Quark PDFs from non-LHC experiments

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HU Nuclear Physics Group Meeting
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(With a few ideas and slides from P. Nadolski)

Non-LHC experiments – a non exhaustive list…

- **Fixed target experiments**
  - JLab 6 / 12 GeV
  - Compass, HERMES
  - E906 / E866
  - …
- **Lower energy colliders**
  - RHIC
  - EIC / LHeC
  - …

Quark PDFs

d/u $\bar{d}/\bar{u}$ $s-\bar{s}$ intrinsic sea

Valence

Sea quarks

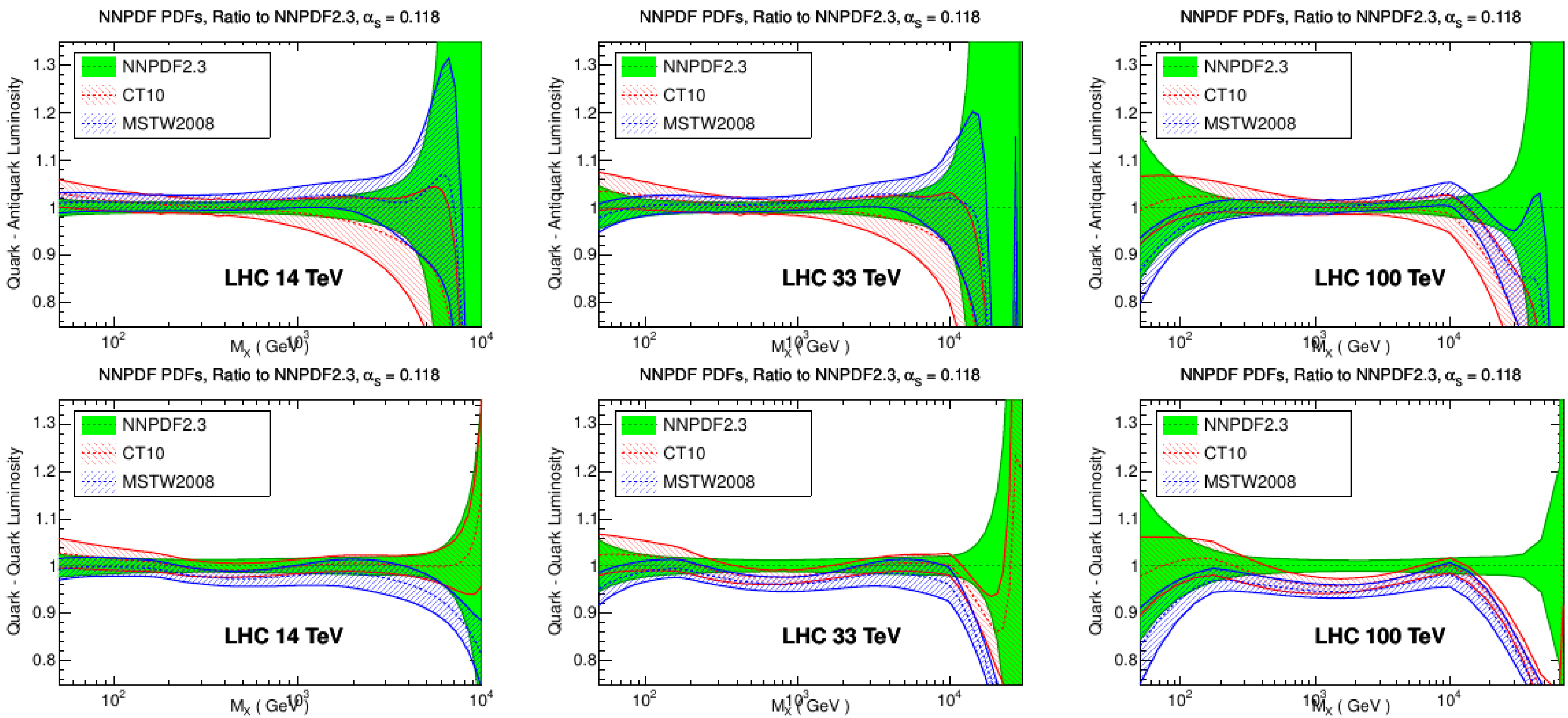
Why? *[high-energy]*

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

- **Reduce uncertainties**
  - Increase potential for LHC discoveries
  - Precision measurements of particle properties
- **Control Q^2 evolution**

http://www.bbc.co.uk/news/science-environment-26250716

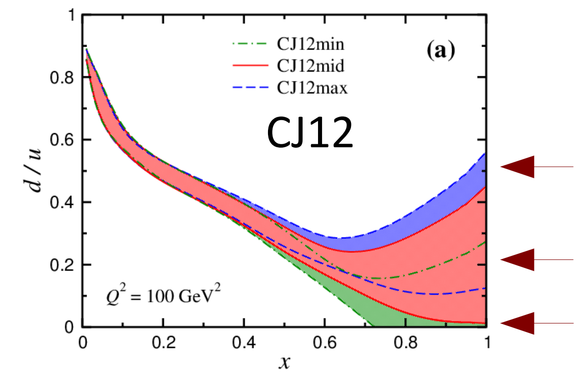
Energy frontier @ Snowmass, arXiv:1310.5189

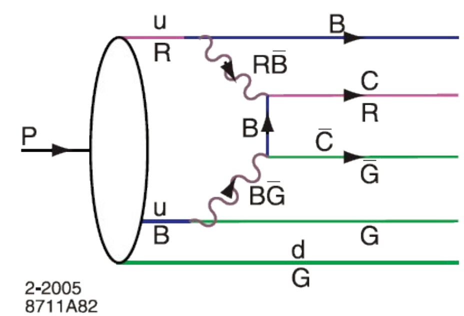


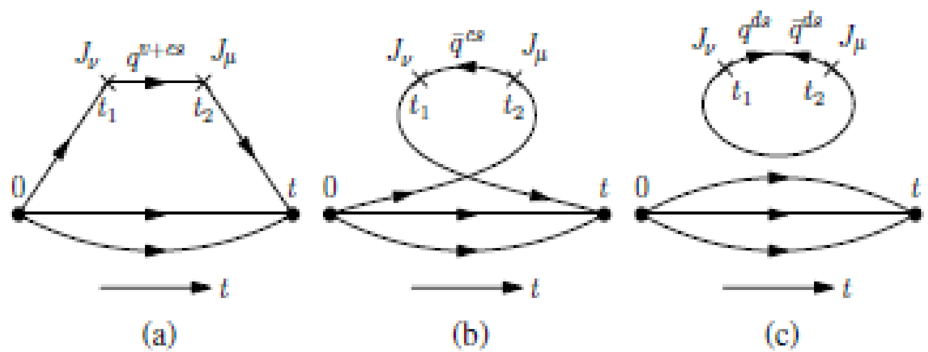
Why? *[hadronic physics]*

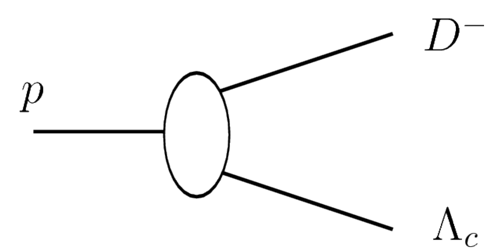
Accardi, Mod.Phys.Lett. A28(2013)35

- **Non-perturbative structure of the proton**
  - Effects of confinement on valence quarks
  - Intrinsic sea generation
  - q – qbar asymmetries
  - Isospin symmetry violation
  - Comparison to lattice QCD
  - …









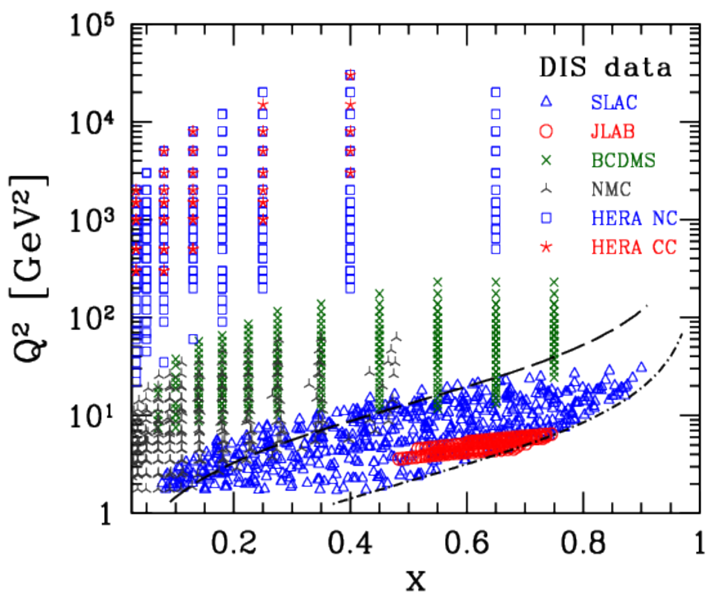
Valence quarks

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

- **CJ12: CTEQ-JLab global parton PDF fits**

  Owens, Accardi, Melnitchouk, PRD87 (2013) 094012

- **Use large-*x*, low-Q^2 data (SLAC, JLab 6)**
  - 3 GeV ^{2} < W^2 < 14 GeV ^{2}
  - PDF errors reduced by 50% at x>0.5



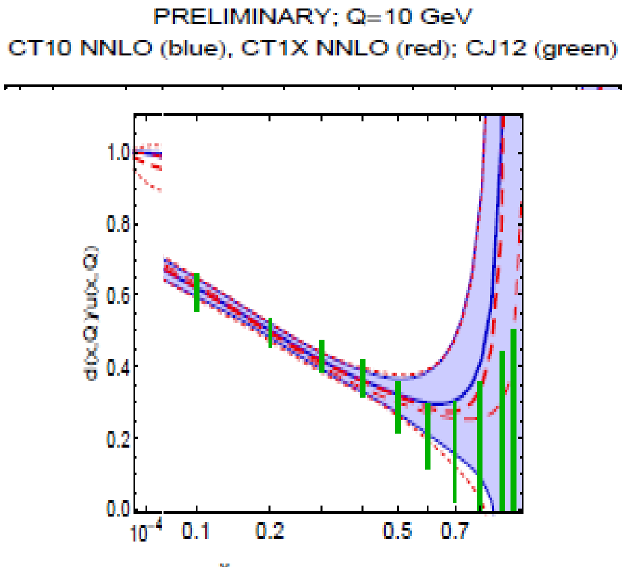
- **Theoretical improvements**
  - Target mass & higher-twist corrections
  - Generalized d-quark functional form to allow d/u → finite as x → 1

$$d'(x) = d(x) + \alpha x^{\beta} u(x)$$

  - Nuclear corrections for deuteron targets (Fermi motn., binding, offshellness)

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

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



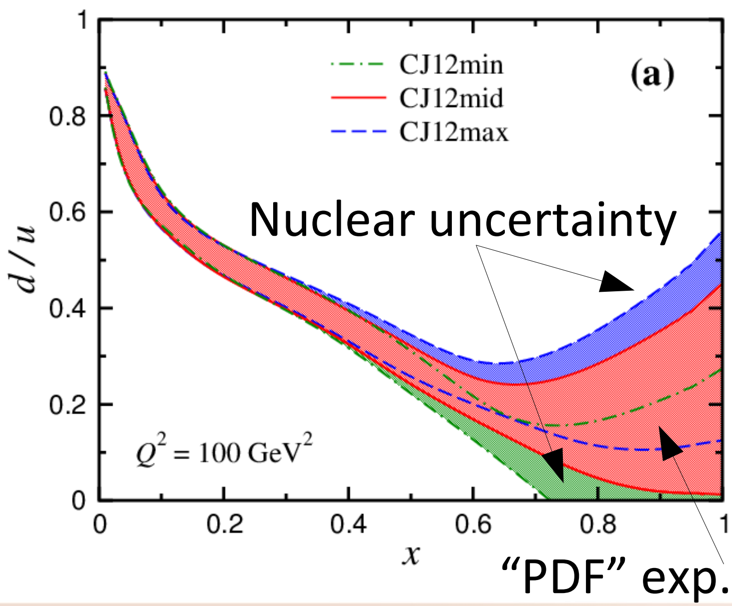
- **Results**
  - Large reduction in *d*-quark error
  - Large *d*-quark suppression
  - Meaningful extrapolation to x → 1

    $d/u(x=1) \in [0.0.5]$ instead of $[0,\infty]$!!
  - Almost distinguishes proton models

} Nucl. Corr.

} Extended d-quark parametr.

