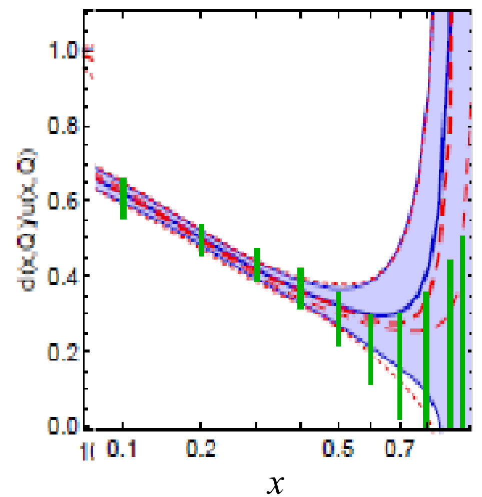
Non-perturbative proton models

SU(6) spin-flavor

hard gluon exchange

S=0 diquark dominance

Large-x *d/u* quark ratio: state-of-the-art



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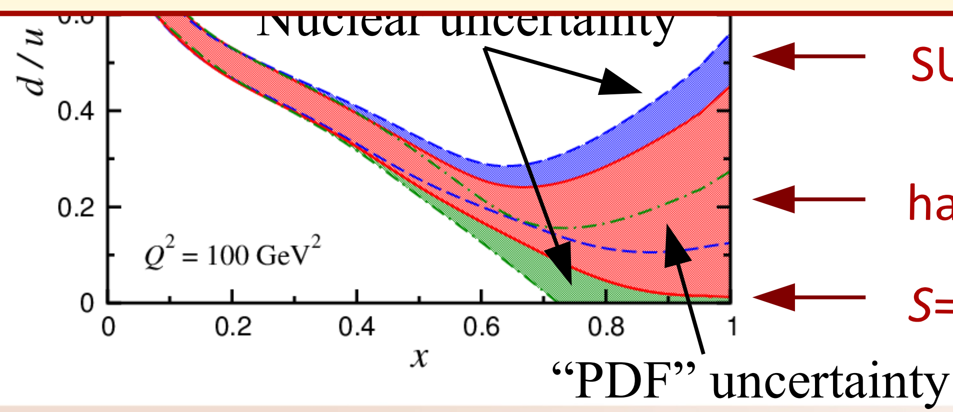
} Nucl. Corr.

} Extended d-quark parametr.

Owens, Accardi, Melnitchouk, PRD87 (2013) 094012

$$d/u \xrightarrow[x\to 1]{} 0.22 \pm 0.20\,(\mathrm{PDF}) \pm 0.10\,(\mathrm{nucl})$$



← SU(6) spin-flavor

← hard gluon exchange

← *S*=0 diquark dominance

HEP ↔ Nucl symbiosis

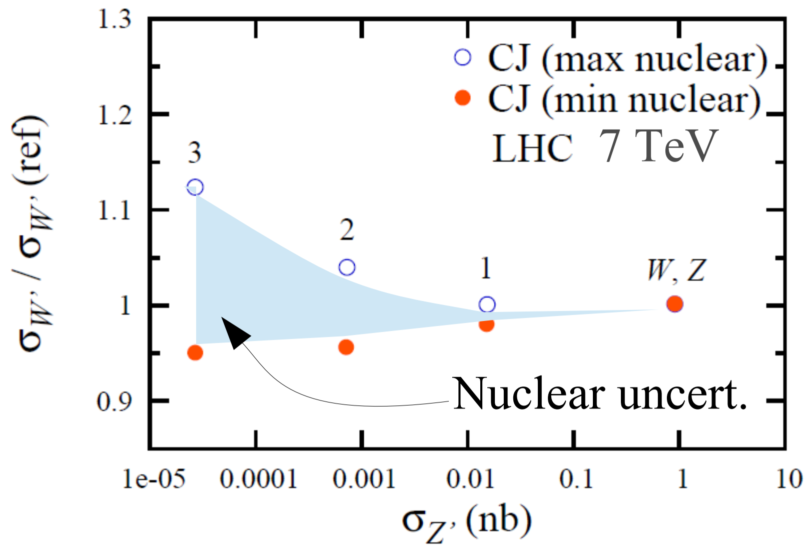
Impact on new physics searches

Accardi, Mod.Phys.Lett. A28(2013)35
Brady, A.A., Melnitchouk, Owens, JHEP 1206 (2012) 019

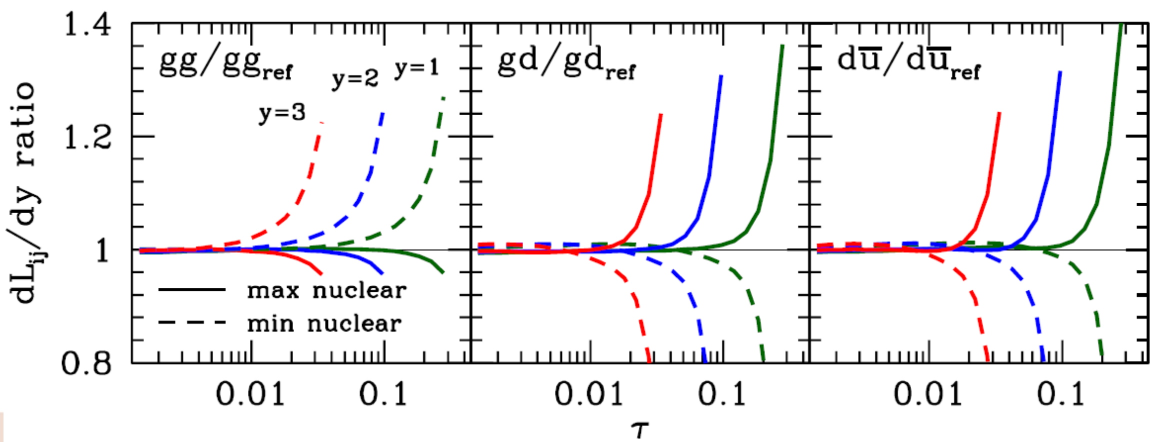
- **Large mass / forward physics**
  - Kaluza-Klein, $M > 1.5$ TeV, $M_n = n\, M_1$
  - Excited quarks, $M > 3.5$ TeV
  - Contact interactions, $M > 8$ TeV
  - Z+jets at large y
  - LHCb, ...

$$x = \frac{M}{\sqrt{s}} e^y$$

W' and Z' total cross sections



Differential parton luminosities



Need to constrain the nuclear corrections

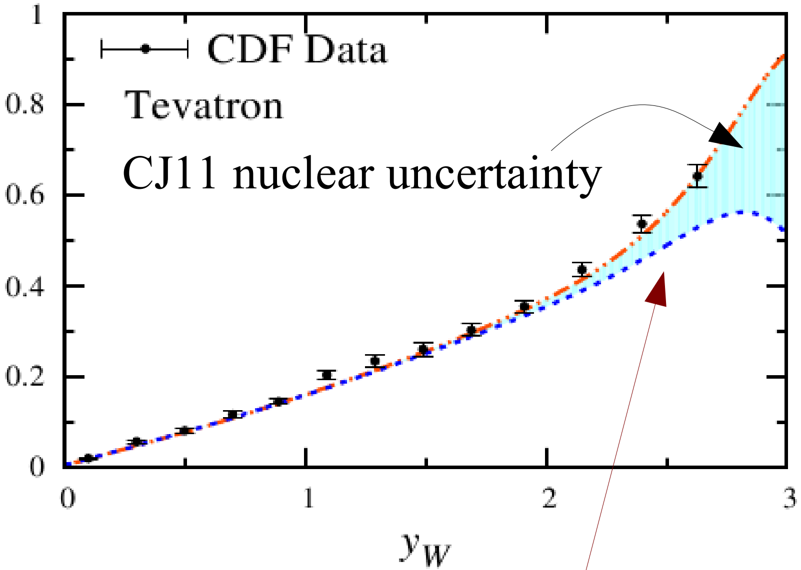
Use protons to study nuclei (!)

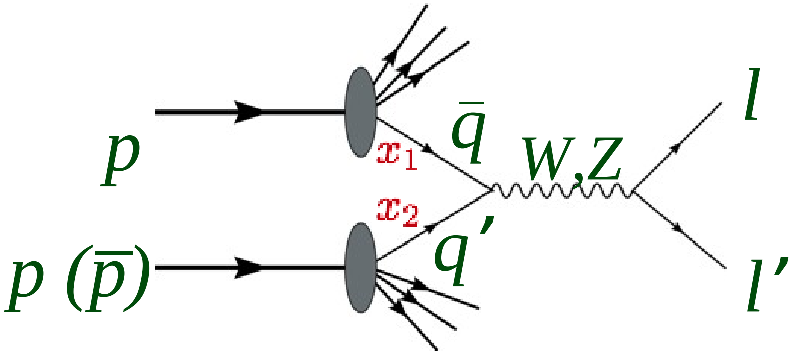
Accardi, Mod.Phys.Lett. A28(2013)35

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

Directly reconstructed W:

- highest sensitivity to large *x*





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

sensitive to *d* at high *x* → Can constrain Deuteron models!

- Preliminary indications of "small" to "medium" nuclear corrections

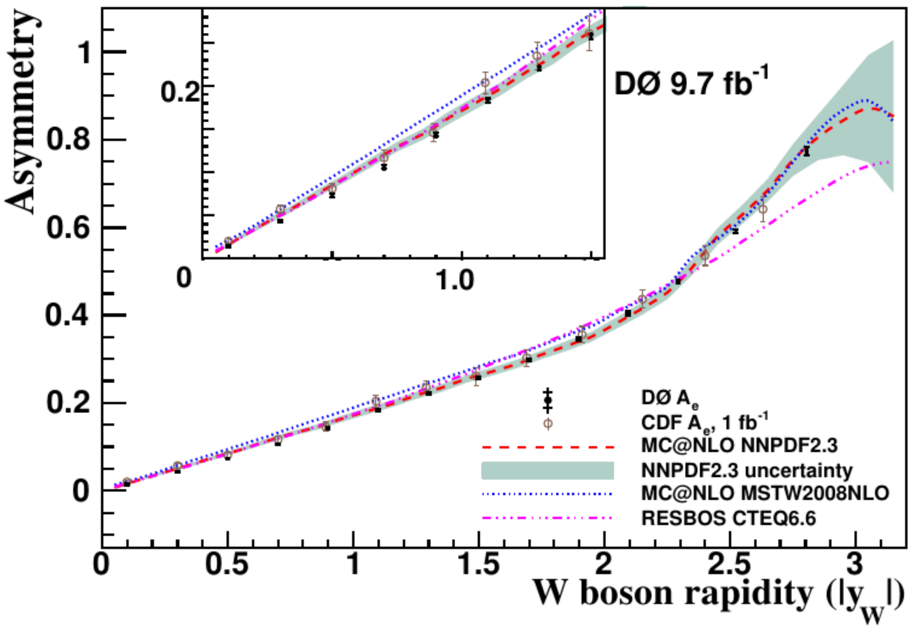
A.A., Owens, Menitchouk, PRD87 (2013); MMSTWW, EPJ C73 (2013)

Use protons to study nuclei (!)

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

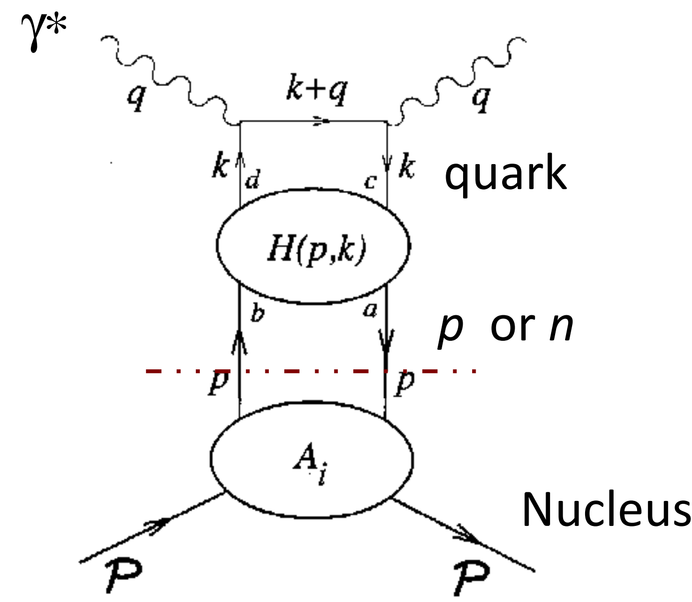
- New D0 data, 10 x statistics, large y_W coverage
  - Will likely fix:
    - size of nucl. Effects
    - Nuclear w.fn.
  - Let's be bold:
    - Shape??
    - Born approx / final st. int's?

D0 coll. arXiv:1312.2895



- Needs to corroborate, consider PDF errors, extend method:
  - ***W, Z* at RHIC**, *Z* (*W*?) at LHC,
  - **BONUS**, MARATHON , PVDIS at JLab 6/12
  - CC @ EIC / LHeC

Two complementary strategies



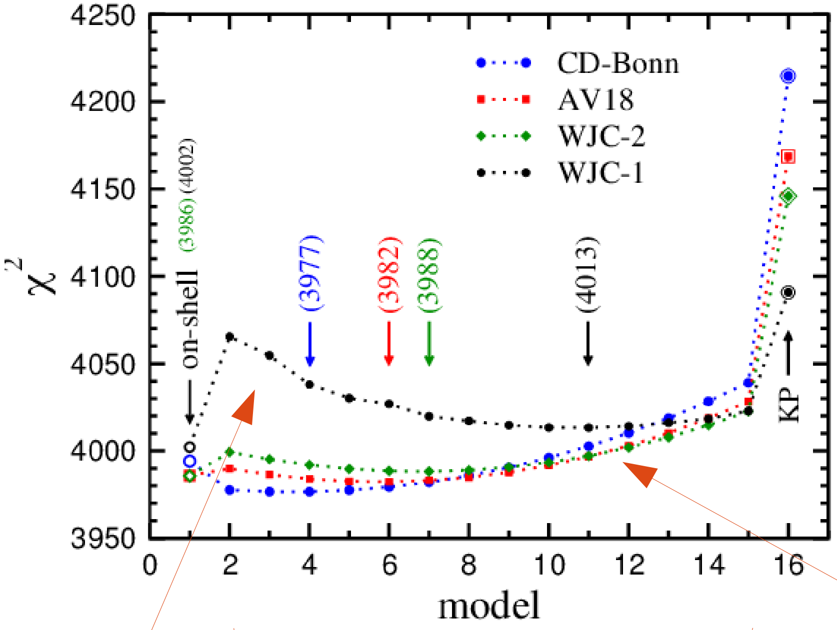
Low-energy factorization issues

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

- **CJ: Nuclear modeling**
  - ✔ Connects to underlying nuclear theory
  - ✔ Can reject models → verify assumptions
  - ✔ Extendible to other processes, e.g., DY(d)
  - ✘ How to explore the model space?
    - Continuous vs. discrete parameters
  - ✘ Limited to shapes provided by models

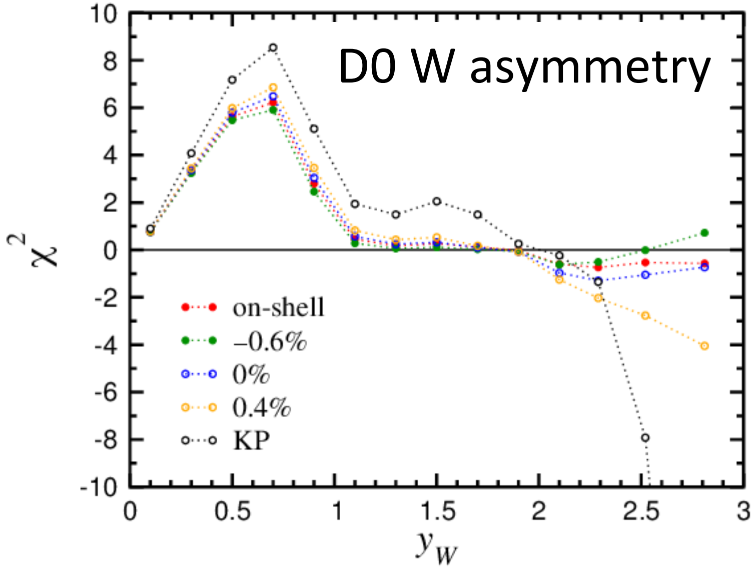
- **MMHT: parmetrize D/(p+n) ratio**
  - ✔ Nuclear uncertainty straightforward
  - ✔ No "model bias" (beside parametrization itself)
  - ✘ Limited nuclear physics output
  - ✘ Cannot be extended to nDY, ...