Owens, Accardi, Melnitchouk, PRD87 (2013) 094012



Non-perturbative proton models

SU(6) spin-flavor

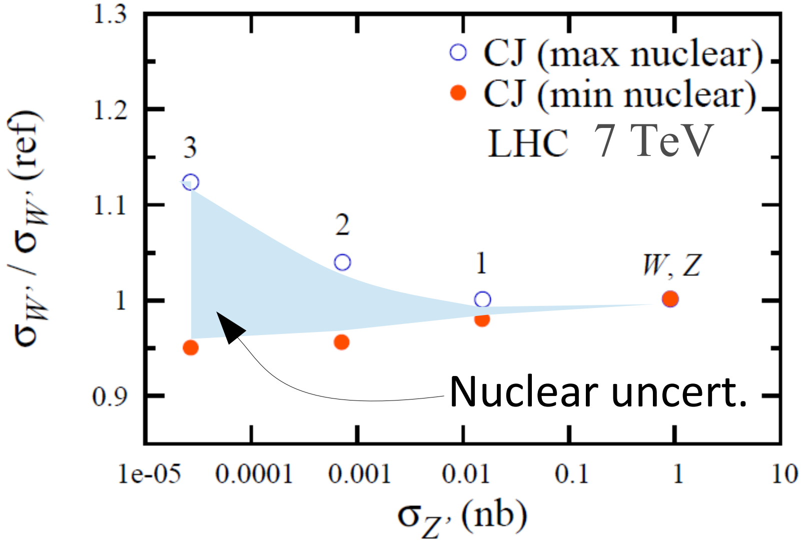
hard gluon exchange

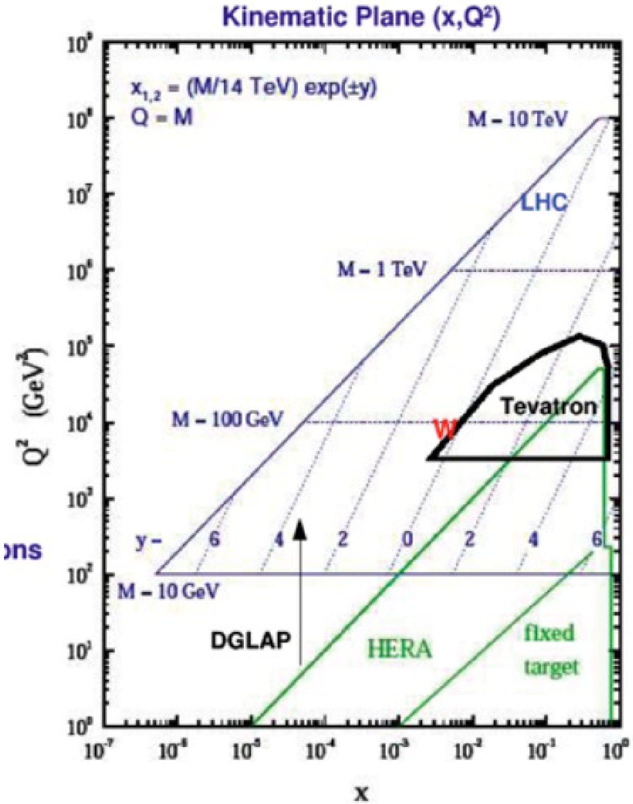
S=0 diquark dominance

Example:

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

- **W' and Z' total cross sections**





- **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 [Mangano]
  - LHCb, ...

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

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)
- **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

Jlab

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*

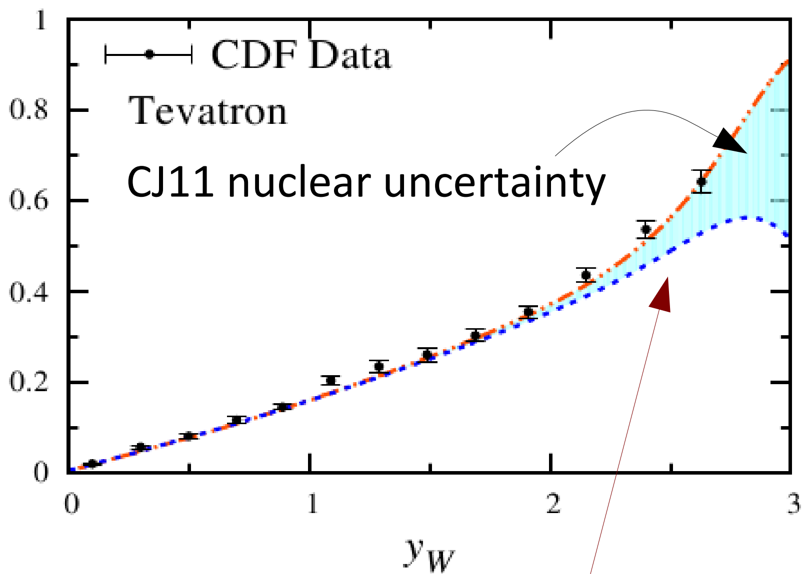
RHIC ??
AFTER@LHC

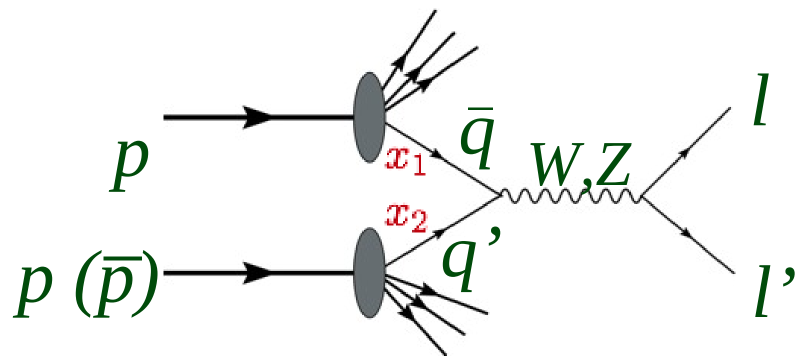
Use protons to study nuclei (!)

Brady, Accardi, 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!

See also: MMSTWW EPJ C73 (2013)

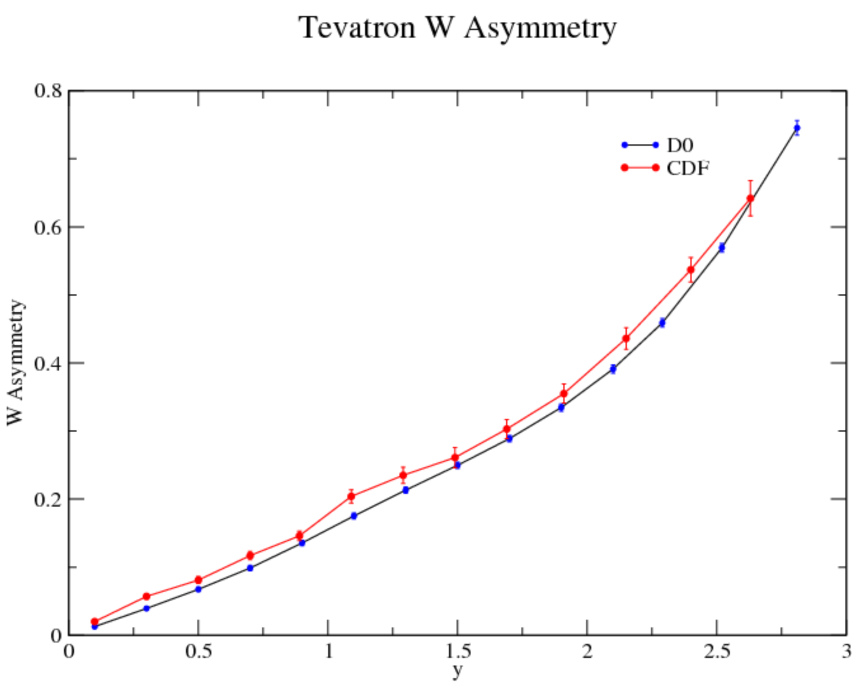
Use protons to study nuclei (!)

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

- Present data
  - Favor minimum – medium nuclear corrections

    [CJ12, PRD87 (2013) 094012; MMSTWW, EPJ C73 (2013)]

- Needs to corroborate, consider PDF errors, extend method:
  - *New W data from DØ*
    - *10x statistics*
    - *Tension with CDF*
  - *W, Z* at RHIC
  - *Z* (and *W* ?) at LHC,
  - PVDIS at JLab 12
  - **CC @ EIC / LHeC**



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: 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, … ??

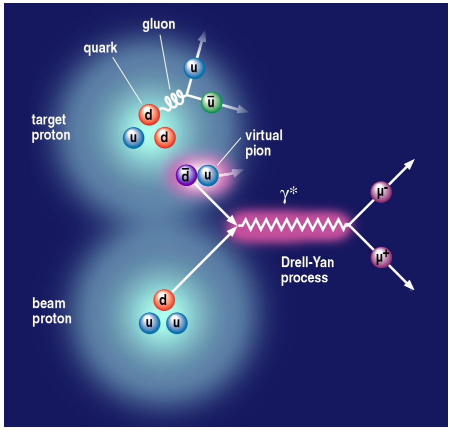
Sea quarks

Charge symmetry breaking

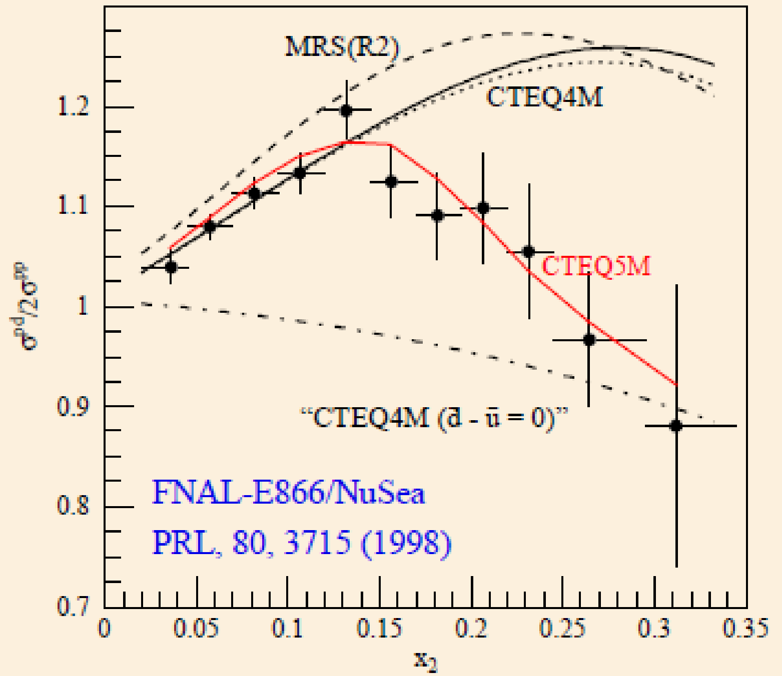
$$\bar{d}(x) \neq \bar{u}(x) \ , \ \bar{q}(x) \neq q(x)$$

May be caused by

- DGLAP evolution
- Fermi motion
- Electromagnetic effects
- Nonperturbative meson fluctuations
- Chiral symmetry breaking
- Instantons