Very preliminary analysis - χ^2

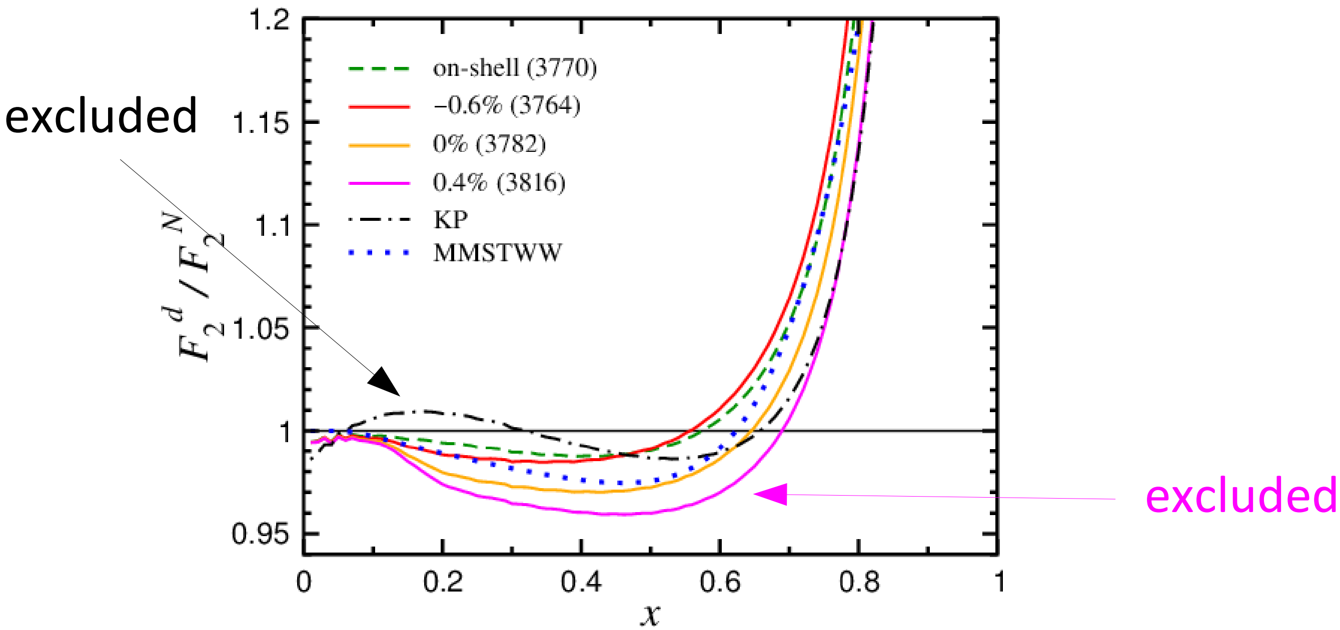


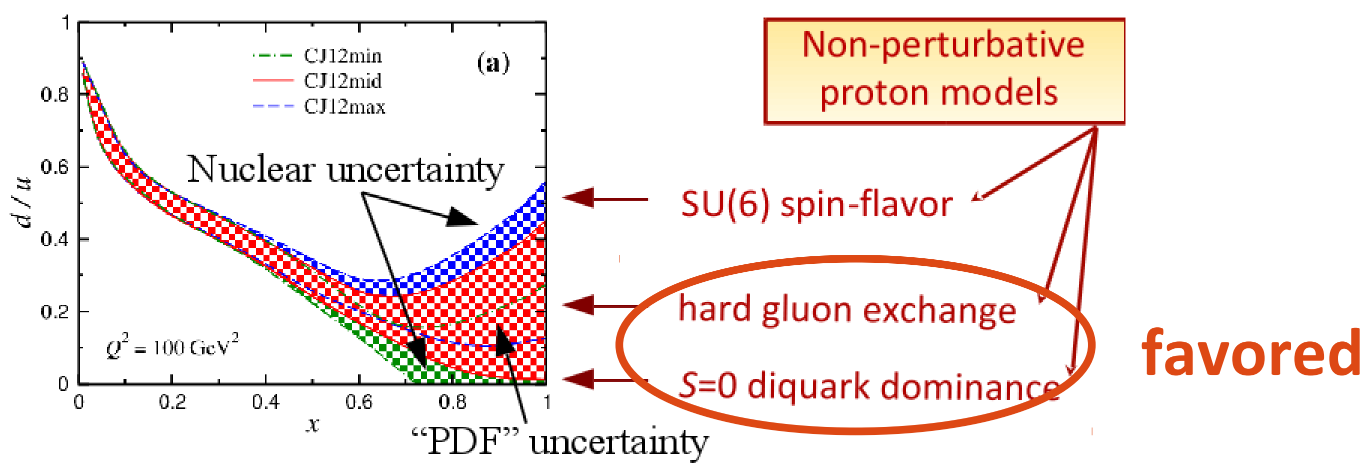
Off-shell strength

SLAC deuteron



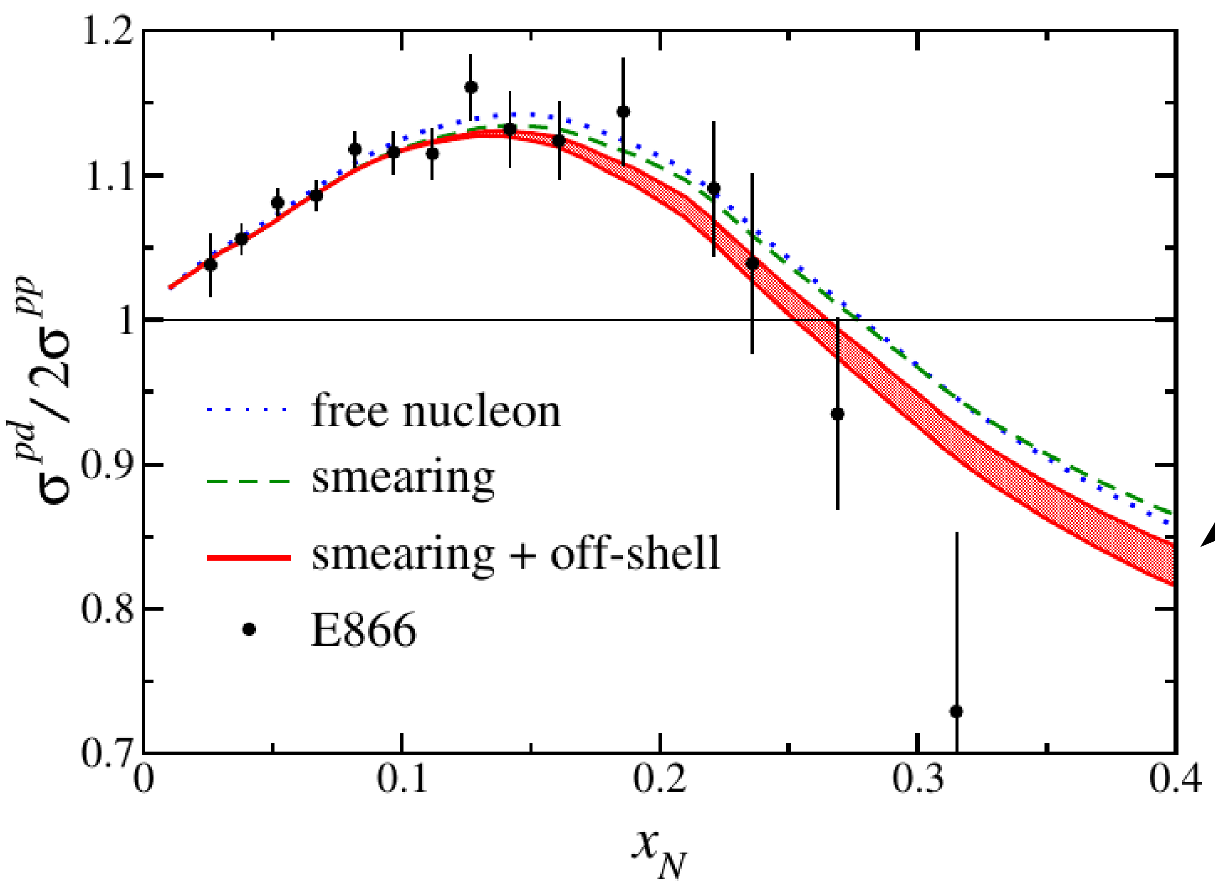
Very preliminary analysis – nuclear corrections





Nuclear corrections...

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

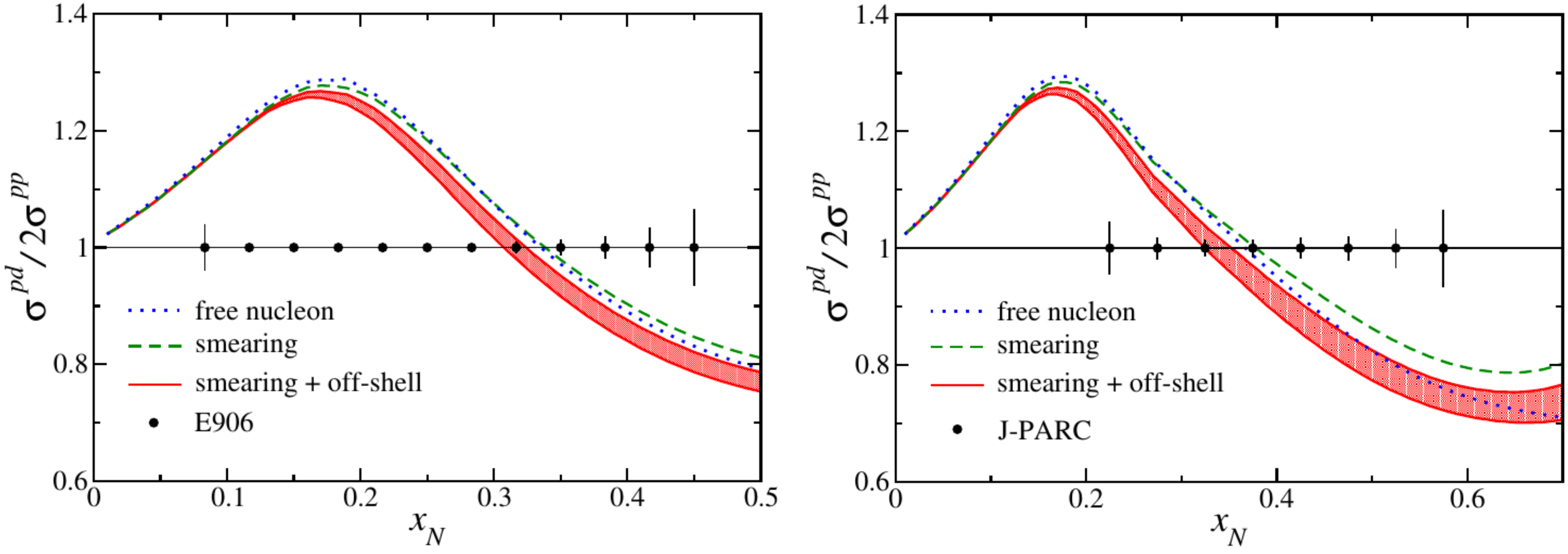


Red band: combined wave fn. & off-shell model uncertainty

❑ **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

Plans

Large-x: how to move forward?

- **Experimental data:**
  - Few existing, planned experiments probe large-x quarks on proton targets before EIC / LHeC in year 2025++
  - LHC will not be able to "measure its own PDFs" in this region (last chance was at 7 TeV, otherwise needs too large rapidity)
  - Plentiful existing & near future data on deuterium (but need nuclear corrections)
- **Proposal 2014-2025: mixed strategy**
  - Use proton data to constrain nuclear corrections (!!)
  - Fully utilize the deuteron target statistics
- **Past 2025**
  - EIC / LHeC will allow full flavor separation (NC & CC), high statistics
  - Others: LHCx, AFTER@LHC, … ??

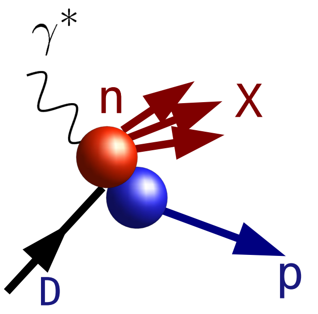
Work in progress, plans → "CJ15"

- **New data:**
  - D0 recent Z, W- and muon-asymmetry
    - Large-x d-quark, dbar/ubar
  - BONUS data on quasi-free *e+n*
  - LHC *W* and *Z* $\longrightarrow$ strangeness ($\kappa = 1$?) **<u>w/o neutrinos</u>** (*)
  - DIS fixed target cross sections (instead of F_2)
    - Info on F_L $\longrightarrow$ gluons; longitudinal higher-twists
    - Release of Structure Functions grids
    - New JLab data as available
  - new HERA combination, maybe combined F_2(charm)
  - Future: JLab 12, E906, **W asymmetry at RHIC**, ...

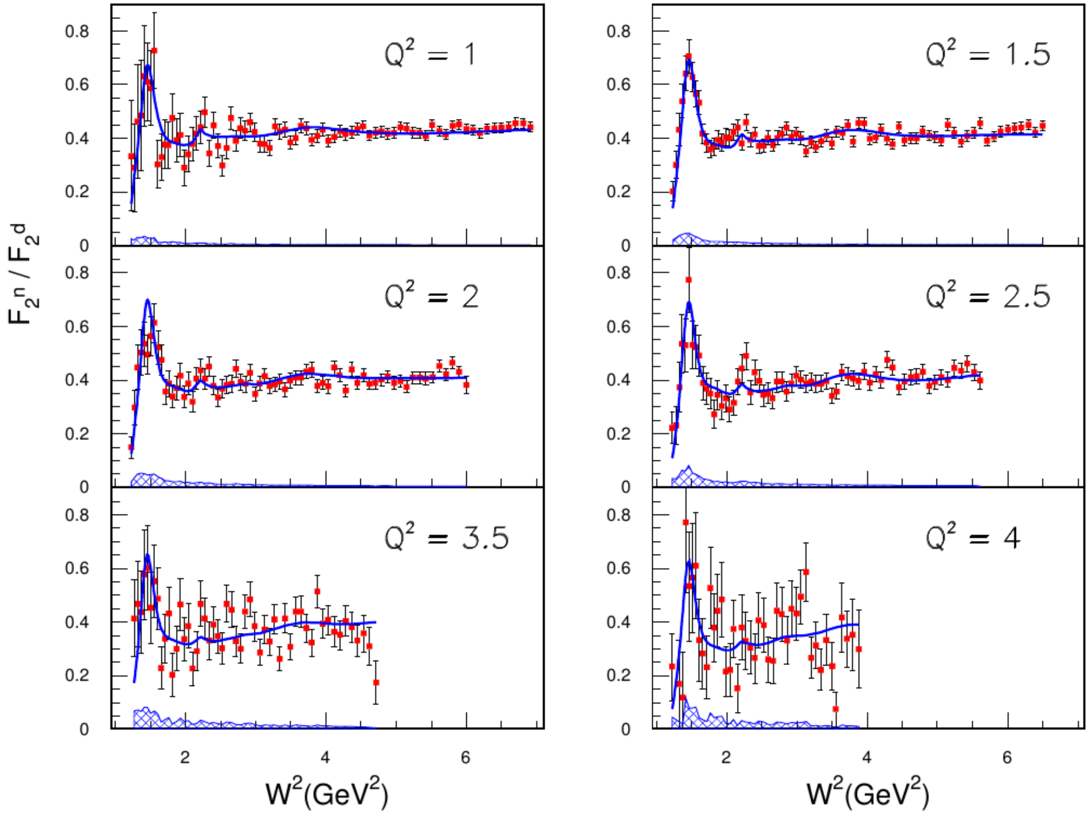
(*) ask me, please!

JLab 6 GeV: Quasi-free neutrons for today

- **Spectator proton tagging**
  - Nuclear corrections minimized experimentally



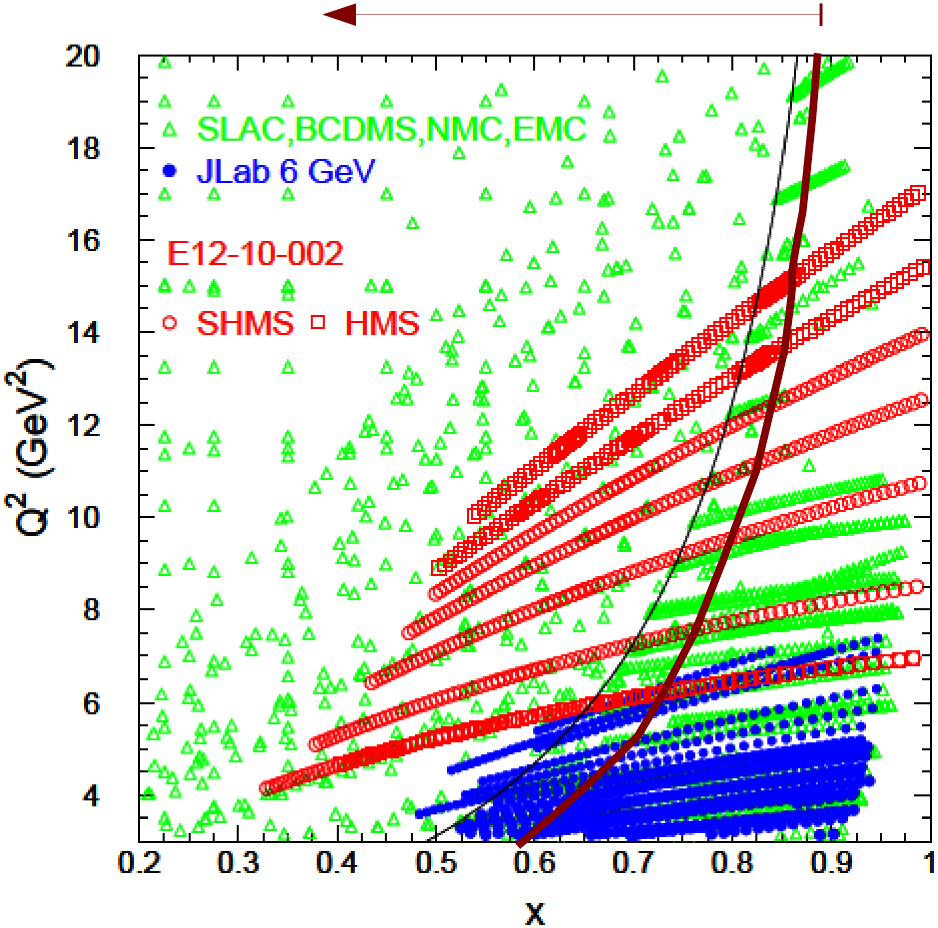
BONUS coll.,,. Tkachenko et al. arXiv:1402.2477



JLab 12 - proton, deuteron structure functions

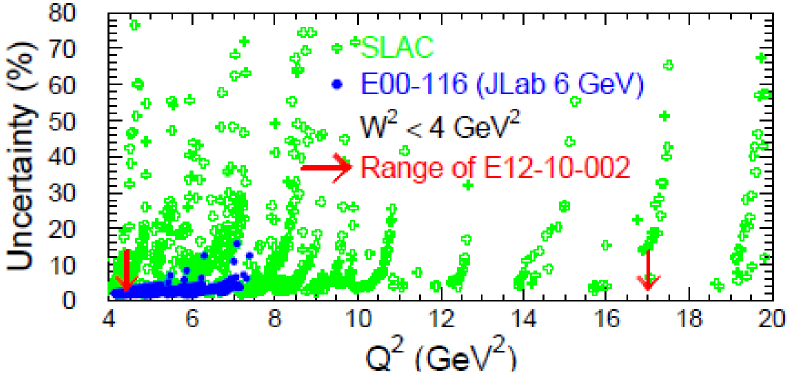
Jlab12 experiment E12-10-002

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



DIS region

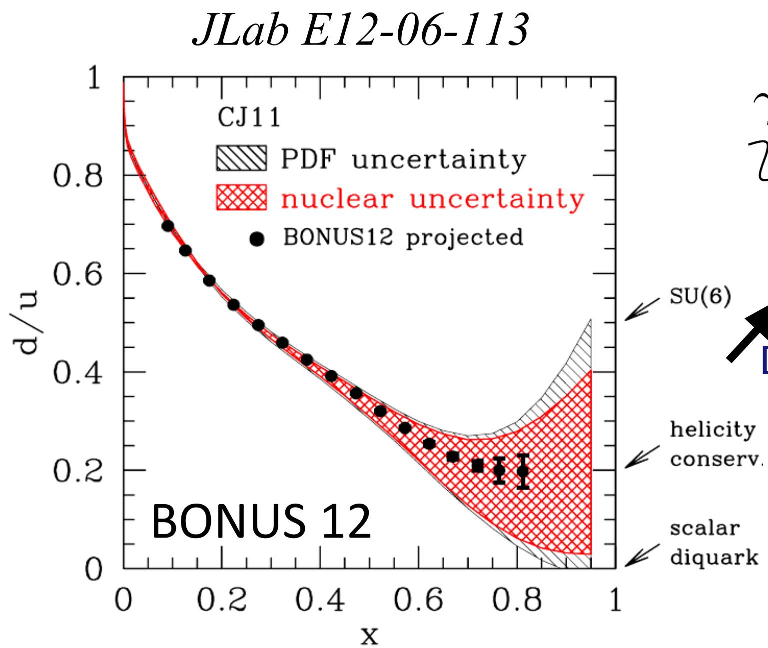
Resonance region

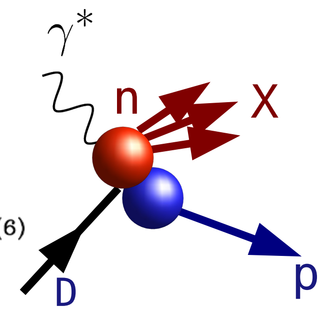


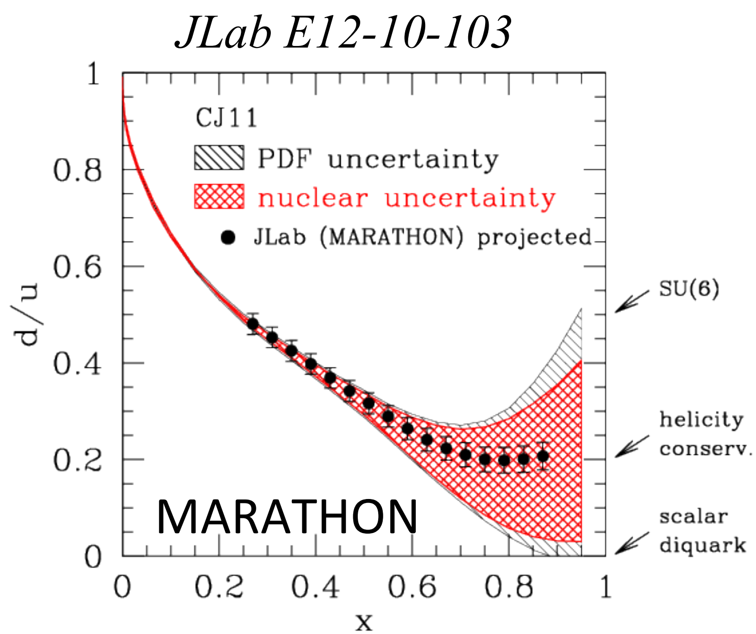
- **JLab 12 GeV**
  - More than double Q^2 range
  - Similar precision as JLab **6 GeV** (largely improve cf. **SLAC**)

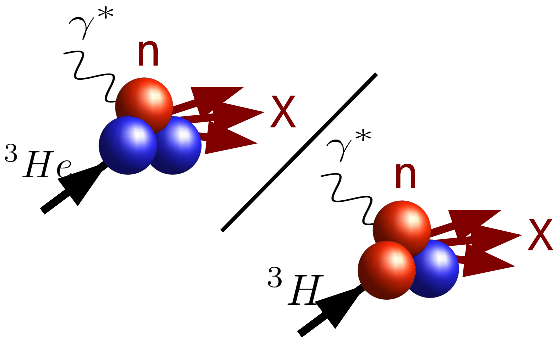
JLab 12: Quasi-free neutrons for tomorrow

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







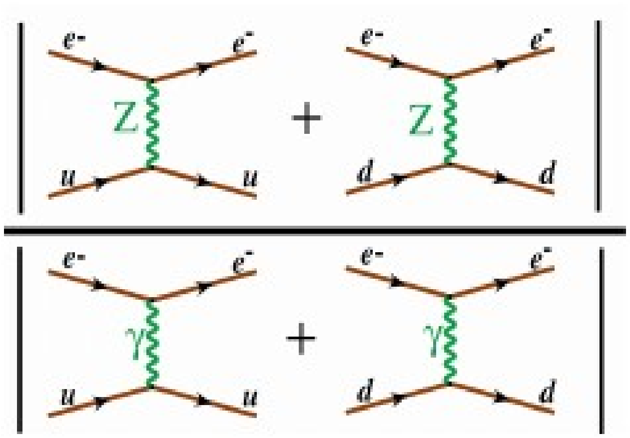


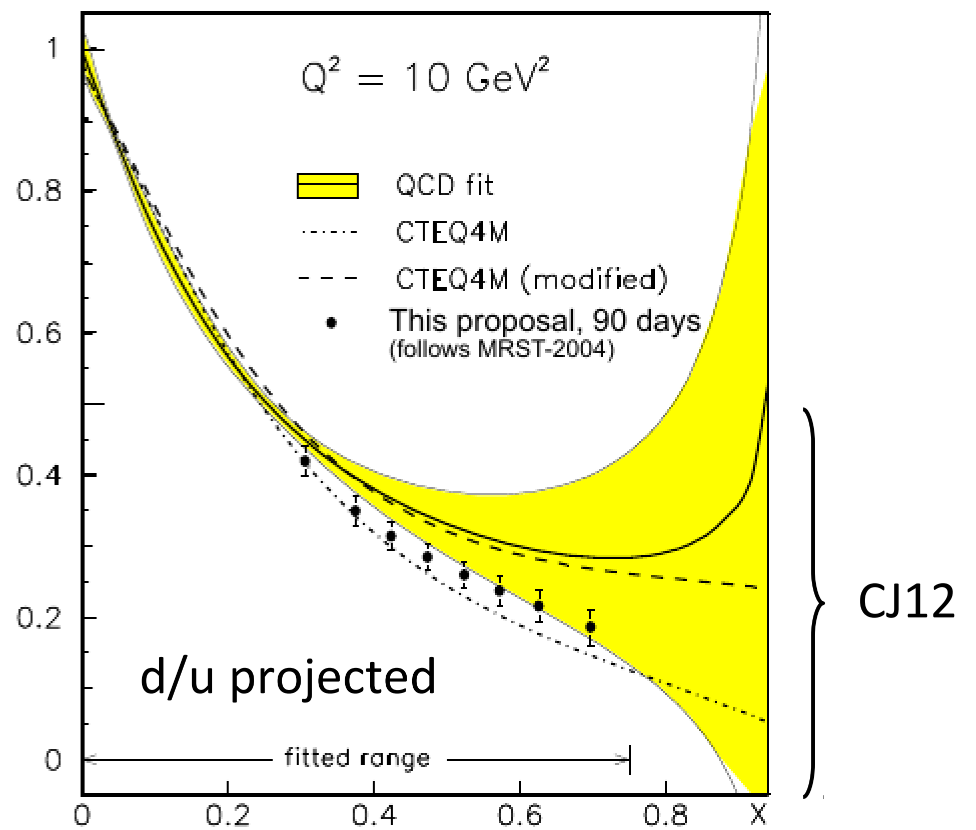
JLab 12: Parity-Violating DIS

Jlab12 experiment E12-10-007

- Longitudinally polarized electrons → PV asymmetry

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

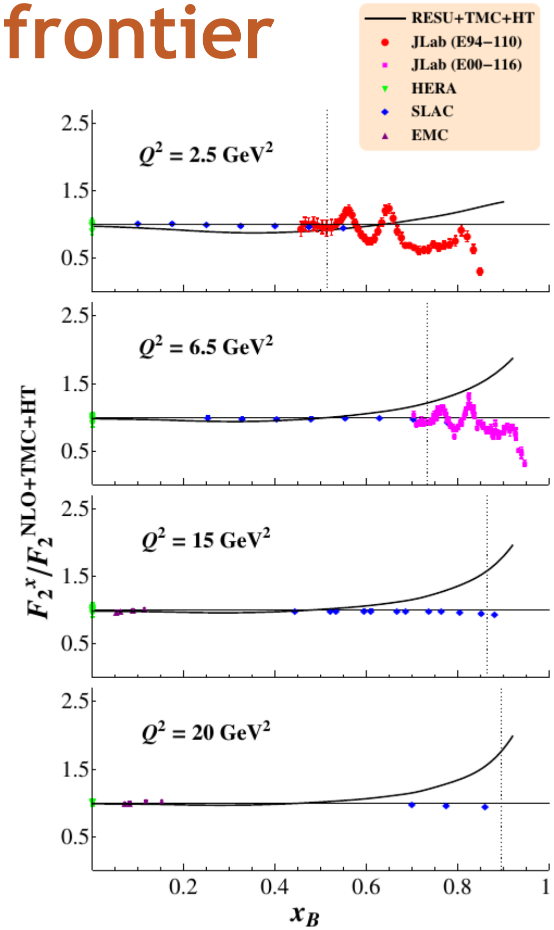




Work in progress, plans → "CJ15"

- **pQCD theory:**
  - sACOT heavy quark scheme
  - Fits of α_s
  - New, better behaved parametrization for dbar/ubar
    - dbar remains positive,
    - sum rule in line with other global fits
- **Nuclear theory:**
  - Off-shell for sea quarks, gluons also in DIS
  - Nuclear effects in DY (p+d)
    - Larger dbar/ubar;
    - any tension with DIS (d) already ?

Threshold resummation - the new frontier

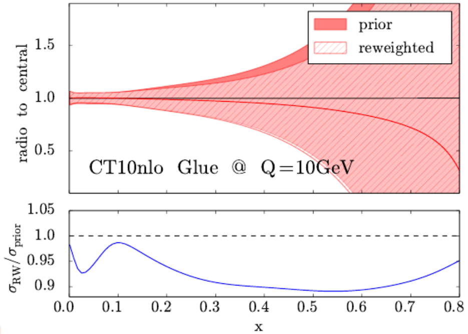


- **DIS:** *Accardi, Anderele, Ringer – arXiv:1411.3649*
  - Can be combined with TMC w/o threshold problems
  - Large corrections, will affect PDFs
  - Resonance region via quark-hadron duality ?