$\sigma_{pd}/(2\sigma_{pp})$ at large $x_F = x_A - x_B$



Theory curves reflect different assumptions about $\bar{d}/\bar{u}$

Charge symmetry breaking

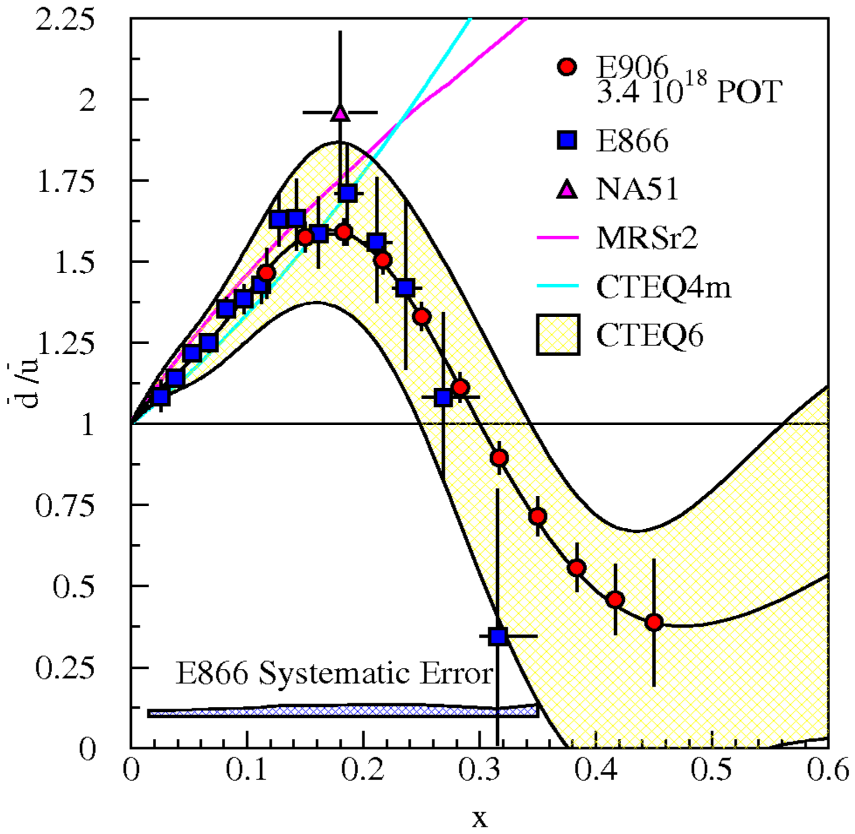
- **E866 lepton pairs:**

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

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

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

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

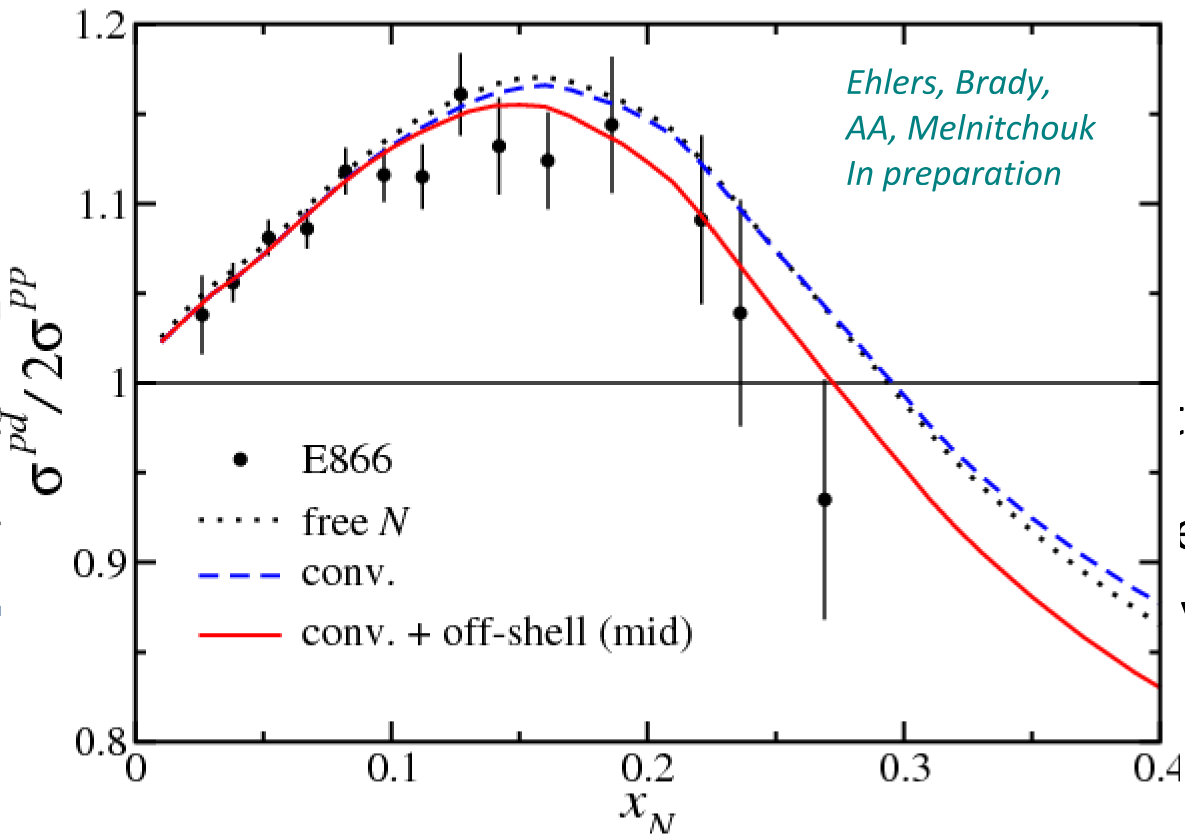


Theory corrections…

- But $\frac{\bar{d}}{\bar{u}} \approx \frac{\sigma_{pp}}{\sigma_{pd}} - 1$ only assuming
  - Charge symmetry of protons and neutrons $(u_p = d_n,\, d_p = u_n)$
  - Negligible Fermi motion, binding, shadowing corrections
  - Off-shell effects non-negligible, suppress the cross section
    - Increase dbar/ubar ratio comapred to naïve analyss

Theory corrections…

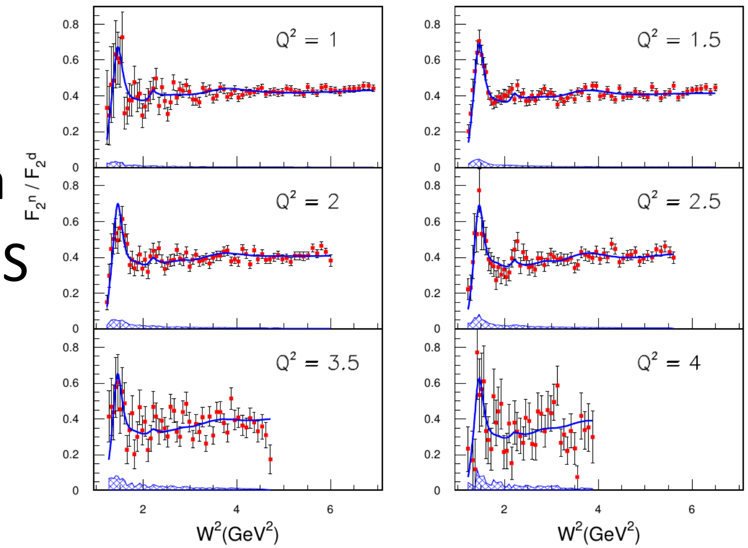
- But
  - Ch… , $d_p = u_n)$
  - Ne… …ions
  - Of… …ection
    - … …yss



At a few-percent accuracy, charge symmetry violation and nuclear corrections must be explicitly estimated if the data on deuterium is used

…through global fits

S. Tkachenko et al. arXiv:1402.2477



- **Example for constraining CSV:**
  - contrast CDF/D0 reconstructed *W* data to BONUS spectator tagged neutron DIS

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

  Accardi et al. PRD81 (2010), Ball et al. ArXiv:1303.1189 (2013)

  - Constrain nuclear corrections in DIS by comparing e+d to p+p data
  - Use the same nuclear model in p+d → Drell-yan

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 (so far) mostly by ν+A data**
  - CCFR inclusive DIS
  - NuTeV muon pair production

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

Strangeness and strangeness asymmetry

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

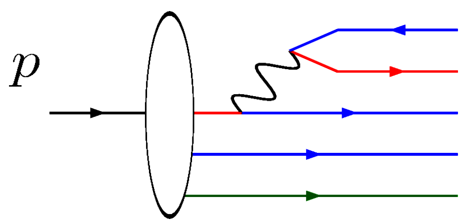
- **Strangeness is important, though!**
  - Large $[s^-]$ could explain alone the NuTeV anomaly!
  - NNPDF 2009: $[s^-]$ = 0 +- 0.009
    - But does not include the mentioned nuclear uncertainty

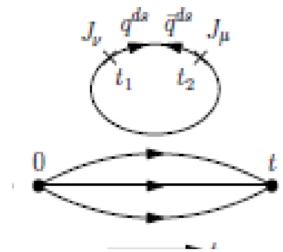
Strangeness and strangeness asymmetry

- **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, CTEQ workshop 2013]*
  - 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
    - ...

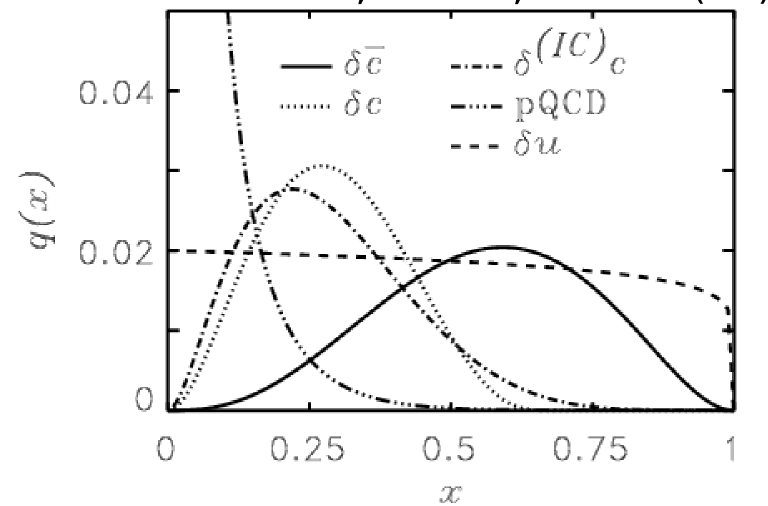
Intrinsic and extrinsic sea quarks

- **Extrinsic sea:** radiatively generated
  - Asymmetries from EM corrections
  - Maps onto disconnected lattice diagrams

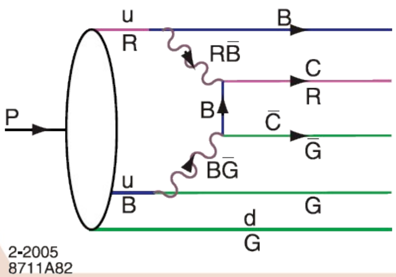


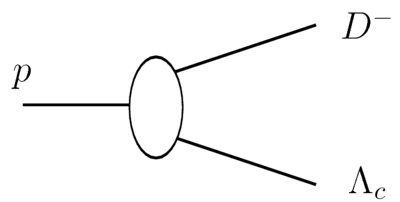


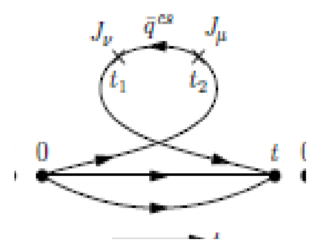
Melnitchouk,Thomas, PLB414(97)



- **Intrinsic sea:** non-perturbative
  - Excited fock states – symmetric
  - p → π+N, K+Λ , D+Λc – asymmetric
  - Connected lattice diagrams

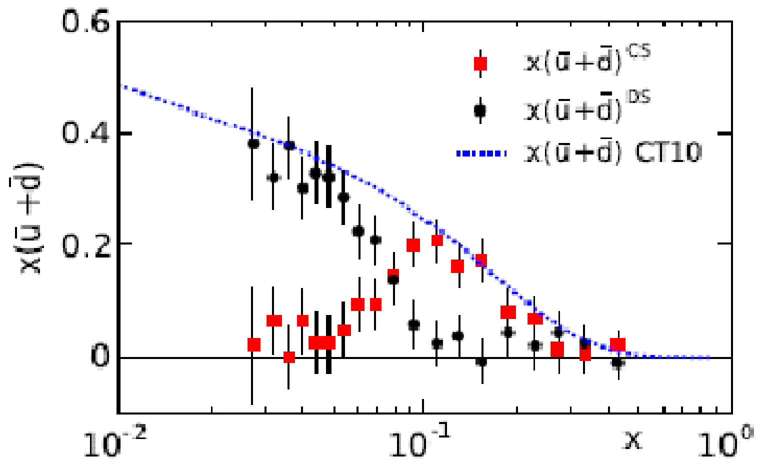






Intrinsic and extrinsic sea quarks

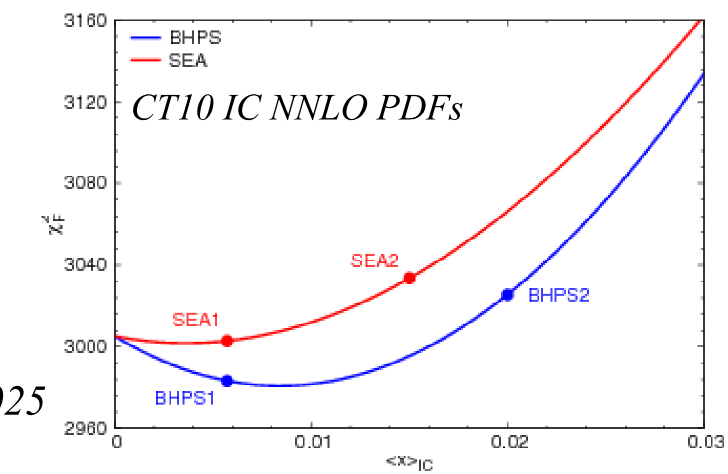
- Smooth parametrizations can hide existence of two components



Liu, Chang, Cheng, Peng, 1206.4339

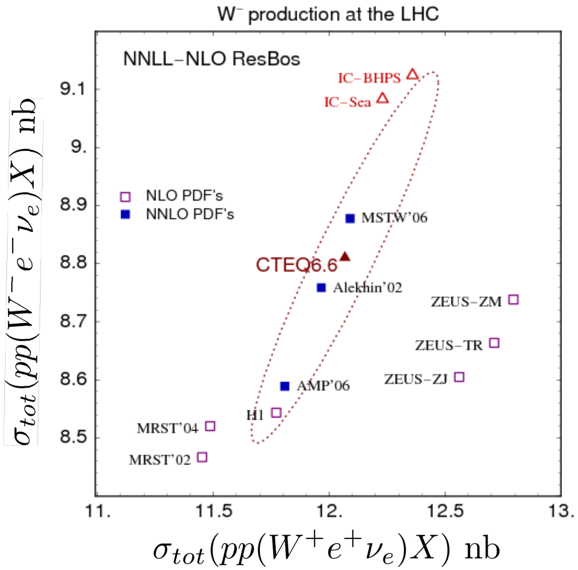
- Intrinsic charm (IC) can carry up to 1% of the proton momentum
  - And if asymmetric, would pull NuTeV anomaly in the wrong direction again...