- **Drell-Yan** *Alekhin et al., PRD74 (2006)*
  - At NNLO, tension with DIS, vector bosons
  - Resummation effects are large
    - Need to be evaluated

N. Sato – Ph.D. Thesis, 2014

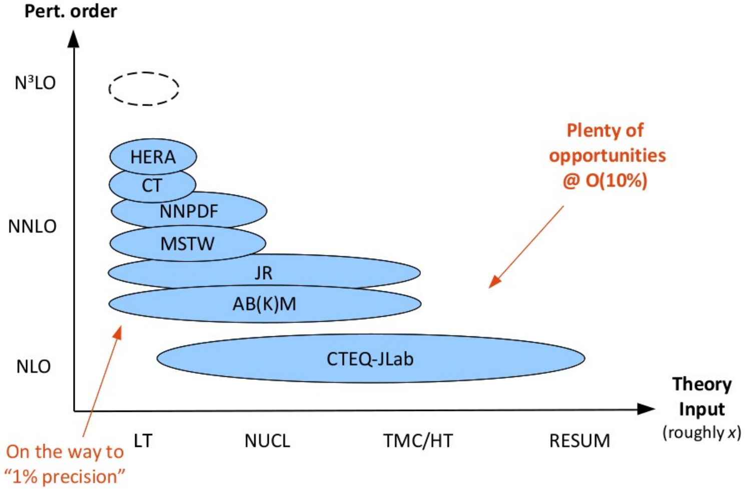
- **Direct photons**
  - Resummation allows use in global fits
  - 10% reduction in large-*x* gluon errors



Conclusions

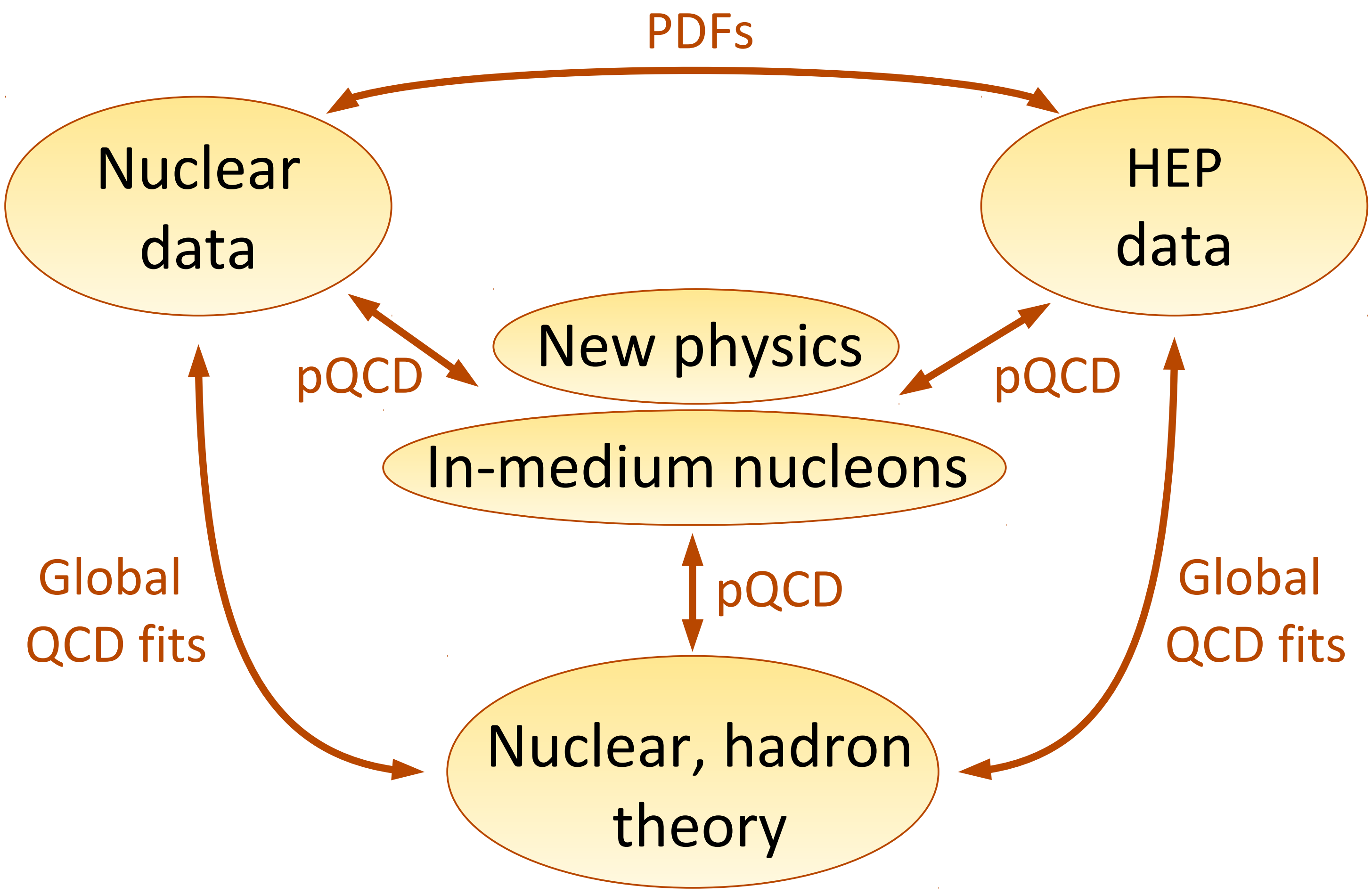
Conclusions

- **Entering a "high-precision" era in large *x* physics**
  - New data, new theory, new global fitting approaches
- **CTEQ-JLab has rekindled the PDF community interest in large x**
  - *e.g.*, MSTW, NNPDF looking into nuclear corrections, JR14 fits with nucl,HT
  - Theory uncertainties (TMC, nucl) under scrutiny
  - Proton data to constrain nuclear models
    - Impact on d/u, dbar/ubar
- **The new large *x* frontier**
  - Put resummation in global fits:
    - DIS, DY, W asymmetry, direct γ, ...
  - Larger impact than going NNLO
    - at least in the near future



Needs the marriage of HEP and NUCL

- A global approach across subfields



PDFs for the future

- **From a combination of**
  - **big, medium, and small (energy) experiments**
  - **old and new**
  - **fixed targets & colliders**
- Complementarity in kinematic ranges, systematics, targets

LHC, Tevatron
LHeC

RHIC, EIC

JLab 6/12, E906,
HERMES, COMPASS, ...

...and lQCD

Appendix: CJ12 details

CJ12: fit framework

- Concentrated on DIS theory corrections, established a baseline fit
- Data
  - DIS: fixed target F_2 (proton and deutron), HERA combined σ
  - Drell-Yan, W asymmetry (lepton & direct), Z rapidity distribution
  - Tevatron jets, γ + jets / no ν+A data
- Parametrization (with *d*-quark and strange sea exception)

$$xf(x) = Nx^a(1-x)^b(1+c\sqrt{x}+dx)$$

$$F_2 = F_2^{LT}\left[\left(1+a_{HT}x_{HT}^b(x)(1+c_{HT}x)\right)/Q^2\right]$$

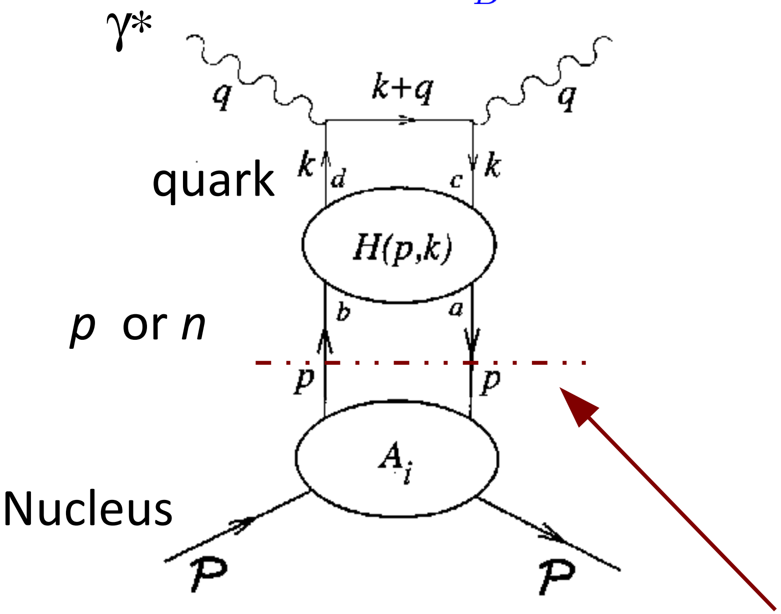
- Other
  - NLO, zero-mass VFN scheme (will upgrade to s-ACOT)
  - α_s = 0.118 (will be fitted in future releases)
  - Correlated errors, Hessian technique, tolerance T=10

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)

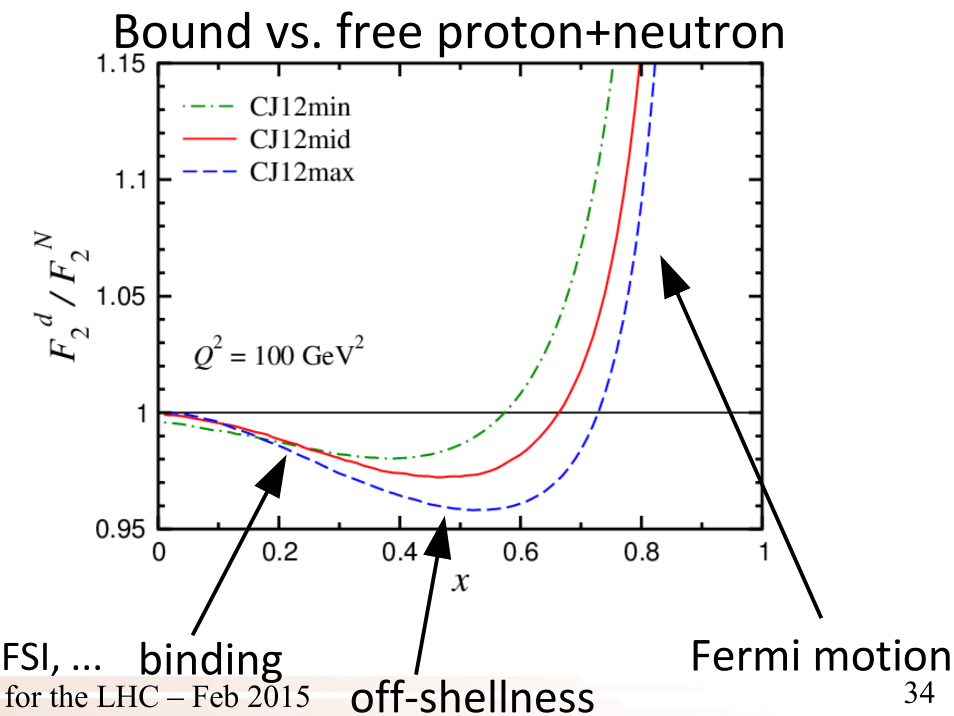
Theoretical uncertainty

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



Low-energy factorization issues

- Renorm. of nuclear operators, gauge inv., FSI, ...



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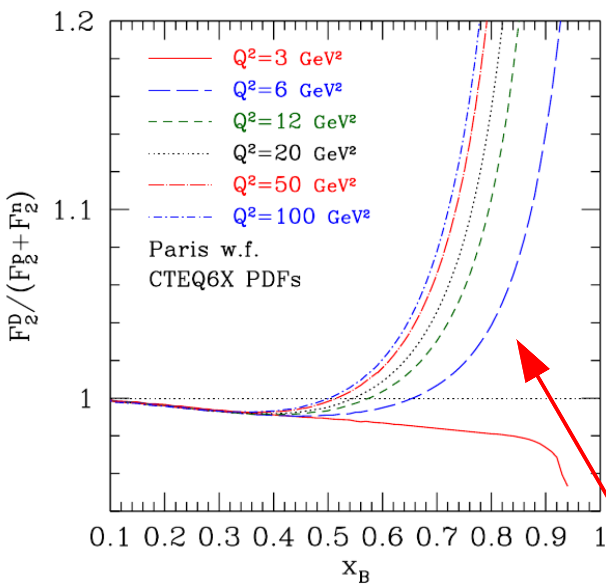
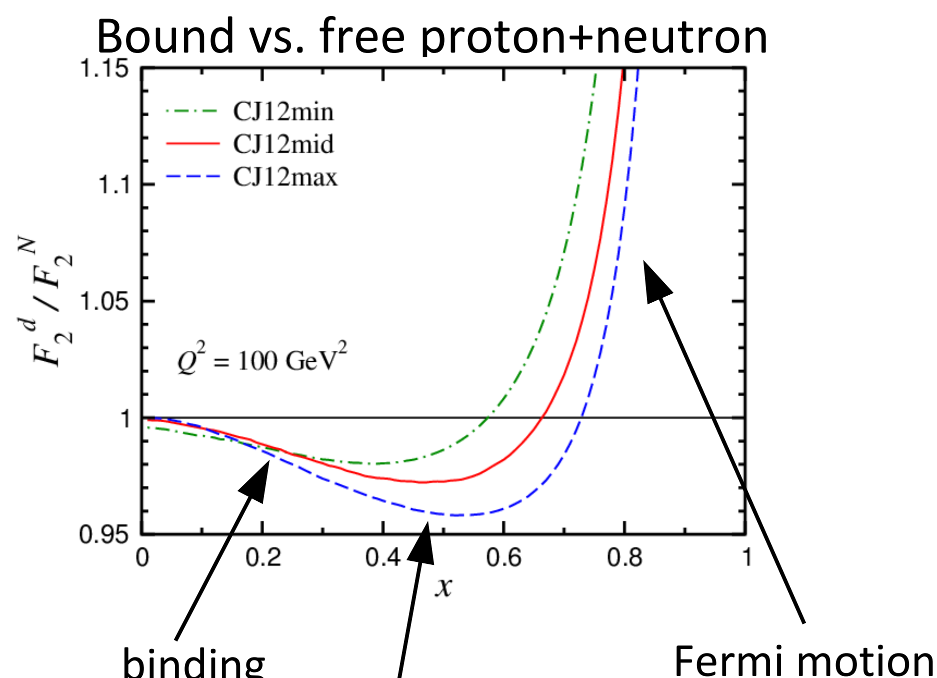
} Theoretical uncertainty

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



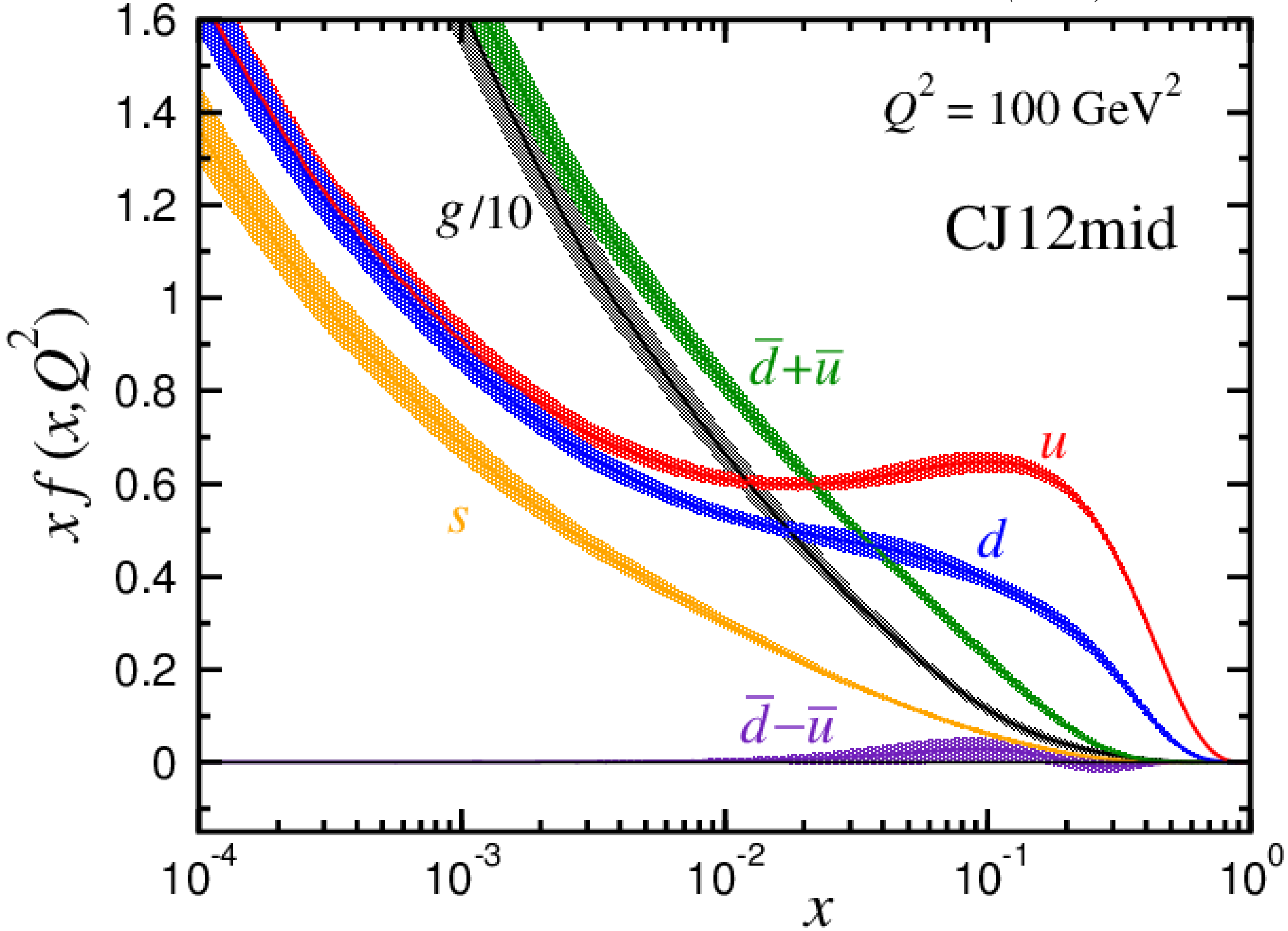
Strong Q^2 dependence at large *x* !

Bound vs. free proton+neutron

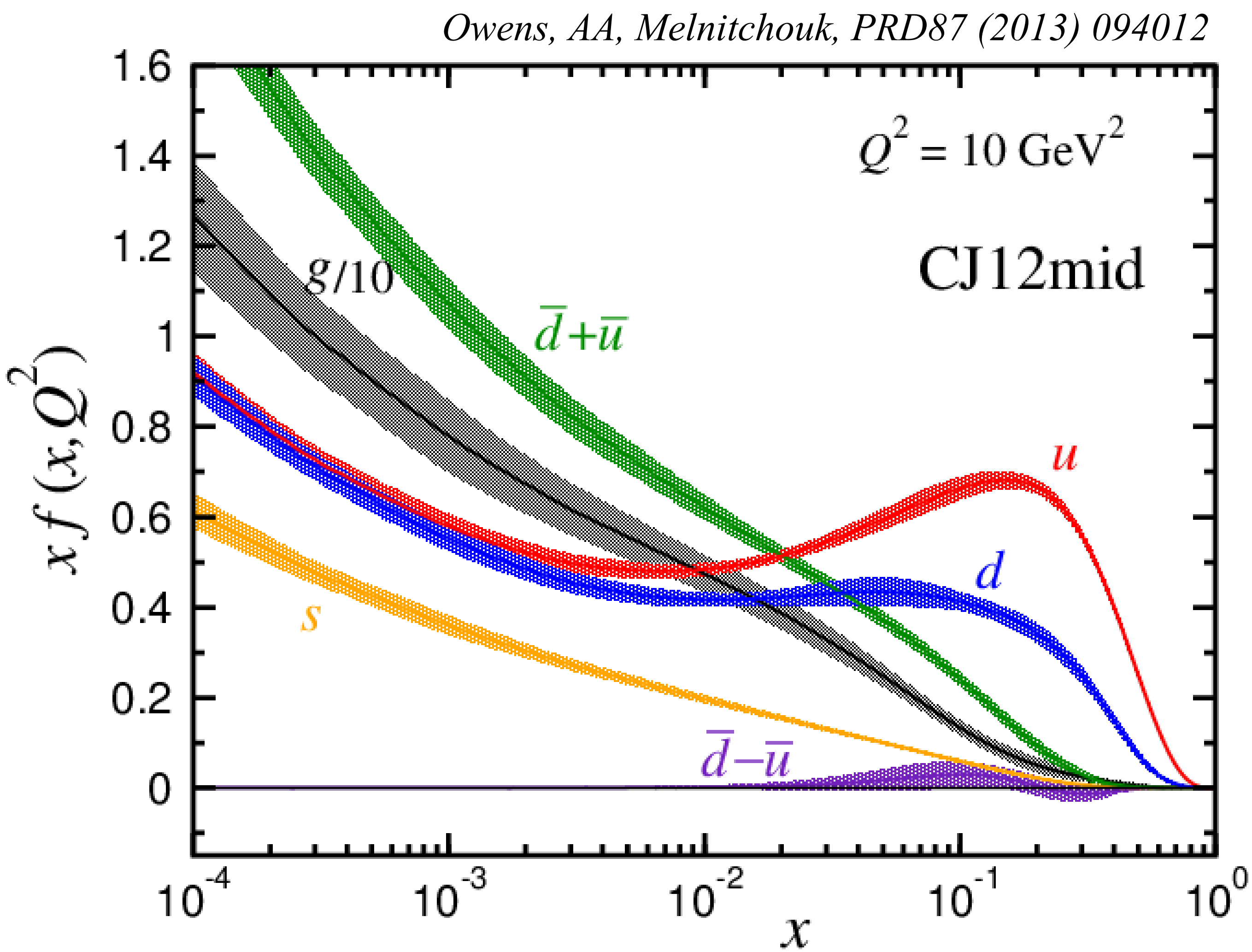


CJ12 parton distributions

Owens, AA, Melnitchouk, PRD87 (2013) 094012

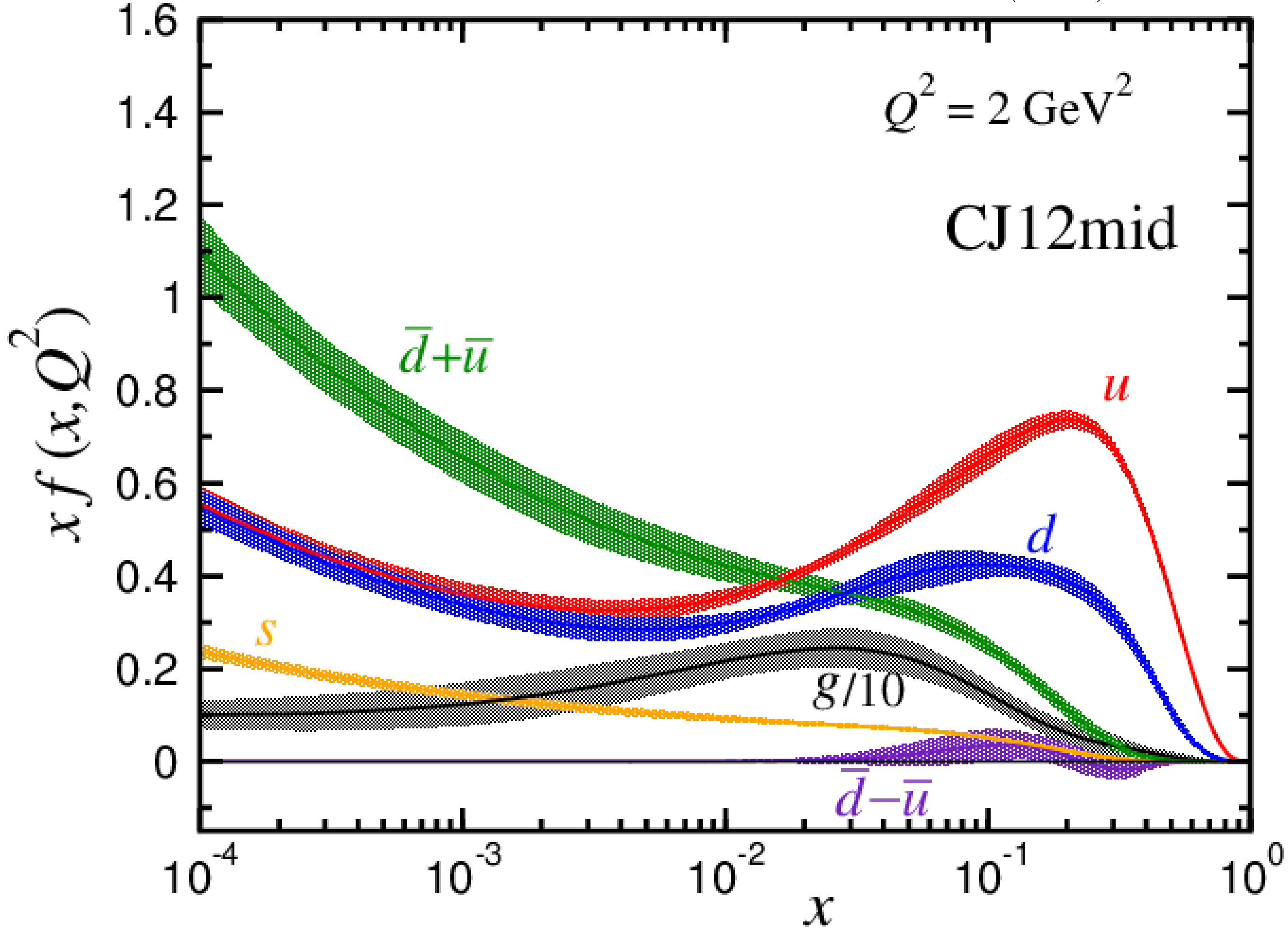


CJ12 parton distributions



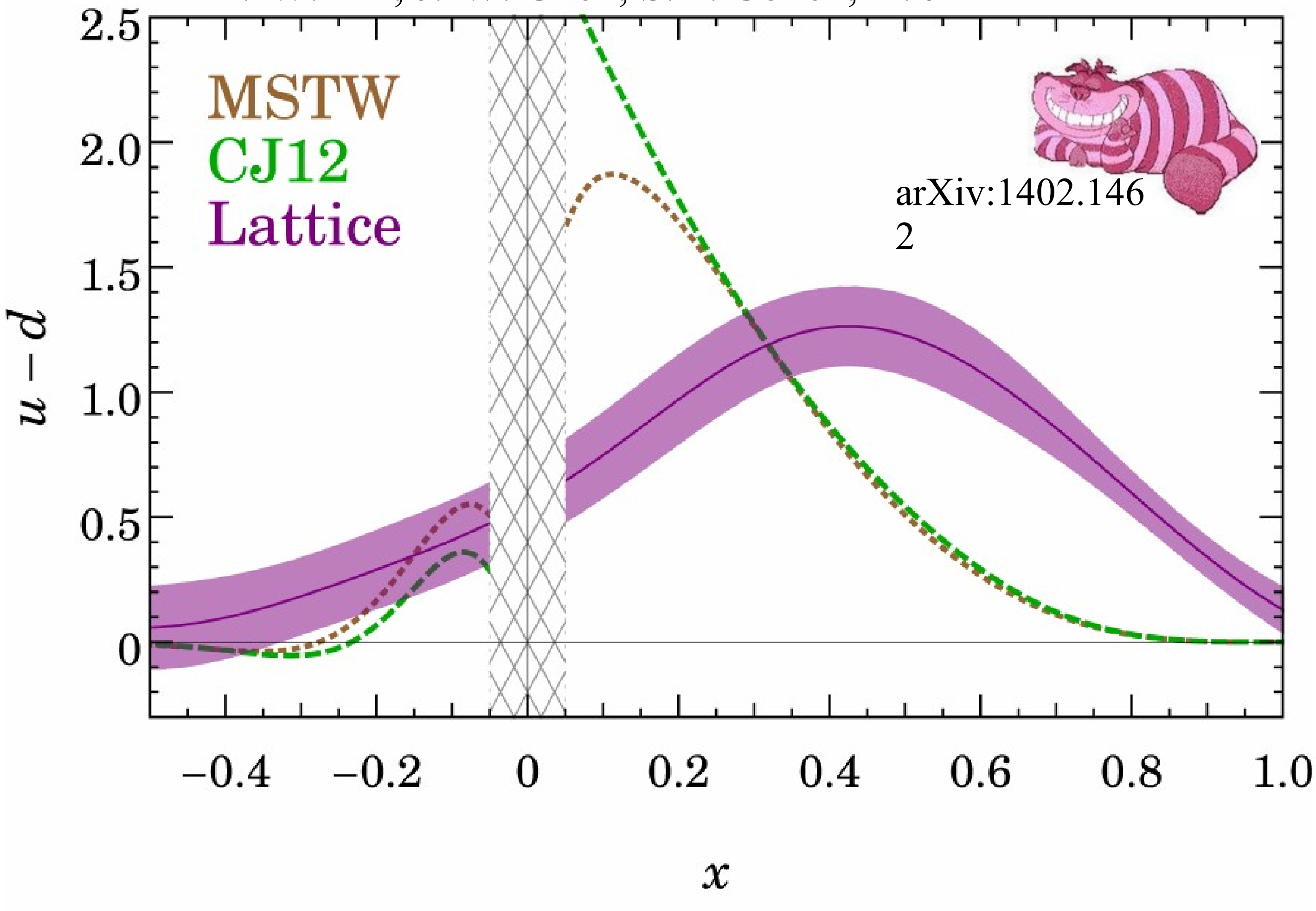
CJ12 parton distributions

Owens, AA, Melnitchouk, PRD87 (2013) 094012



New lattice QCD technique: PDFs in x-space

H.-W. Lin, J.-W. Chen, S.D. Cohen, X. Ji



New lattice QCD technique: PDFs in x-space

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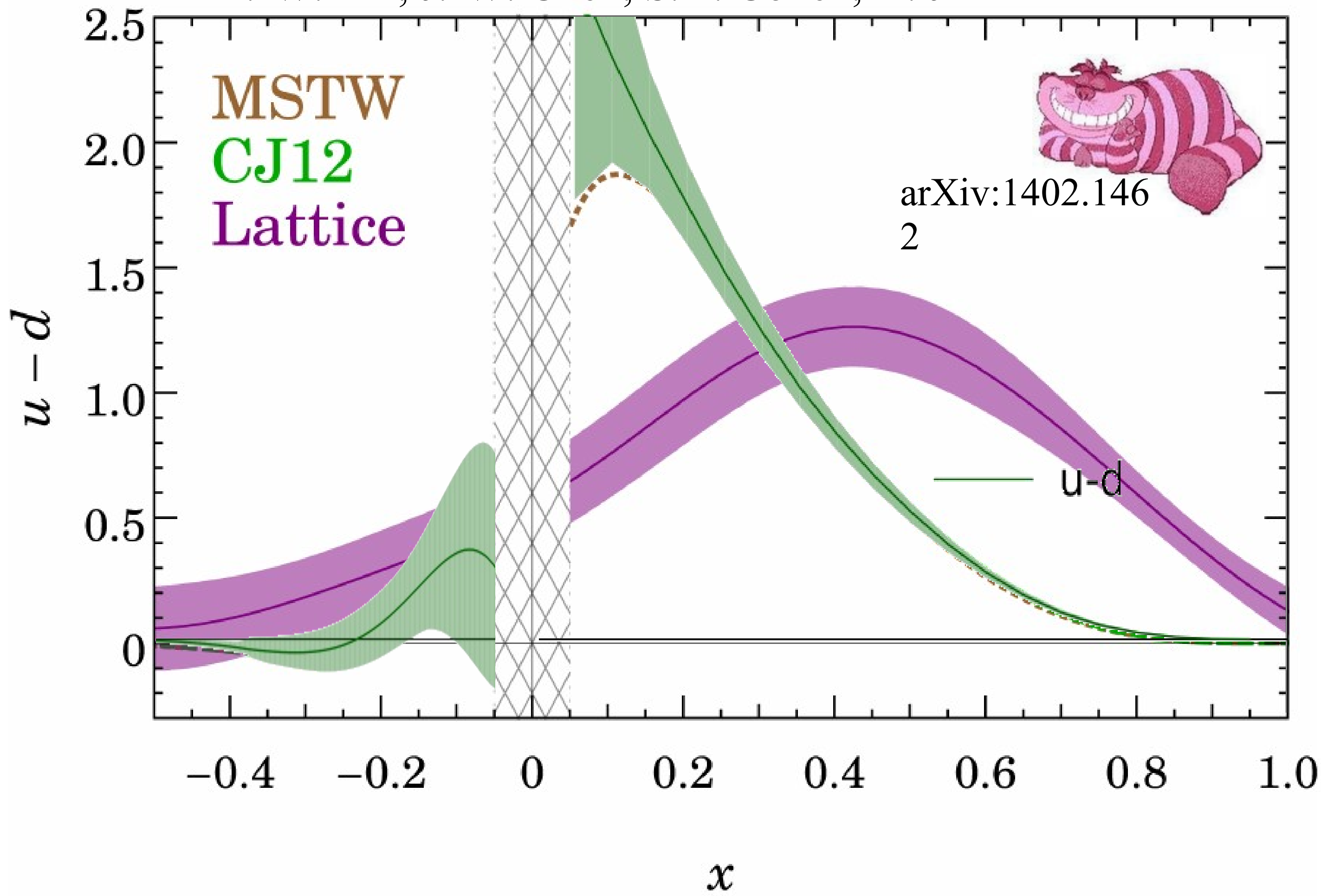