S. Dulat et al., 1309.0025



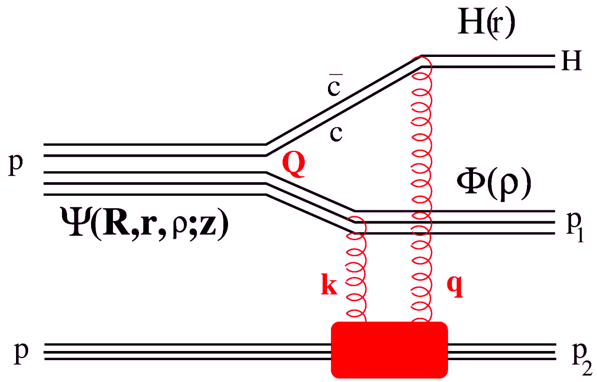
Intrinsic and extrinsic sea quarks

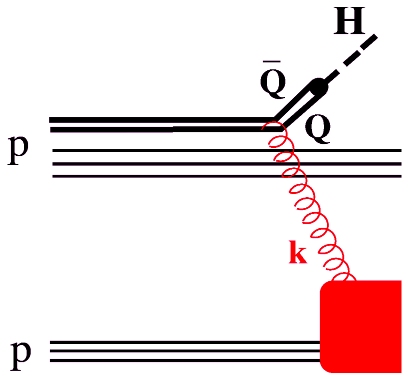
- **Some consequences**
  - Standard candles



Nadolsky et al. PRD78(08)

  - Novel Higgs production mechanism at forward rapidity





Brodsky et al. PRD73(06), NPB907(09)

Conclusions

PDFs for the 14 TeV era

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

LHC, Tevatron
LHeC

RHIC, EIC

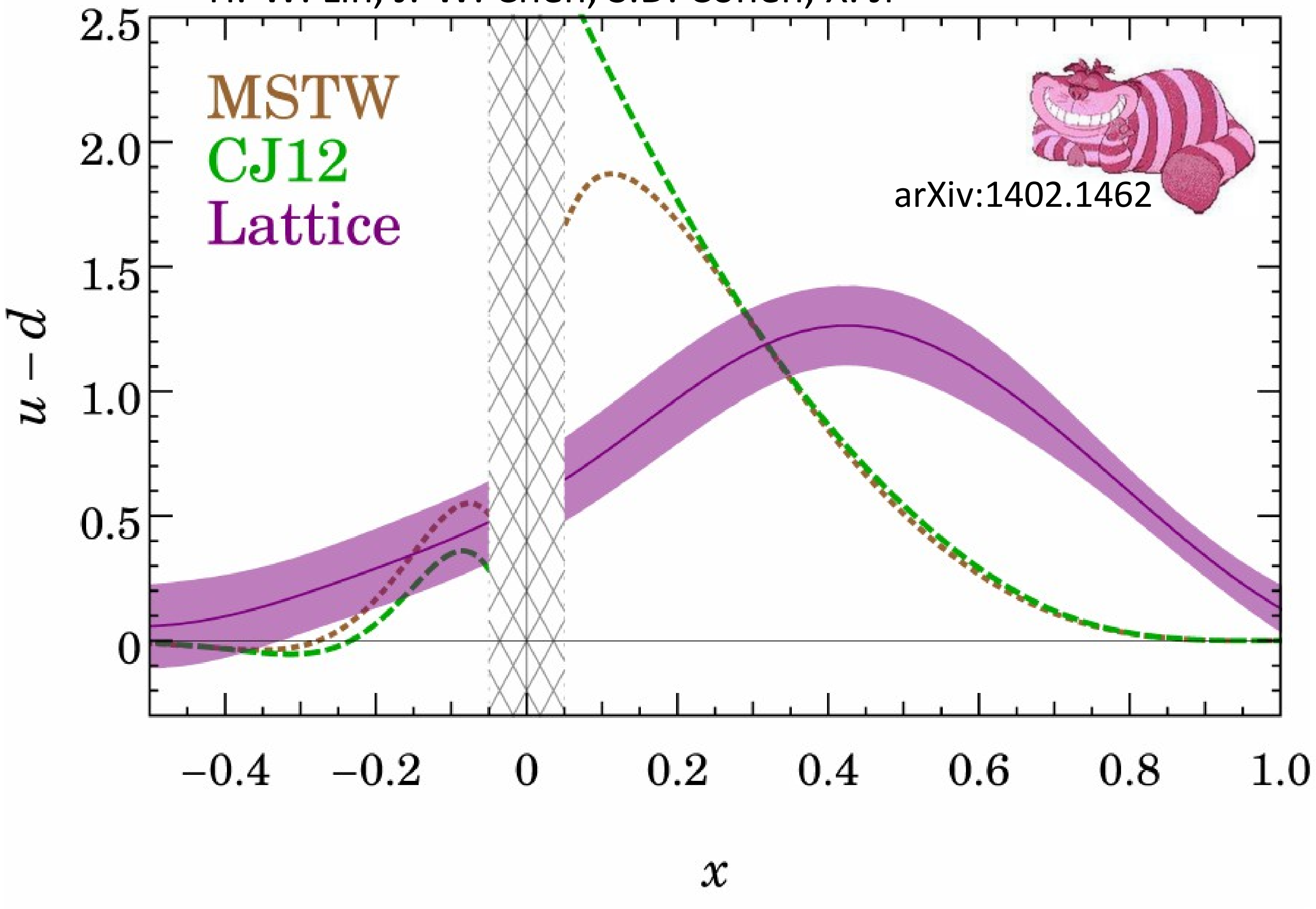
JLab 6/12, E906,
HERMES, COMPASS, ...

...and lQCD

- Physical masses already reached
- Higher and higher PDF moments will become calculable
- New x-space technique

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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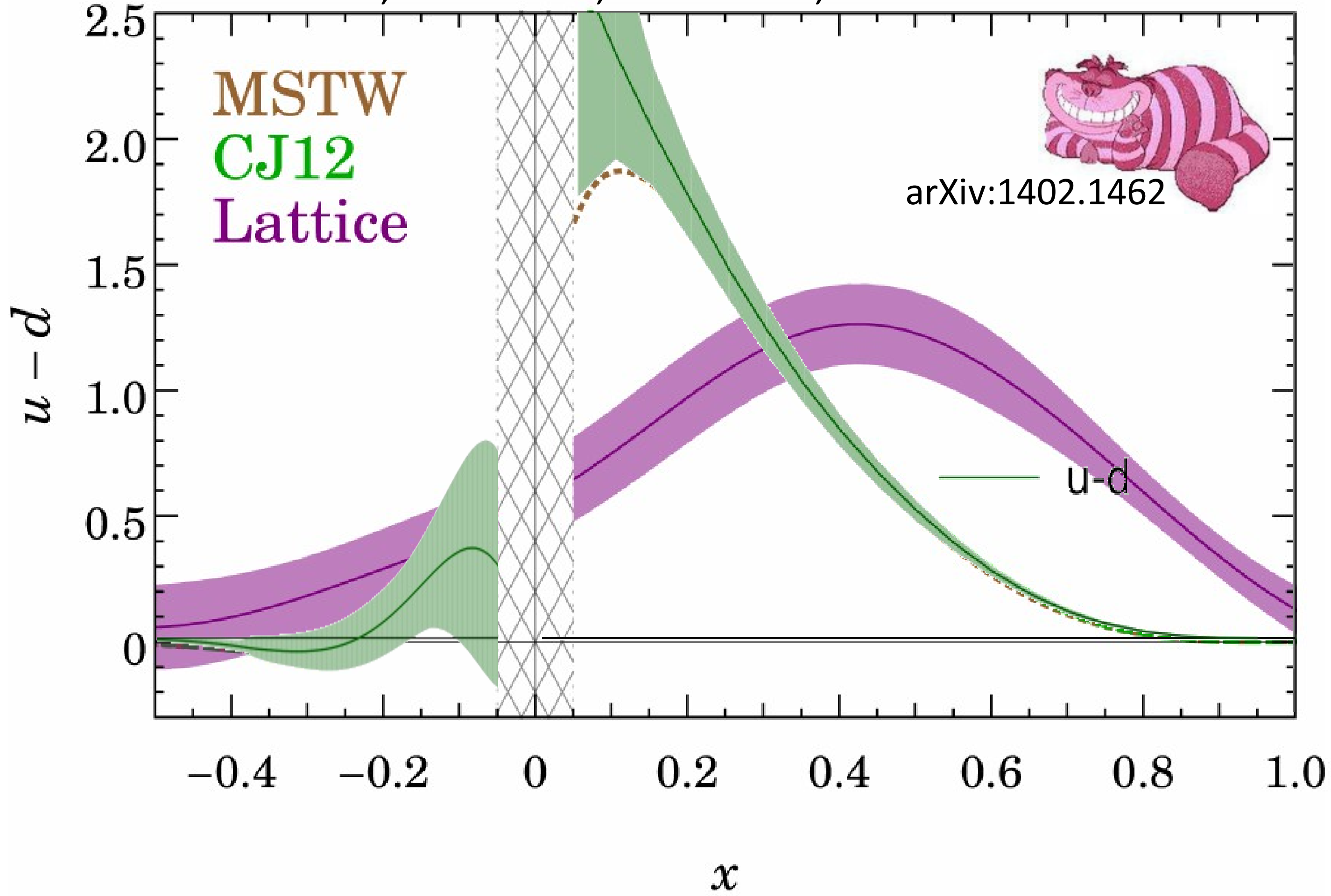
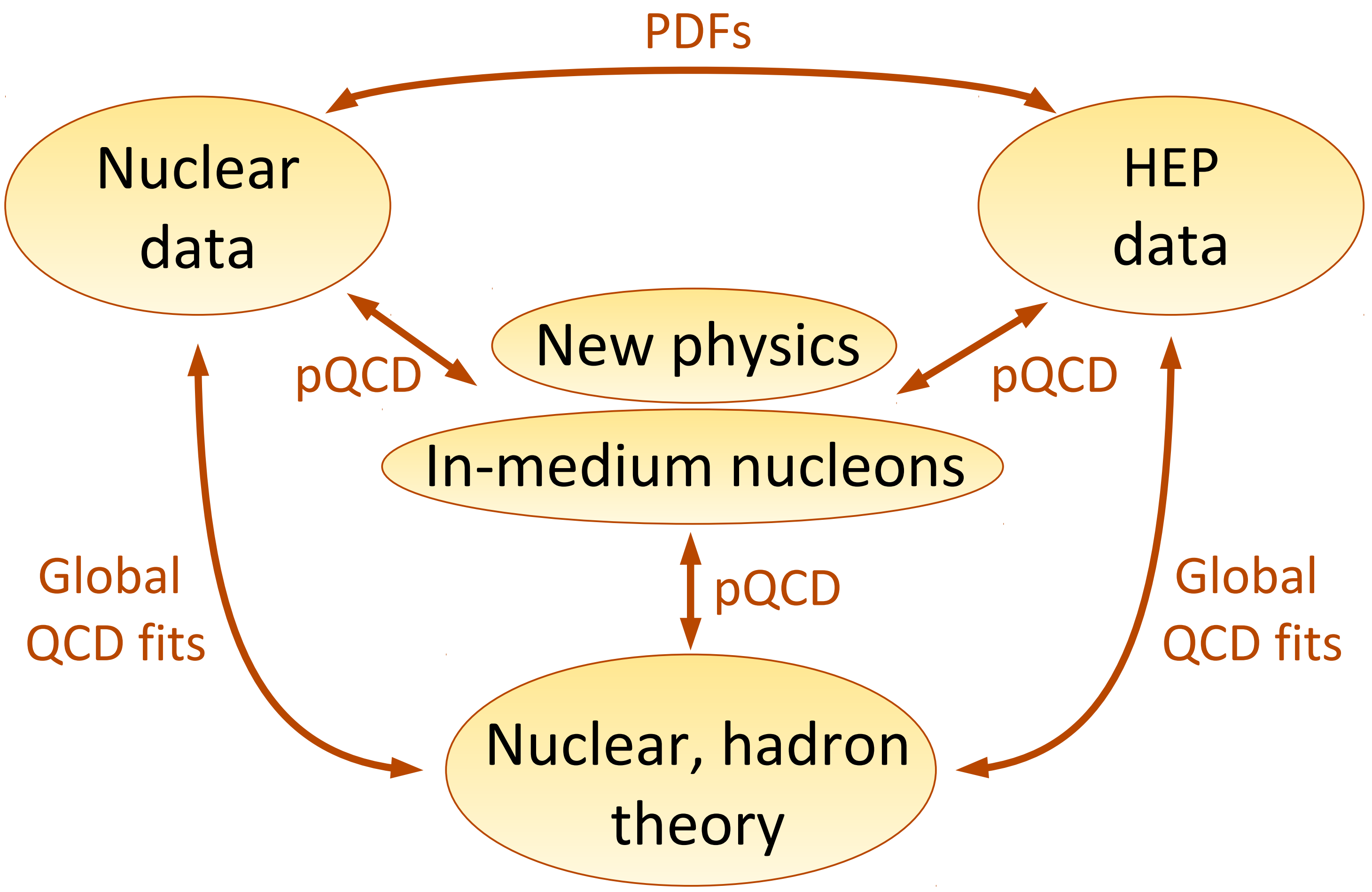