CJ12 error bands courtesy of J. Guerrero

Sea quarks

Charge symmetry breaking

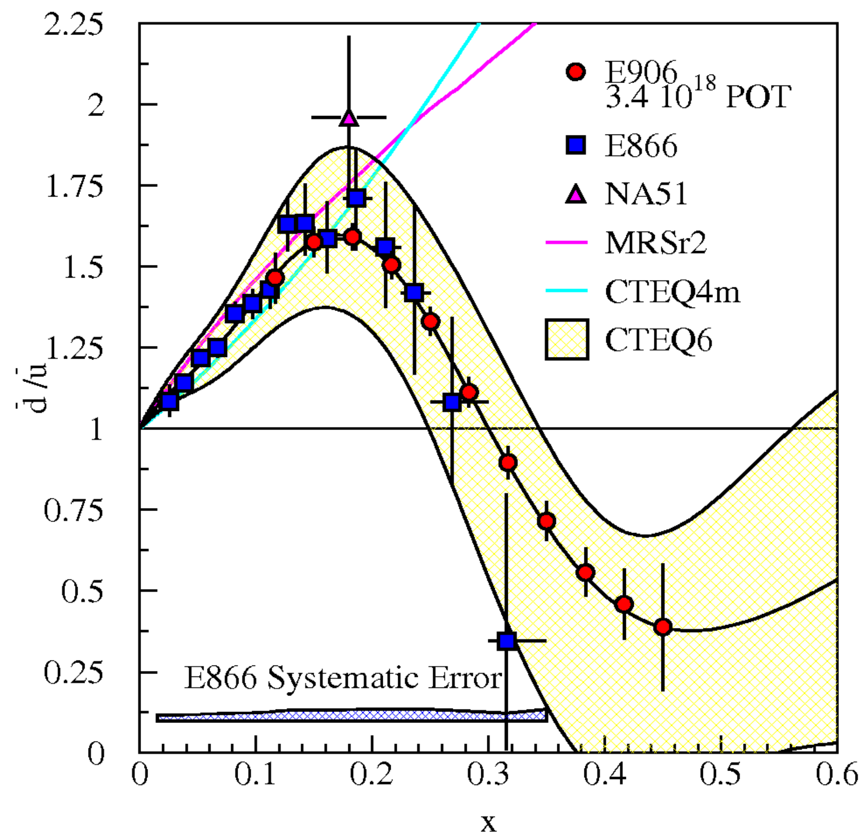
- **E866 lepton pairs:**

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

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

- **E906 / SeaQuest**
  – Will focus on large *x*

- **LHC W/Z production:**
  – Access to *x* ~ 0.01 range



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

Theory corrections needed for few % level accuracy

Nuclear corrections...

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 through global fits

- **Nuclear corrections** are at few percent level at moderate *x*

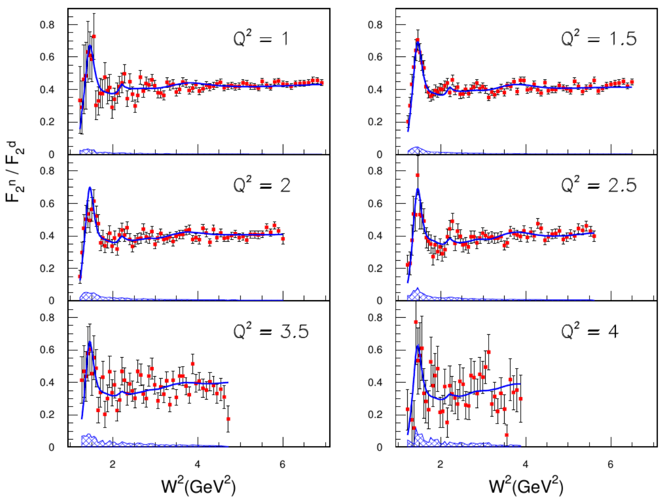
  Accardi et al. PRD81 (2010), Ball et al., PLB723 (2013)

  – **Constrain** nuclear corrections in DIS by comparing ***e+d*** to
    - ***p+p*** data (W asymmetry)
    - quasi-free ***e+n*** (BONUS 6/12)

  – Same nuclear model in ***p+d* → *Drell-yan***
    - **Cross check** at large negative xF
    - Not possible with parametrized corrections

  MMSTWW, EPJ C73 (2013)

S. Tkachenko et al. arXiv:1402.2477



- Similar strategy could be applied to study **CSV:**
  – contrast CDF reconstructed W data to BONUS / MARATHON "neutron"

- W asymmetry vs. **EMC effect, too !!**

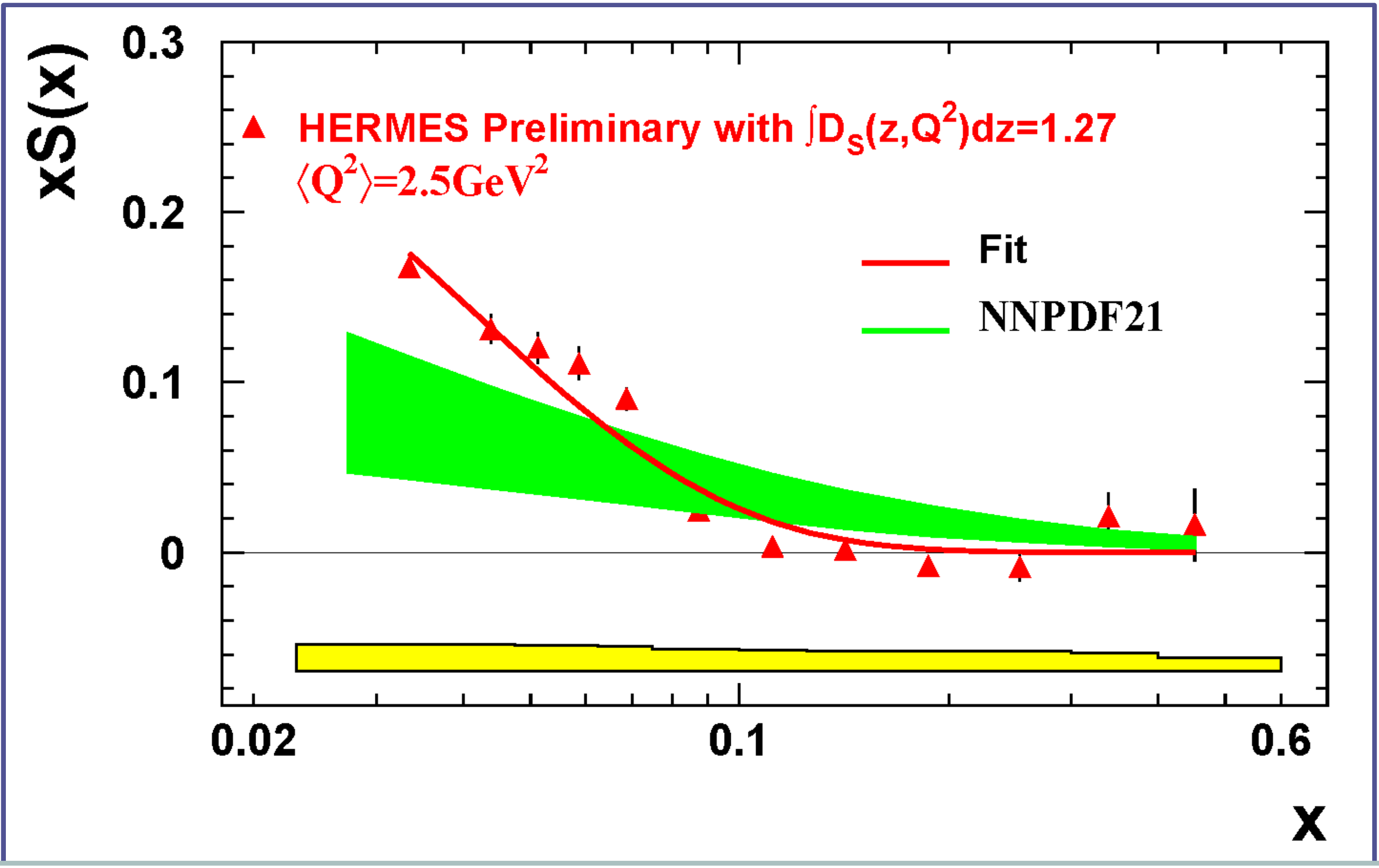
Strangeness and strangeness asymmetry

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

- **In PDF fits, constrained (until recently) mostly by ν+A data**
  - CCFR inclusive DIS
  - NuTeV muon pair production

- **Nuclear corrections again...**
  - Initial state nuclear wave-function modifications
    - Partly under phenomenological control using nPDF
    - But: double counting!!
  - Final state propagation of the charm quark / D meson
    - Out of theoretical / phenomenological control (cf. heavy quark "puzzle" in A+A at RHIC, LHC)

Constraints on strangeness: LO $K^{\pm}$ at HERMES



Difficulty: NNLO QCD corrections are large; dependence on FFs; higher twists?

Strangeness and strangeness asymmetry

- In my opinion: **Don't use n+A data in proton PDF analysis!!**
  - Use neutrino data only for nPDFs, anchor these to proton PDFs
  - For example, CJ + nCTEQ ==> robust nuclear corrections

- **Strangeness is important, though!**
  - Large $[s^-]$ could explain alone the NuTeV anomaly!
  - NNPDF 2009: $[s^-] = 0 \pm 0.009$
    - But does not include the mentioned nuclear uncertainty

Strangeness and strangeness asymmetry

- **Need to find alternative observables sensitive to strangeness**
  - LHC can provide these at lower *x*
    - e.g. ATLAS *W* disfavors strangeness suppression (but Tevatron *W* and Drell-Yan favor it …)
    - *“ W+c* is competitive with ν data *” [Berryhill]*
  - What about moderate *x* at “non-LHC” experiments?
    - kaon SIDIS (but fragmentation uncertainty, higher twists, ...)
    - W lepton asymmetry at RHIC
    - e+A vs. e+p SIDIS at JLab/HERMES/EIC
      ==> measure final state interactions
    - ...

Appendix:
old and new experiments
- examples -

Constraining the nuclear uncertainty

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

Jlab

- **Data on free (anti)protons, sensitive to *d***
  - *e+p*: parity-violating DIS **HERA** *(e^+ vs. e^-),* ***EIC, LHeC***
  - *ν+p*, *$\bar{\nu}$+p* *(no experiment in sight)*
  - *p+p, p+p* at large positive rapidity
    - *W* charge asymmetry, *Z* rapidity distribution

Tevatron: CDF, D0
LHCb(??) RHIC !!
AFTER@LHC

- **Cross-check data**
  - *p+d* at large negative rapidity – dileptons; *W, Z*
    - Sensitive to nuclear corrections, cross-checks *e+d*

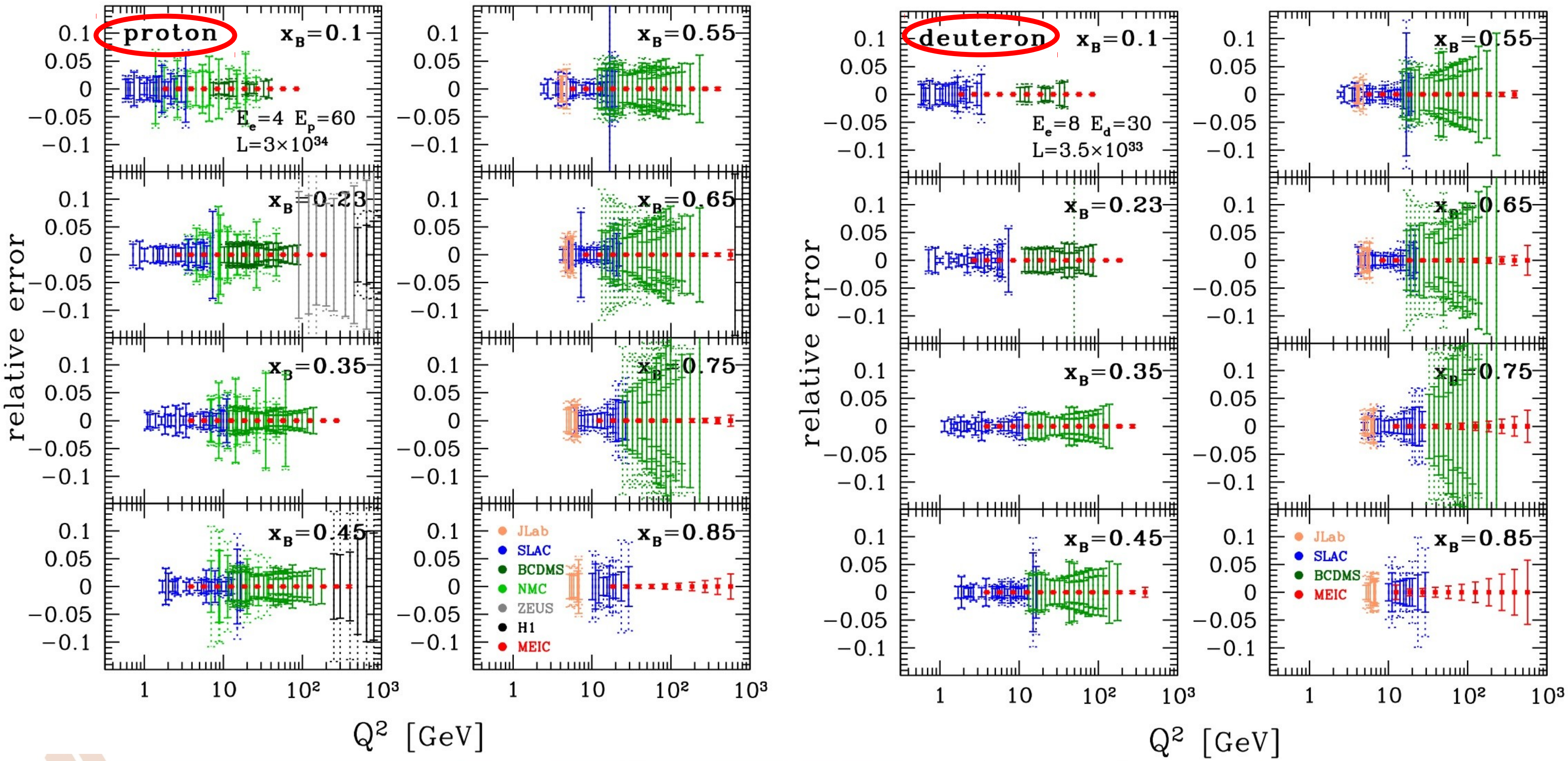
RHIC ??
AFTER@LHC

At the EIC

❑ Neutral current DIS

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

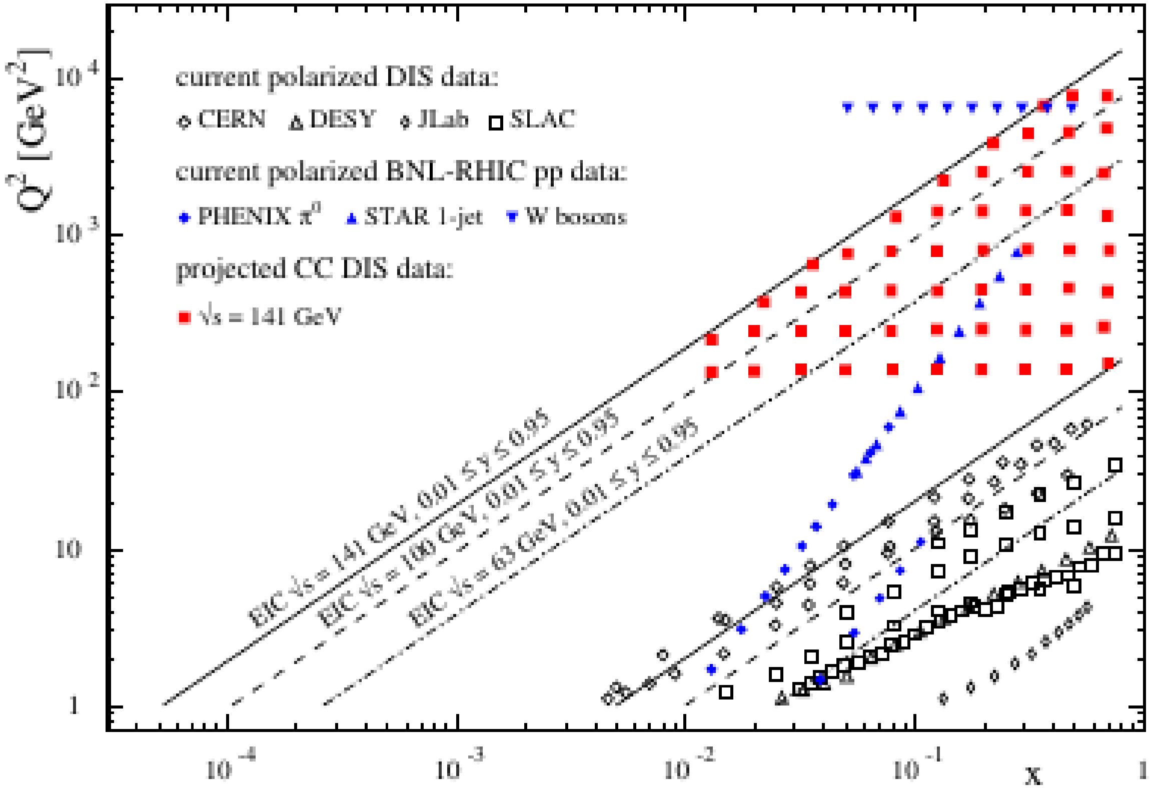
[Accardi, Ent, Keppel, 2010]