CJ12 error bands courtesy of J. Guerrero

Needs the marriage of HEP and NUCL

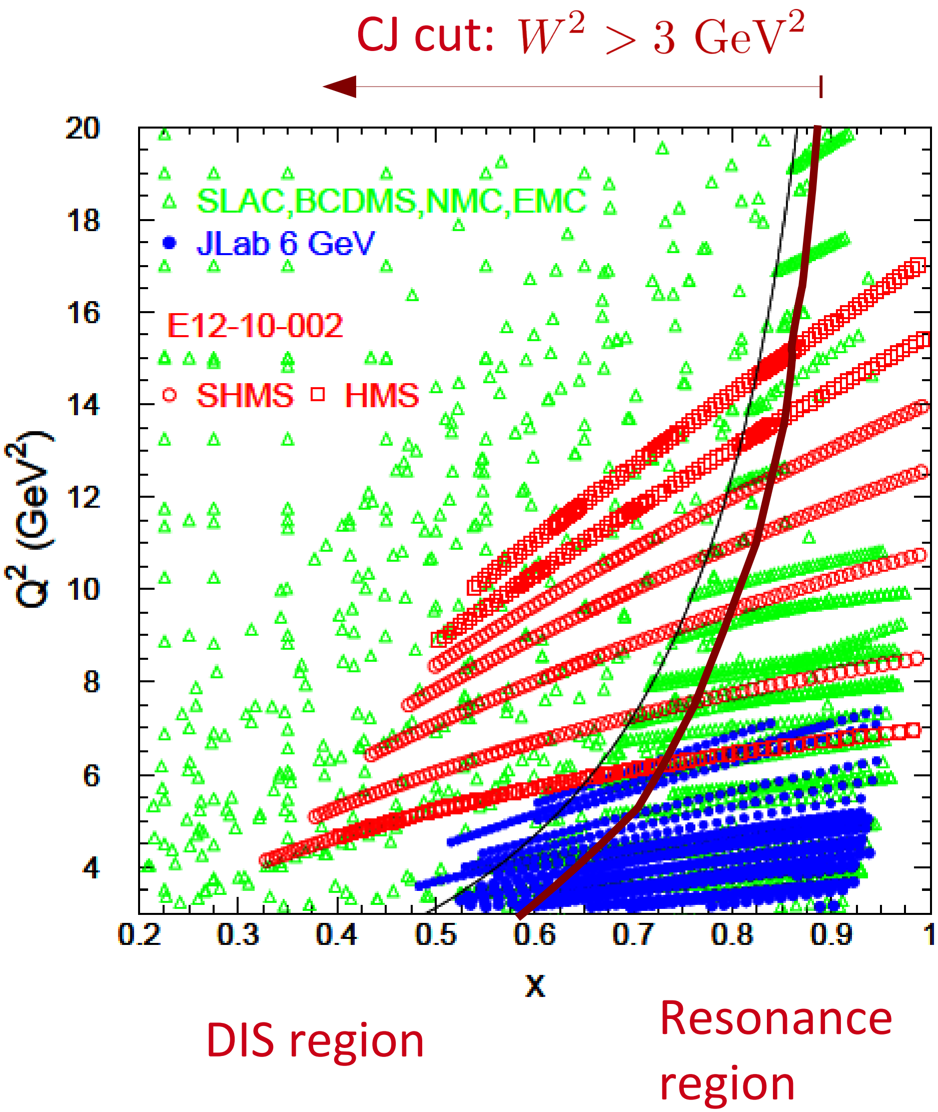
- A global approach across subfields... and DOE/NSF categories, too!



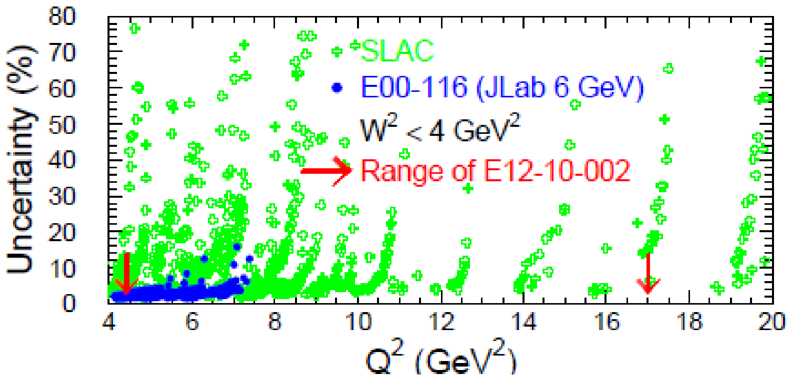
Appendix:
old and new experiments

- examples -

JLab 12 - proton, deuteron structure functions



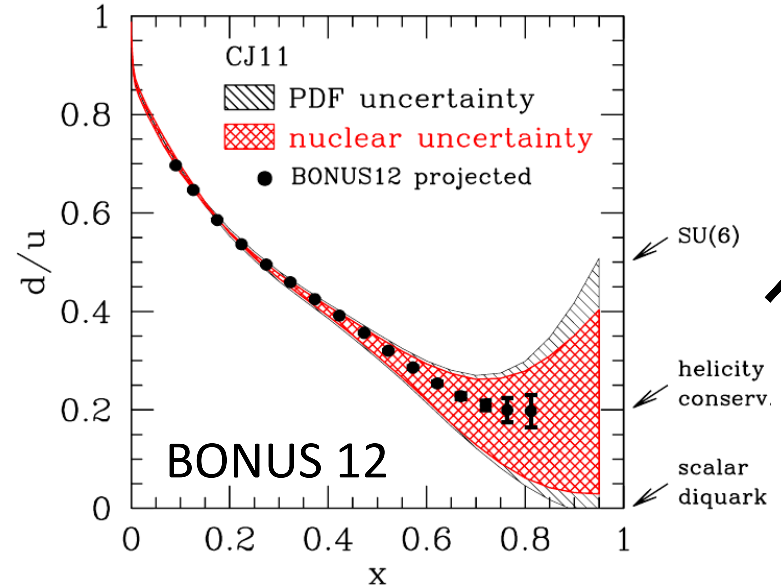
Jlab12 experiment E12-10-002

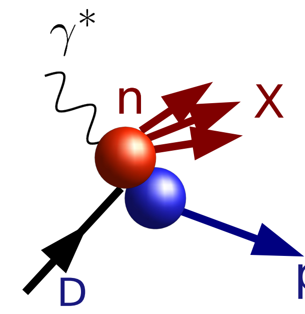


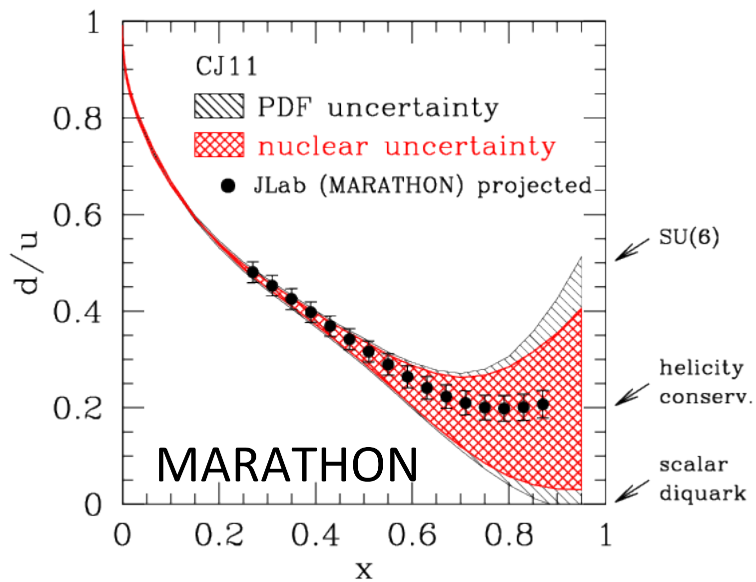
- **JLab 12 GeV**
  - More than double Q^2 range
  - Similar precision as JLab **6 GeV** (largely improve cf. **SLAC**)