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

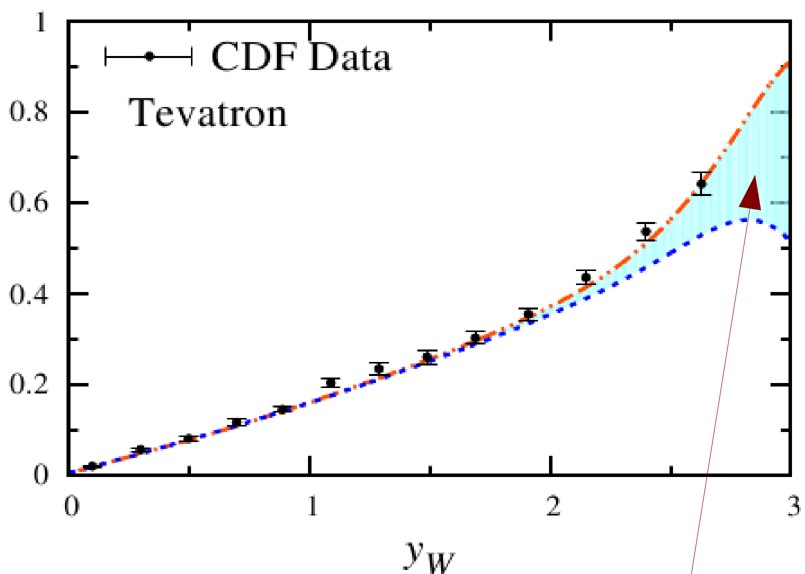
[Aschenauer et al, 2013]



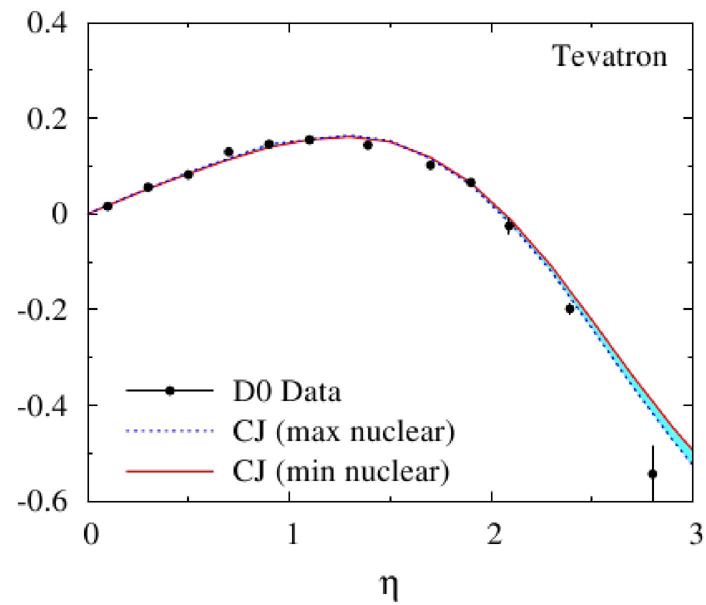
W charge asymmetry at Tevatron

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



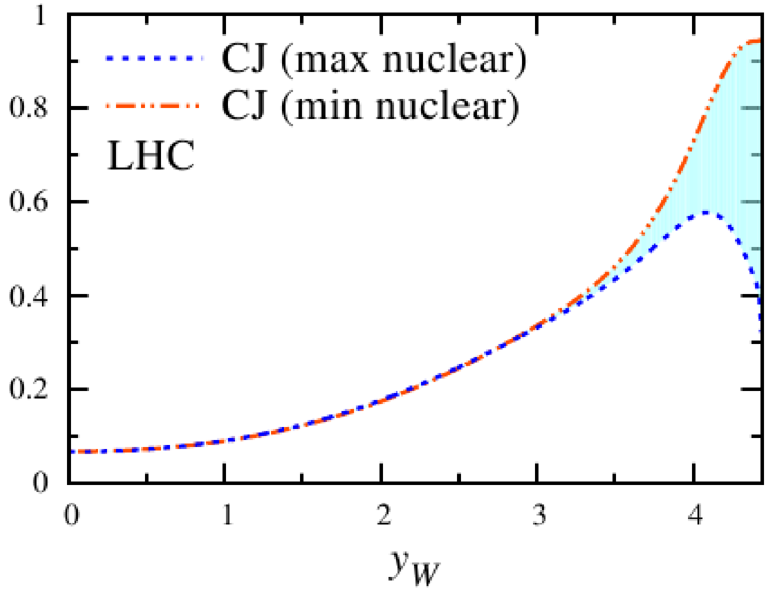
sensitive to *d* at high *x* → Can constrain Nuclear models!

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

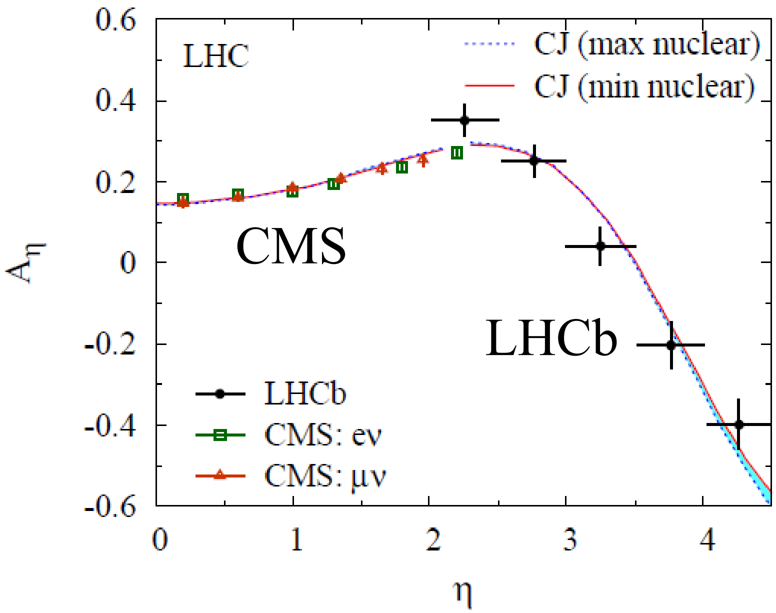
W charge asymmetry at LHC

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

Directly reconstructed W:
- highest sensitivity to large *x*



From decay lepton W → l+ν:
- smearing in *x*

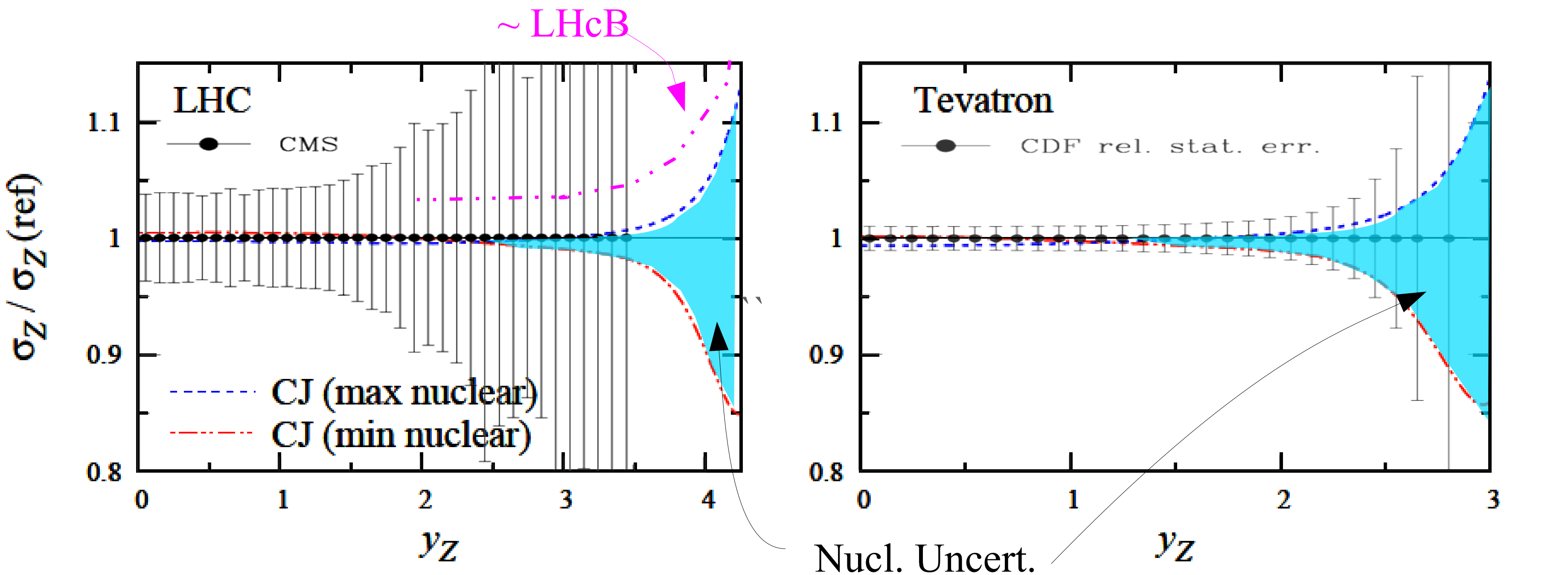


❑ Would be nice to reconstruct *W* at LHCb

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

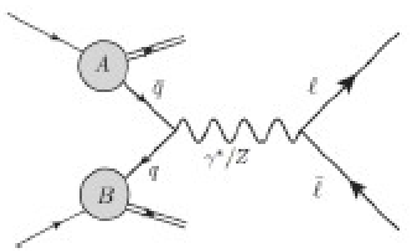
Z rapidity distribution

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

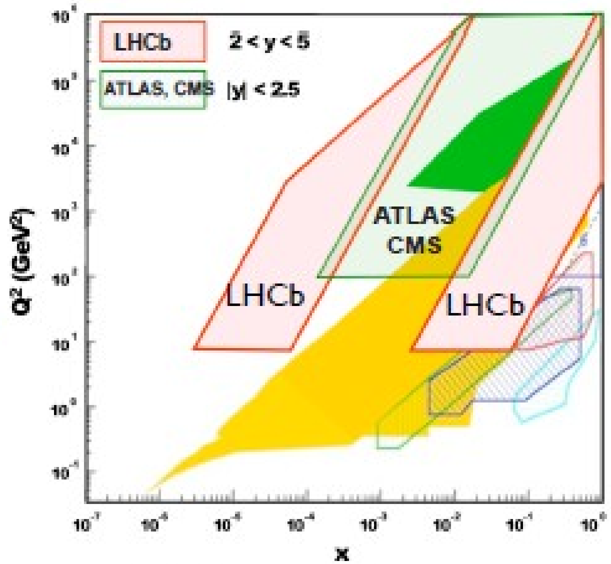


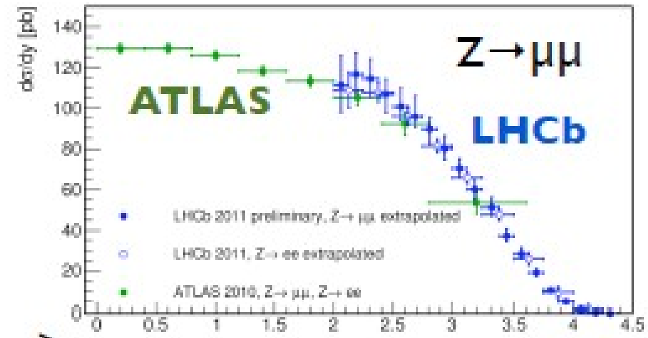
- Direct Z reconstruction is unambiguous in principle, but:
  - **Needs better than 5-10% precision at large rapidity**
  - Experimentally achievable?
    - At LHCb? RHIC? AFTER@LHC?
    - Was full data set used at Tevatron?

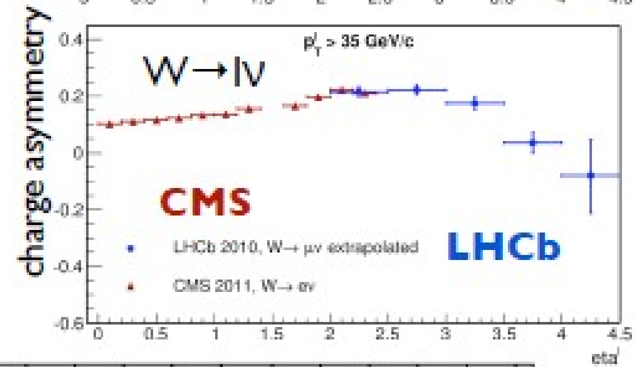
Constraints from the LHC: Electroweak Boson Production



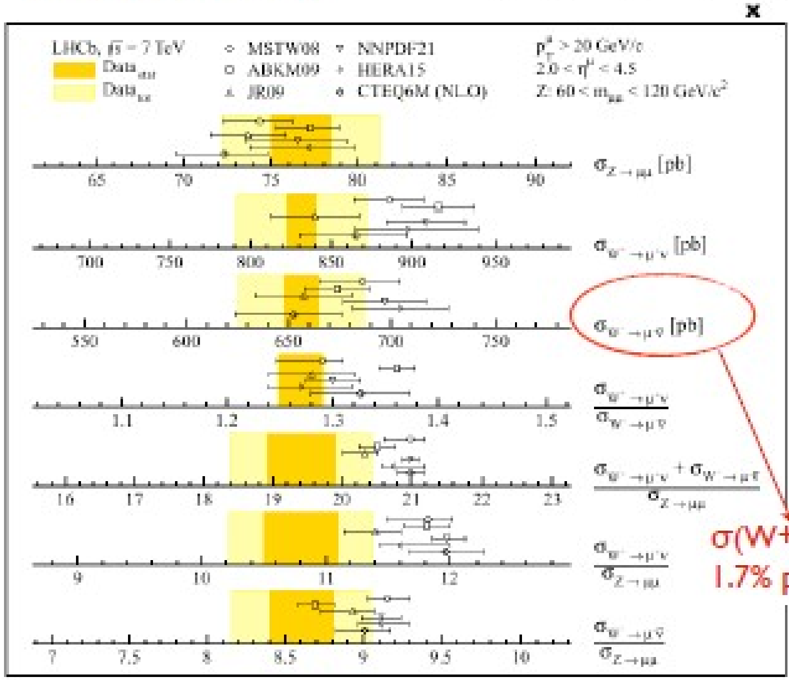
probe light quarks at low and high x



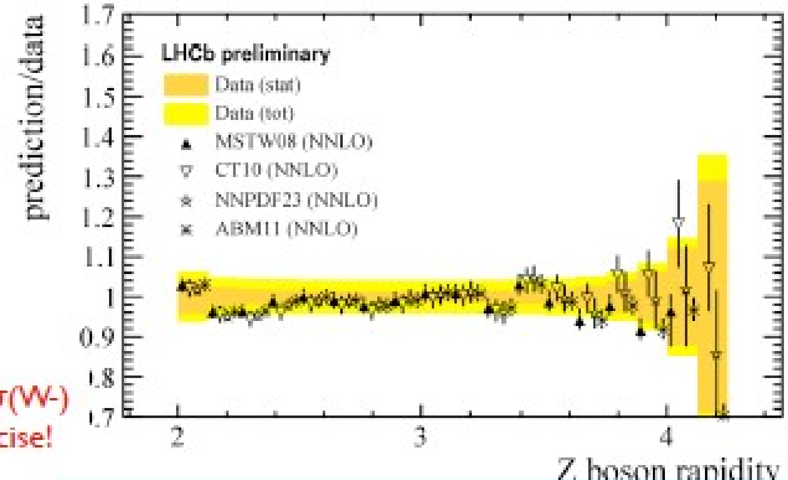




LHCb (S.Tourneur)



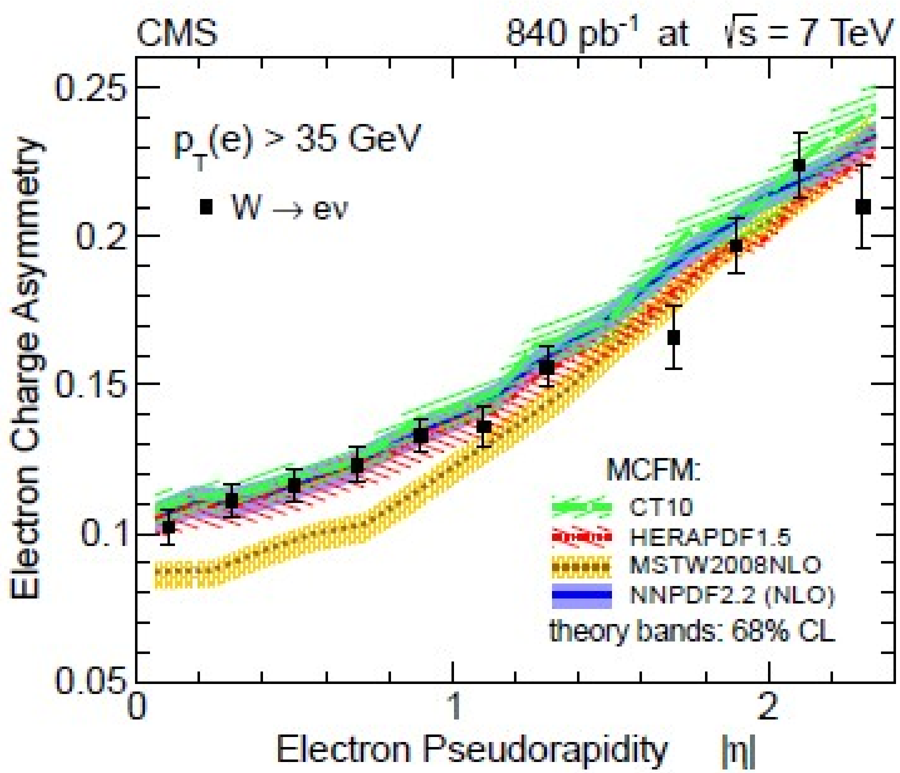
σ(W+)/σ(W-)
1.7% precise!



Systematic error comparable with PDF error
Benchmarking different PDF sets

K. Lipka, DIS'13 WG1 summary

W lepton asymmetry at LHC



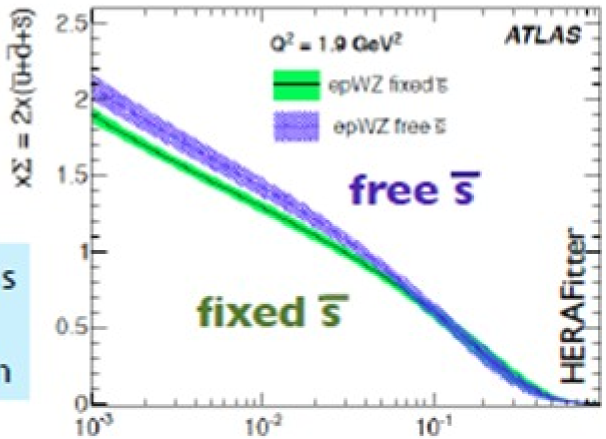
Sensitive both to d/u at $x > 0.1$ and $\bar{u}/\bar{d}$ at $x \sim 0.01$ (not constrained well by other experiments)

Constraints on strangeness: W,Z, W+c

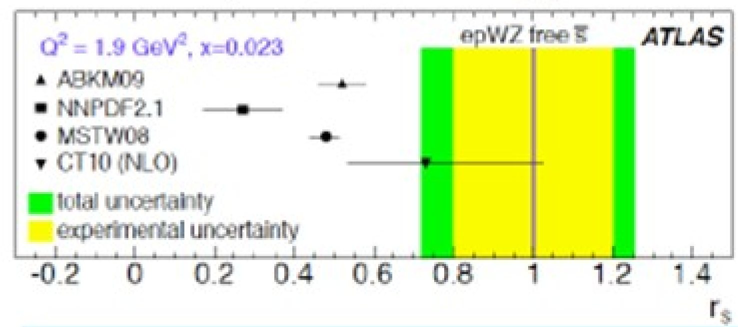
ATLAS *(K. Nikolics)*

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

Z,W rapidity distributions sensitive to strangeness in the proton

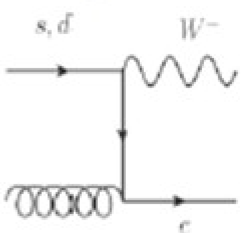


$r_s = 0.5(s+\bar{s})/\bar{d} = 1.00^{+0.25}_{-0.28}$



data disfavors strangeness suppression

W+c probe strangeness



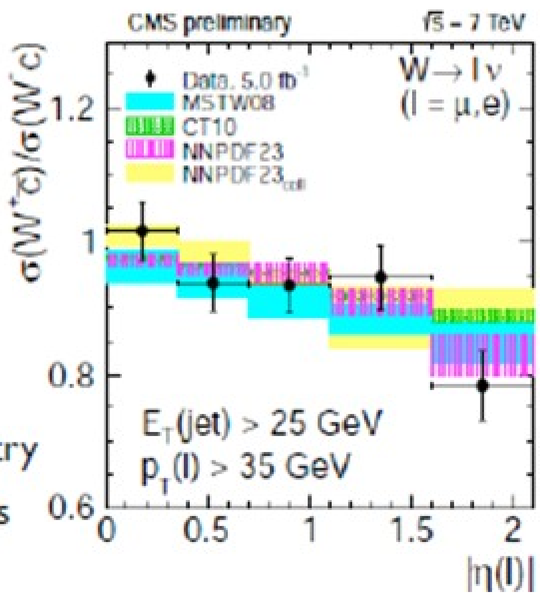
+ c.c.

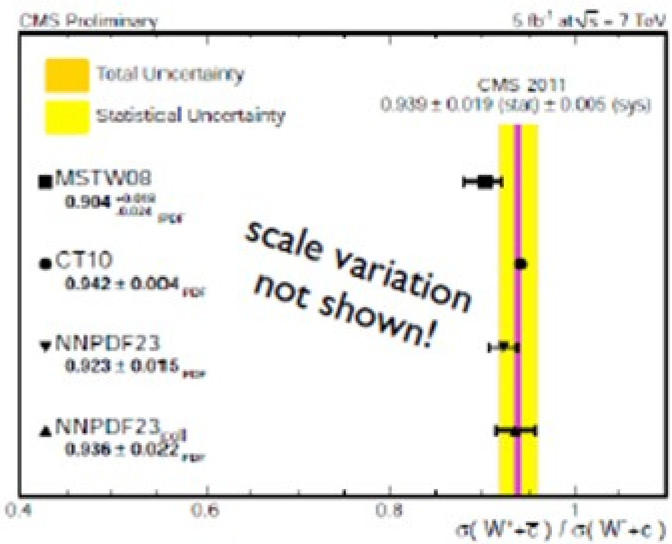
(E.Vryonidou)

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

Strangeness and strange asymmetry

Precise data could constrain PDFs





K. Lipka, DIS'13 WG1 summary

Constraints on strangeness: $K^{\pm}$ at the EIC

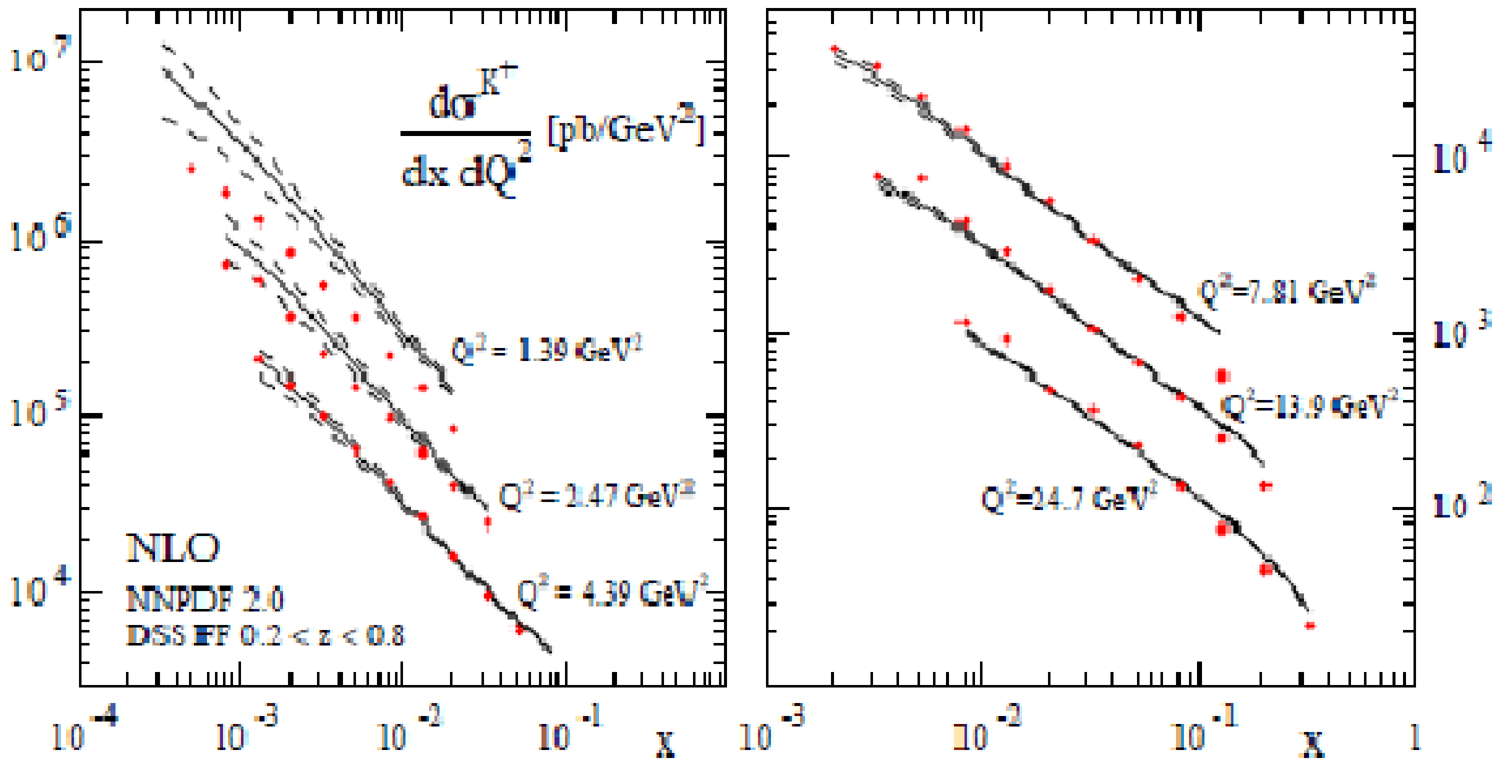


Figure 1.10. SIDIS cross section for K^+ production at NLO accuracy using NNPDF2.0 PDFs [47]. The dashed lines denote the PDF uncertainties. Also shown (points) are the results from a PYTHIA simulation (see text).

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

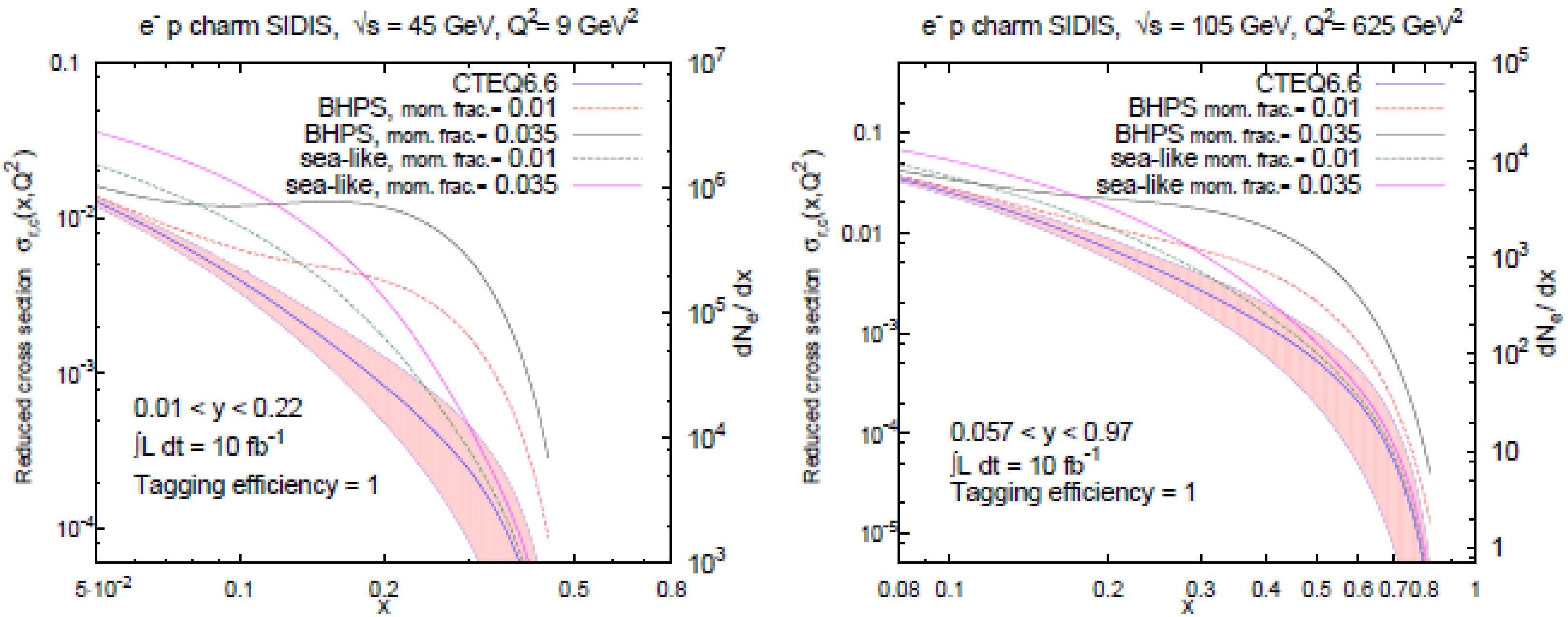


Figure 1.20. Charm contribution to the reduced NC e^-p DIS cross section at $\sqrt{s} = 45$ and 105 GeV. For each IC model, curves for charm momentum fractions of 1% and 3.5% are shown. For comparison we display the number of events dN_e/dx for 10 fb^{-1}, assuming perfect charm tagging efficiency.

Guzzi, Nadolsky, Olness, Sec. 1.9 in 1108.1713