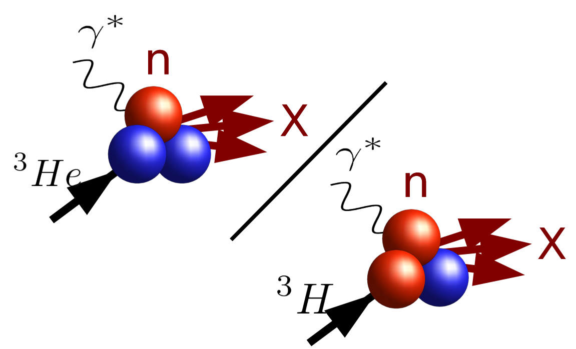
JLab 12: Quasi-free neutrons

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





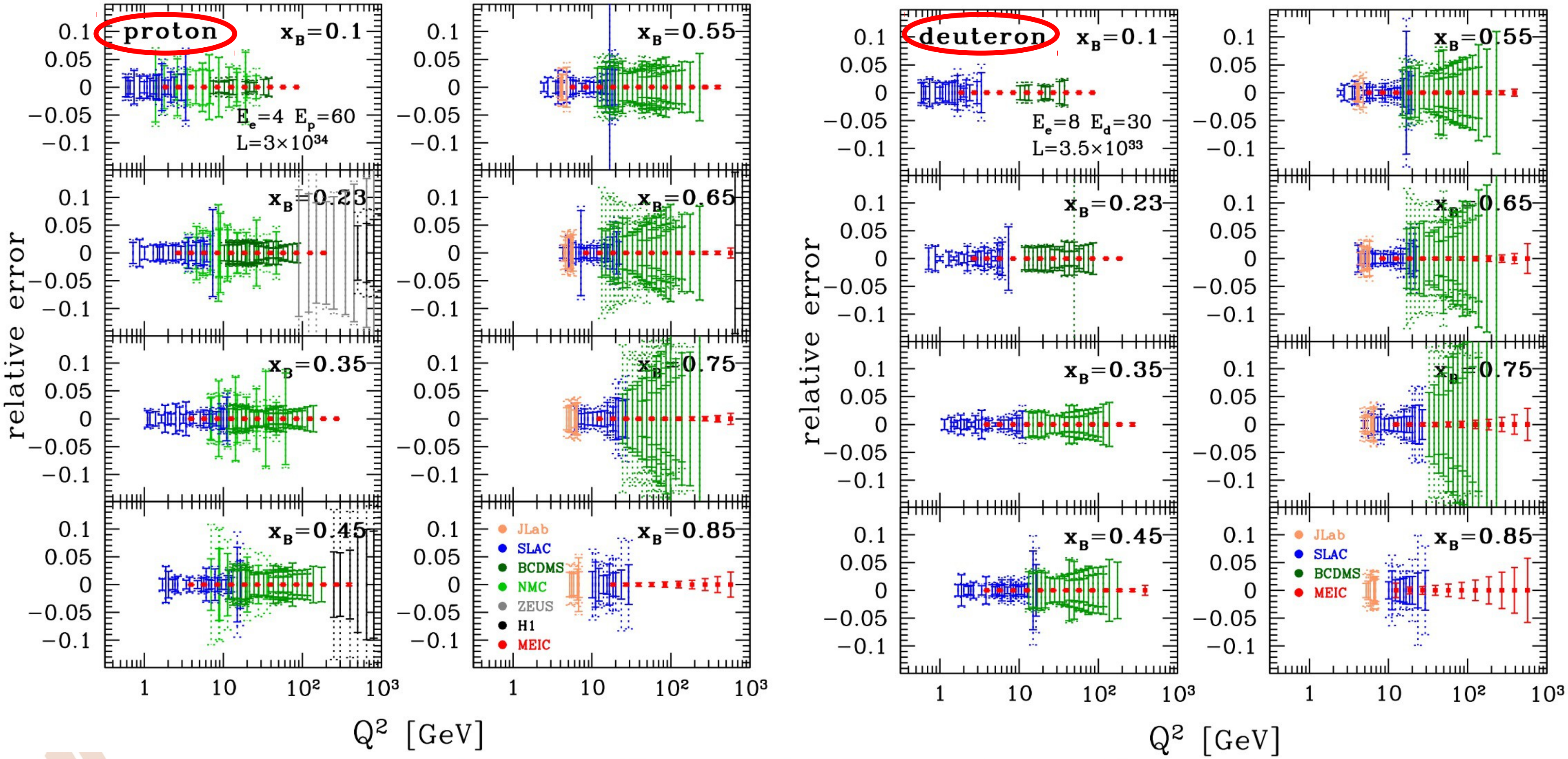




At the EIC

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

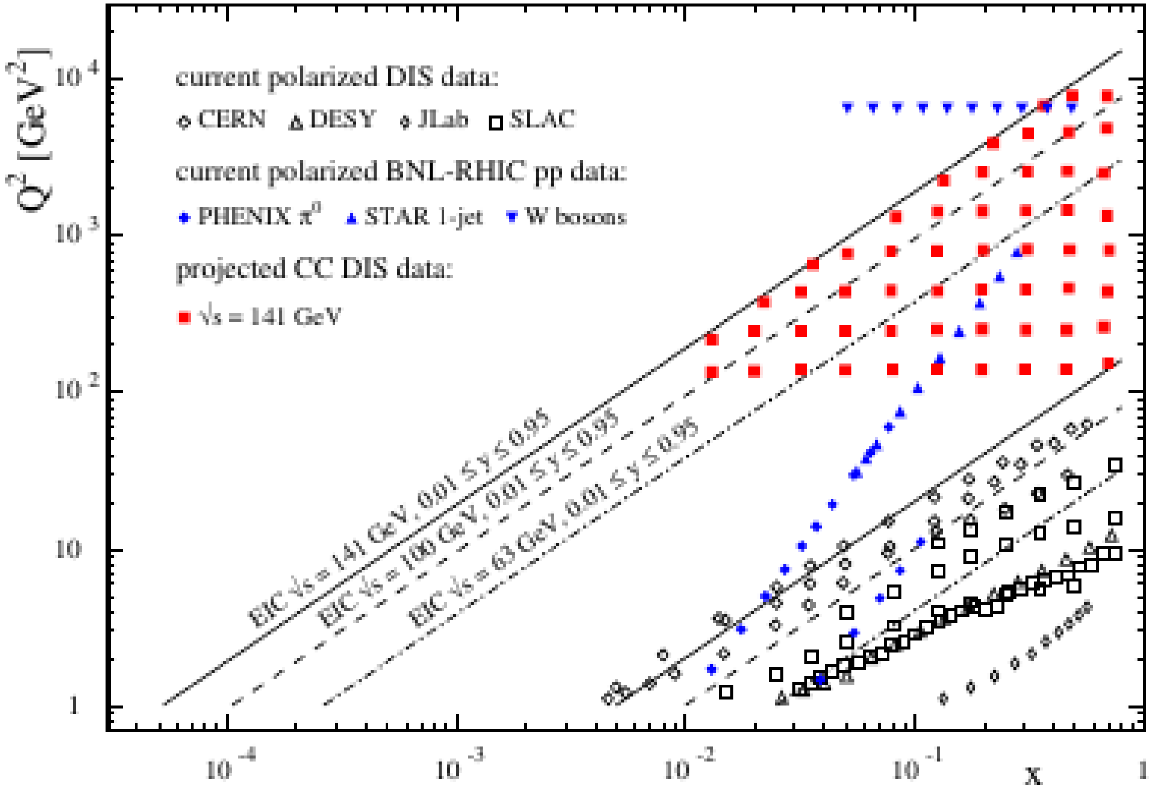
[Accardi, Ent, Keppel, 2010]



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

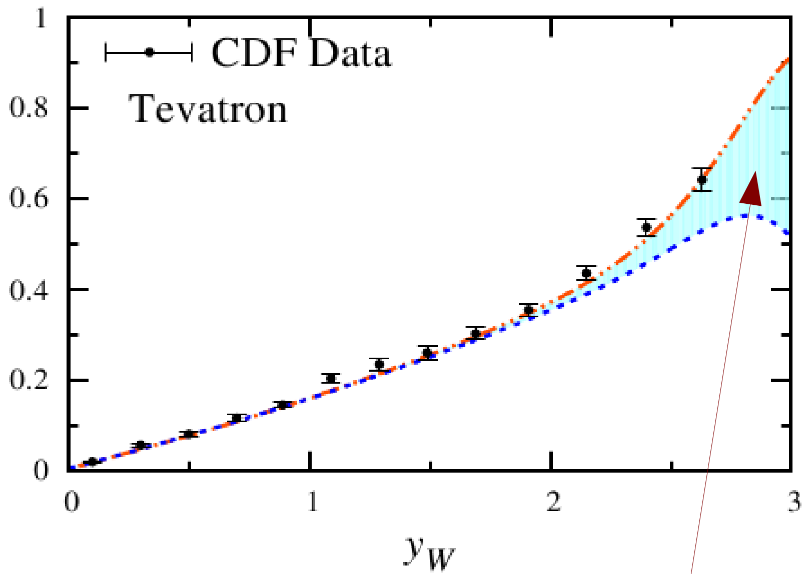
[Aschenauer et al, 2013]



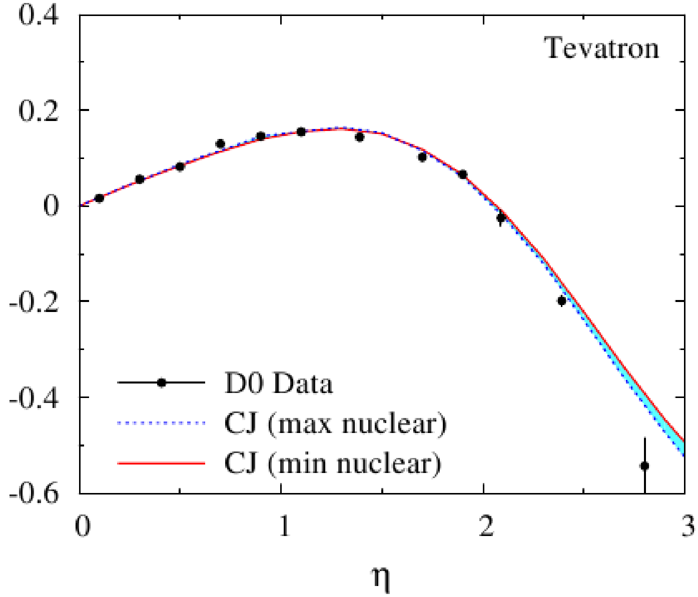
W charge asymmetry at Tevatron

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!

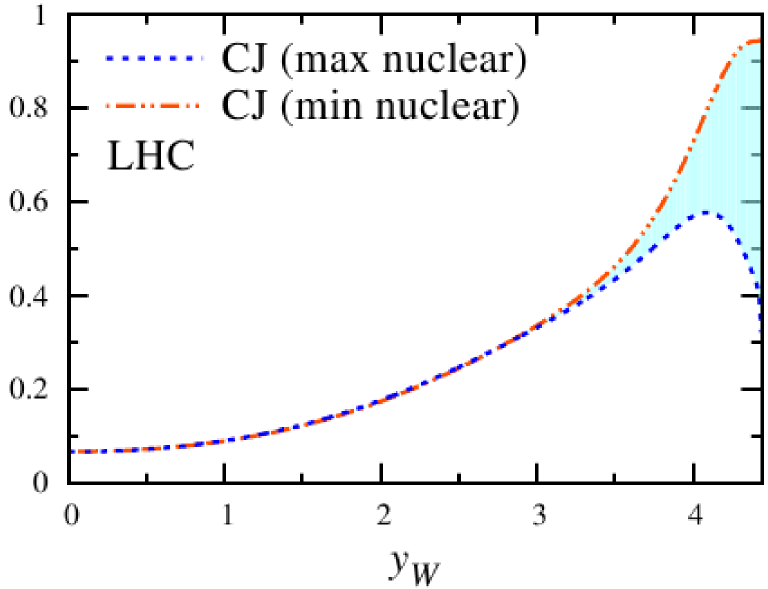
- Too little large-*x* sensitivity in lepton asymmetry:
  - **need reconstructed *W***

W charge asymmetry at LHC

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

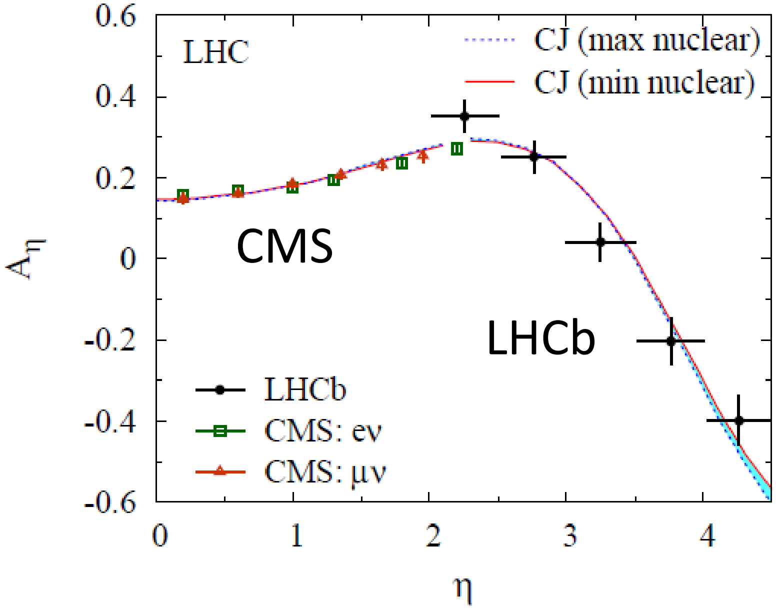
Directly reconstructed W:

➢ 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

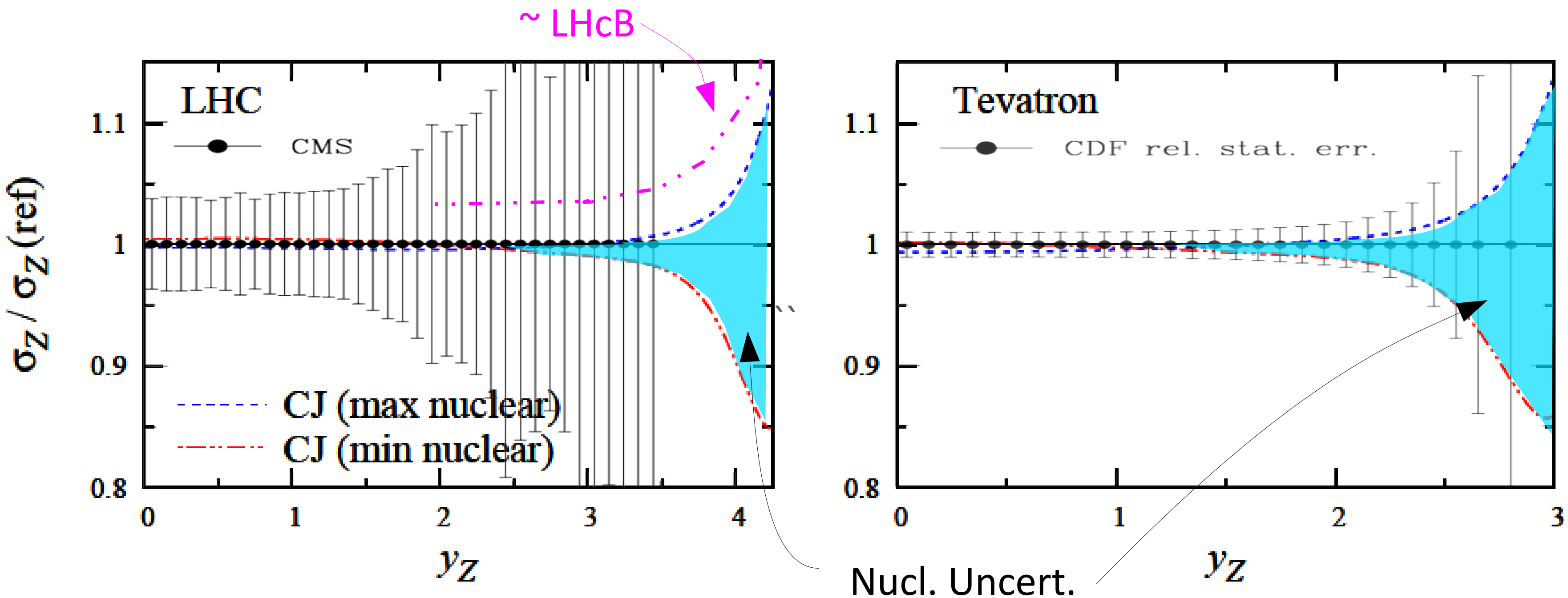
– Is it at all possible?? (too many holes in detector?)

– Systematics in *W* reconstruction?

– **What about RHIC, AFTER@LHC?**

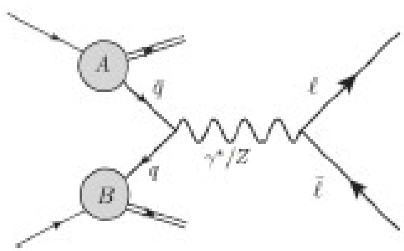
Z rapidity distribution

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

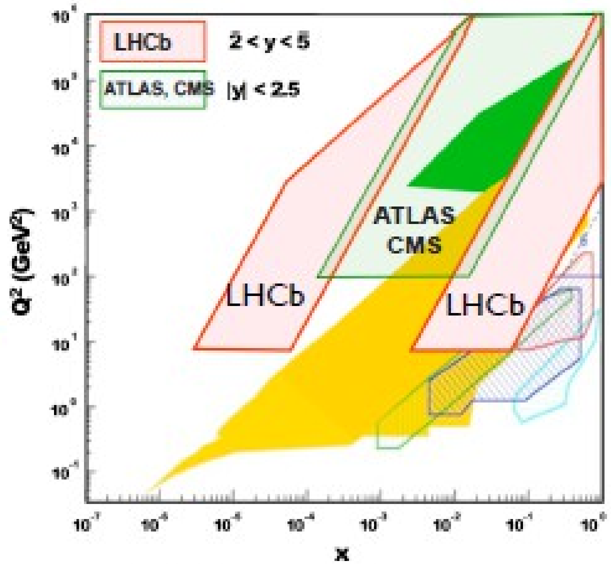


- Direct Z reconstruction is unambiguous in principle, but:
  - **Needs better than 5-10% precision at large rapidity**
  - Experimentally achievable?
    - At LHCb? RHIC? AFTER@LHC?
    - Was full data set used at Tevatron?

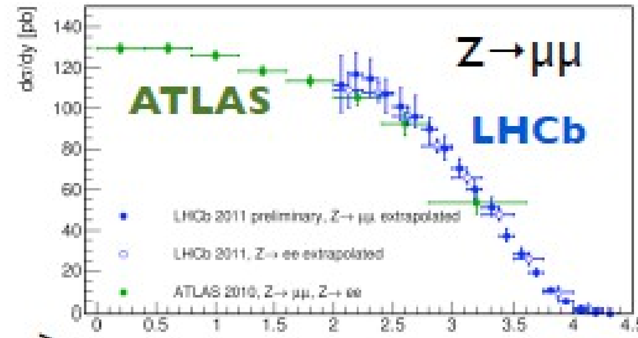
Constraints from the LHC: Electroweak Boson Production

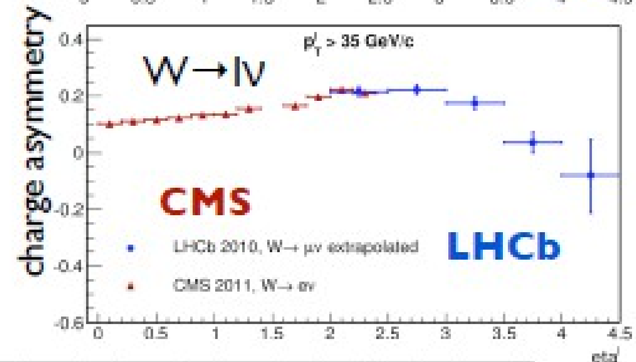


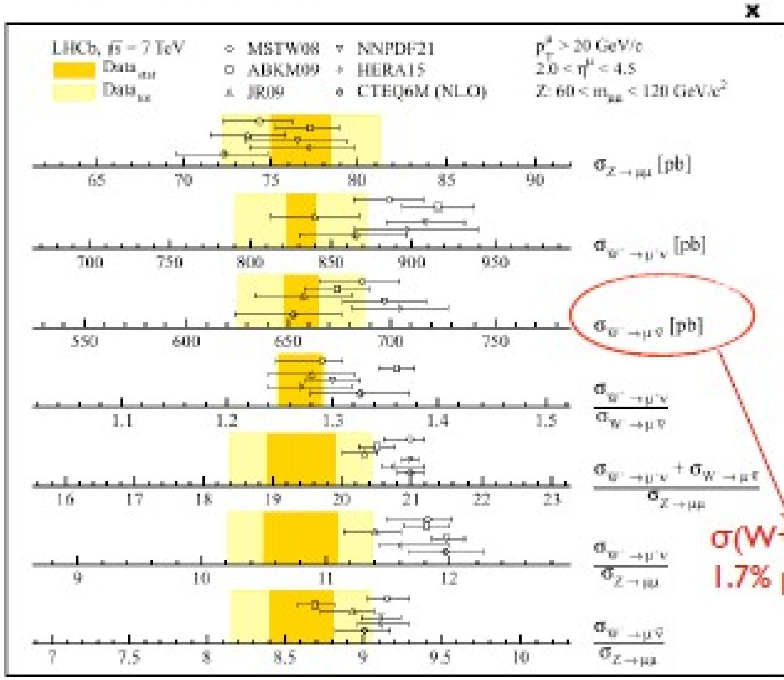
probe light quarks at low and high x



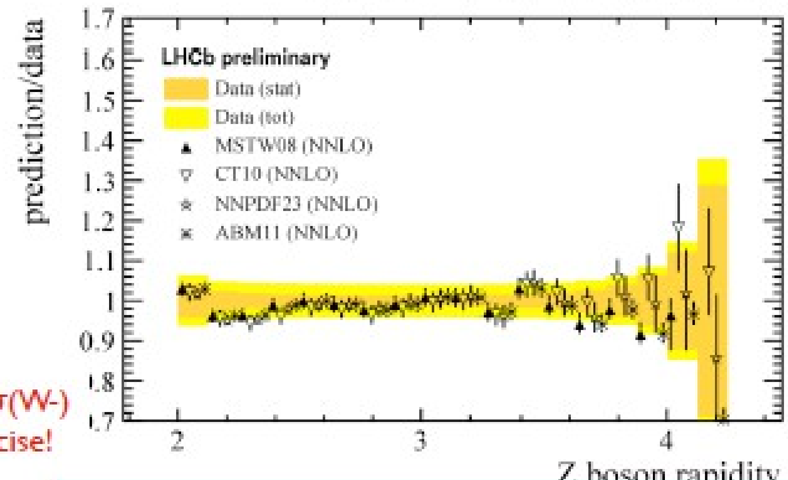
LHCb (S.Tourneur)







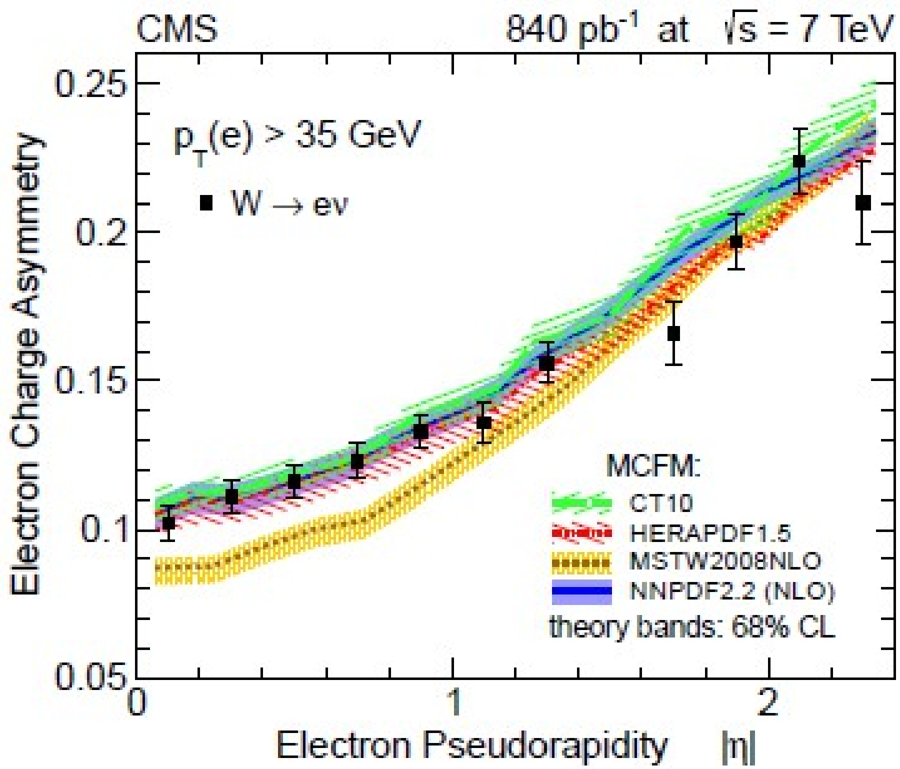
σ(W+)/σ(W-)
1.7% precise!



Systematic error comparable with PDF error
Benchmarking different PDF sets

K. Lipka, DIS'13 WG1 summary

W lepton asymmetry at LHC



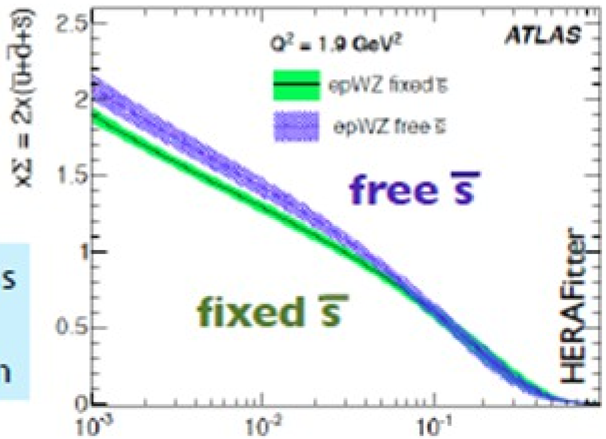
Sensitive both to d/u at $x > 0.1$ and $\bar{u}/\bar{d}$ at $x \sim 0.01$ (not constrained well by other experiments)

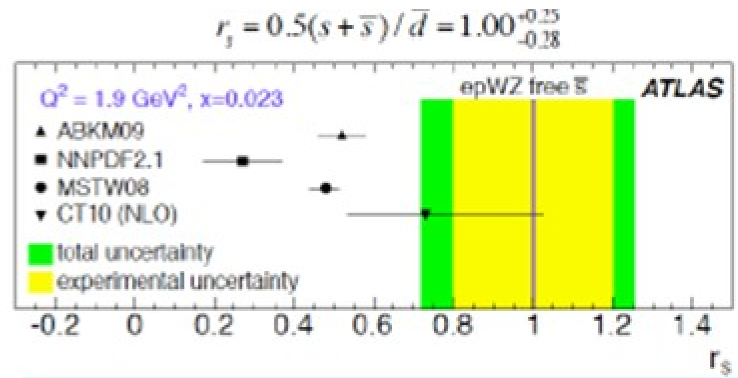
Constraints on strangeness: W,Z, W+c

ATLAS *(K. Nikolics)*

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

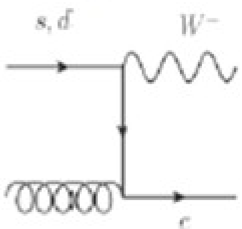
Z,W rapidity distributions sensitive to strangeness in the proton





data disfavors strangeness suppression

W+c probe strangeness



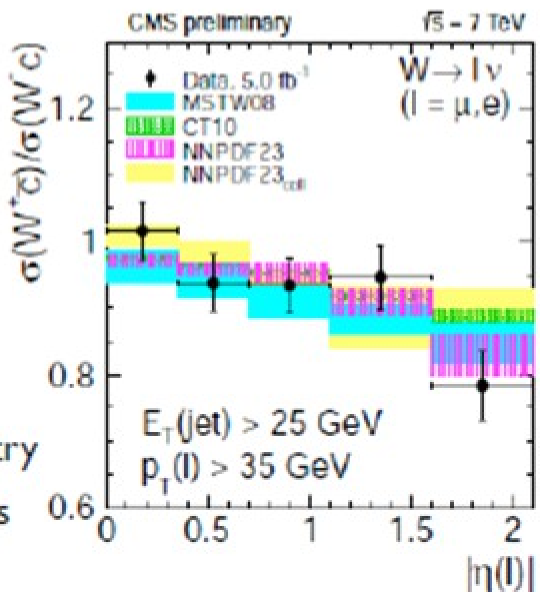
+ c.c.

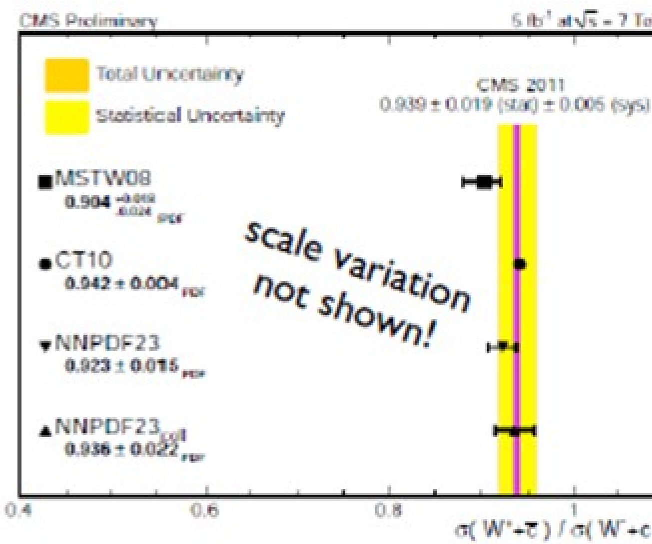
(E.Vryonidou)

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

Strangeness and strange asymmetry

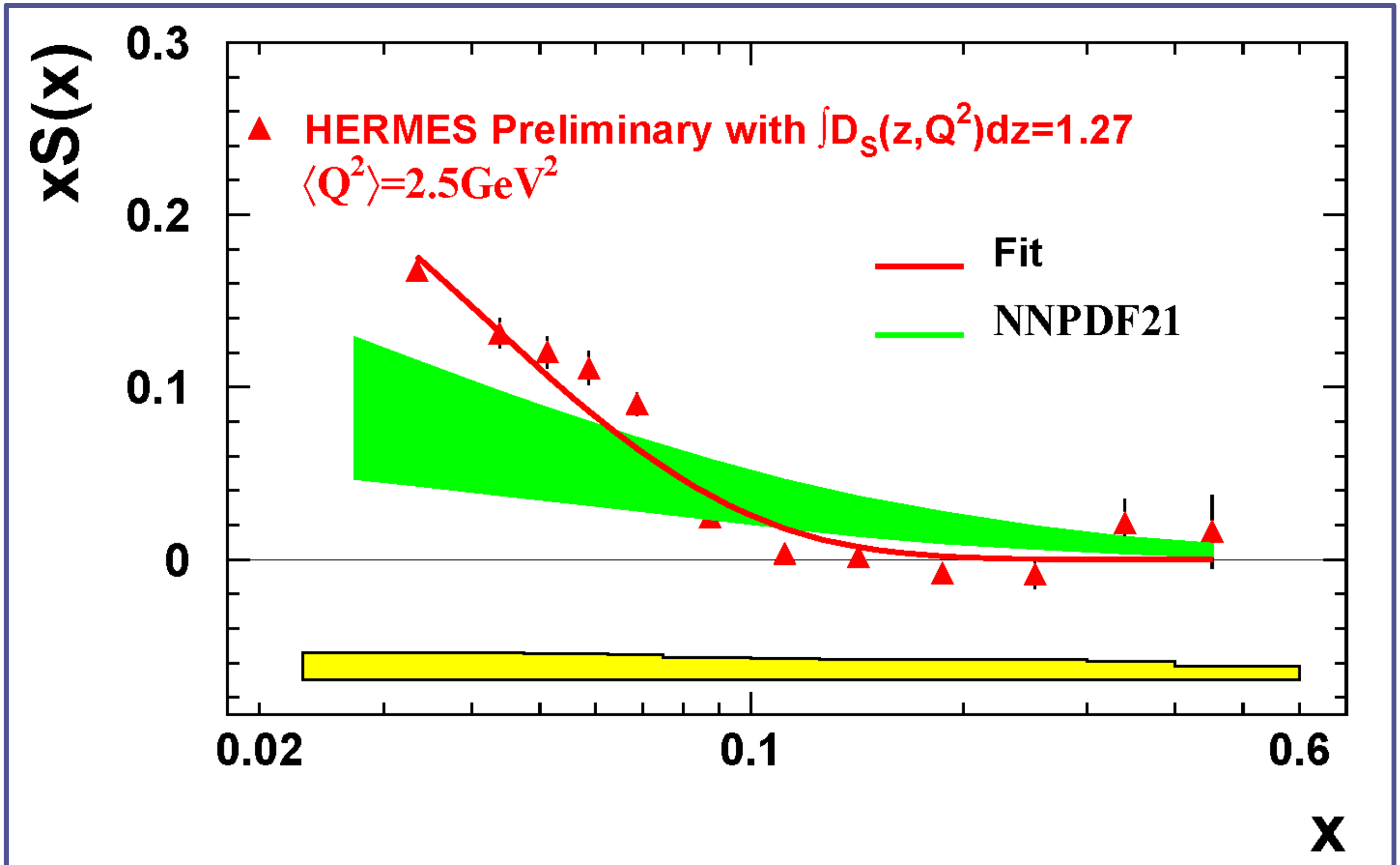
Precise data could constrain PDFs





K. Lipka, DIS'13 WG1 summary

Constraints on strangeness: LO K± at HERMES



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

Constraints on strangeness: K± at the EIC

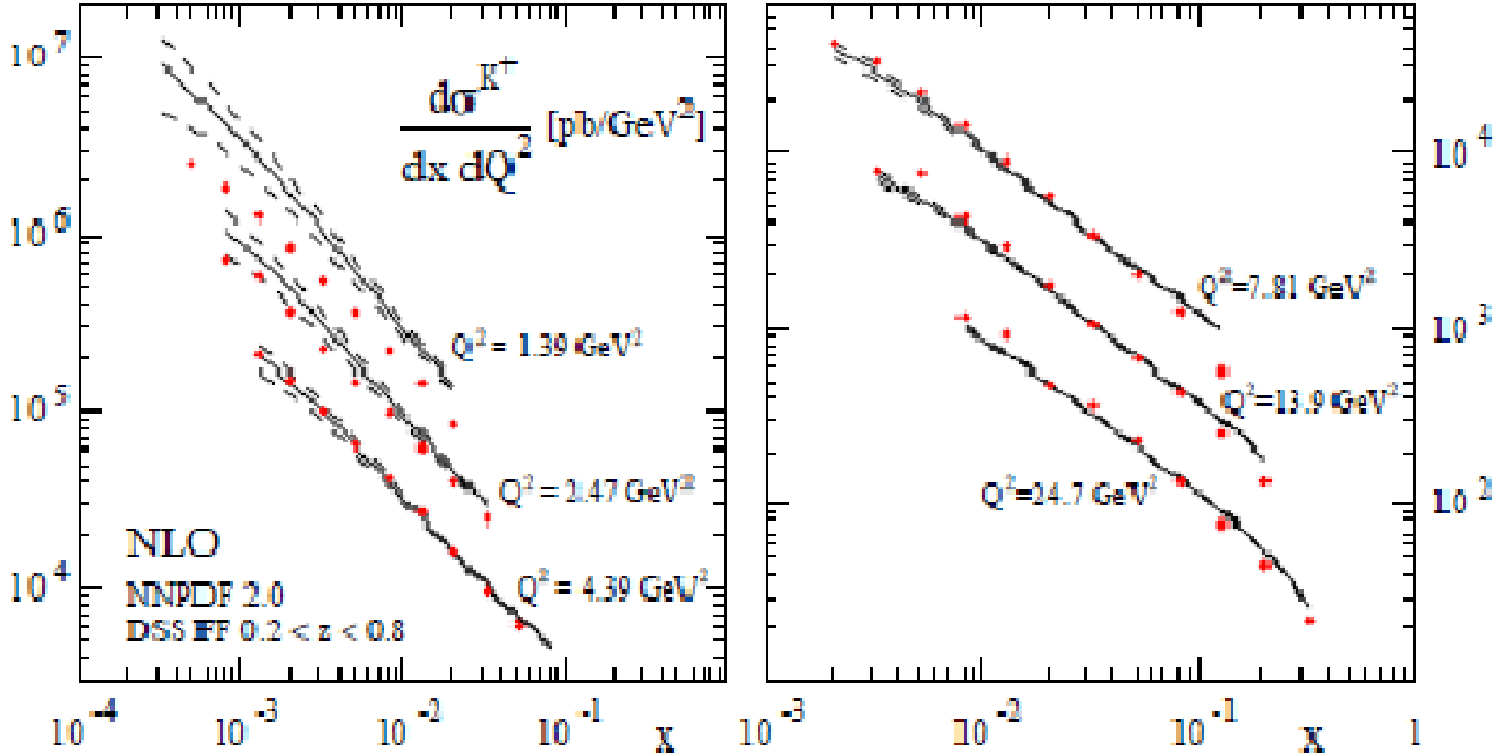


Figure 1.10. SIDIS cross section for K^+ production at NLO accuracy using NNPDF2.0 PDFs [47]. The dashed lines denote the PDF uncertainties. Also shown (points) are the results from a PYTHIA simulation (see text).

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

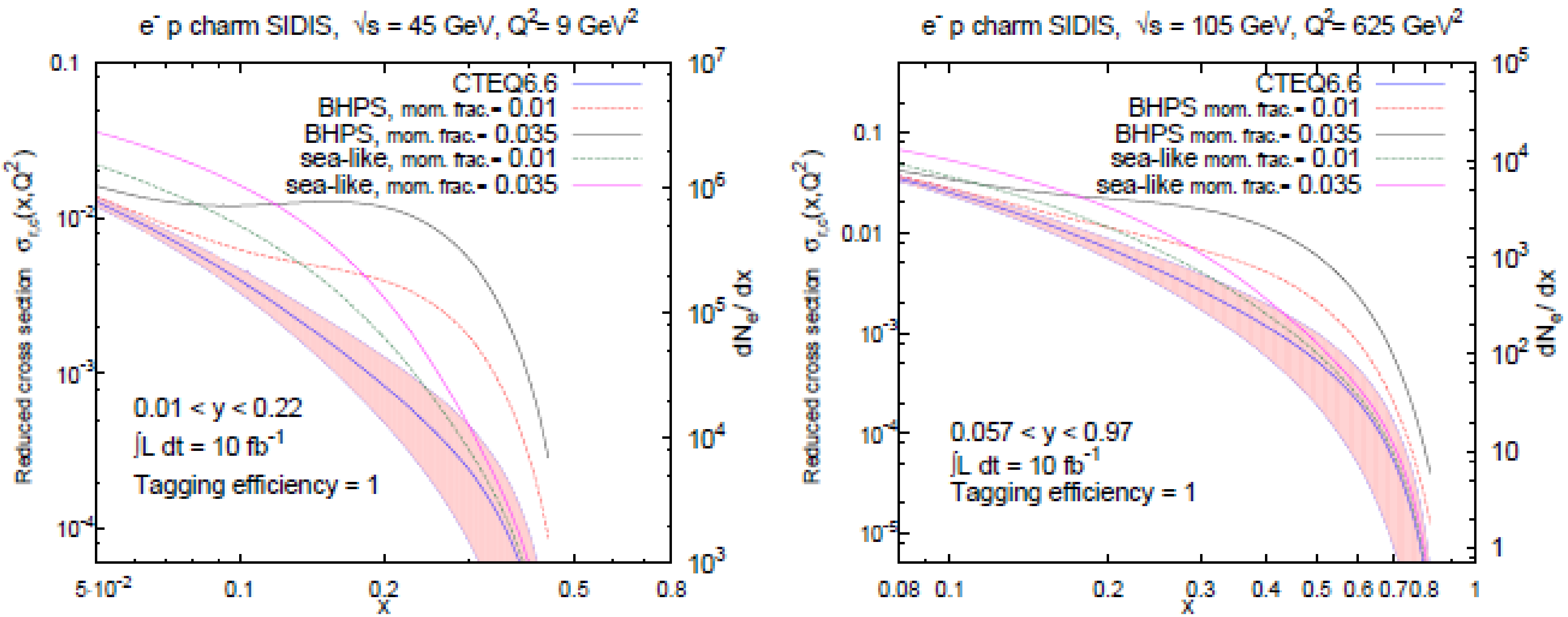


Figure 1.20. Charm contribution to the reduced NC e^-p DIS cross section at $\sqrt{s} = 45$ and 105 GeV. For each IC model, curves for charm momentum fractions of 1% and 3.5% are shown. For comparison we display the number of events dN_e/dx for 10 fb^{-1}, assuming perfect charm tagging efficiency.

Guzzi, Nadolsky, Olness, Sec. 1.9 in 1108.1713