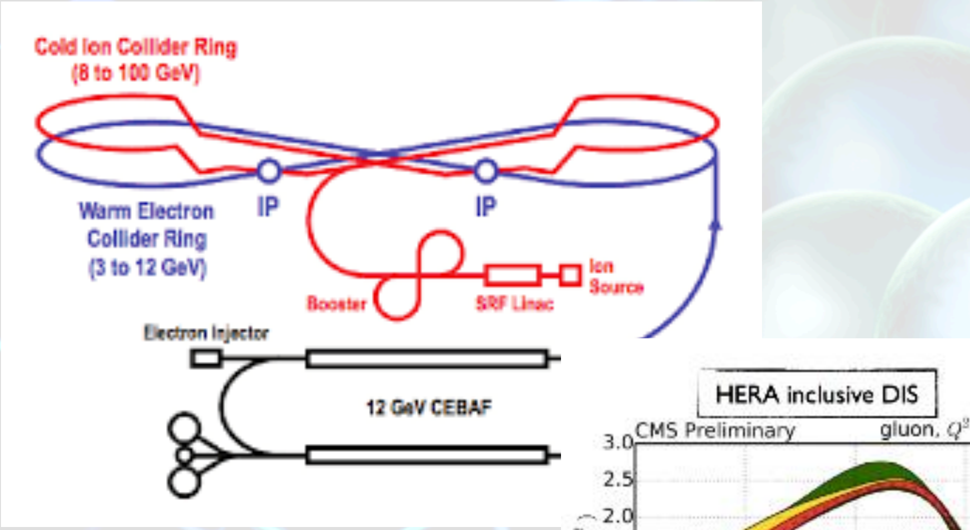
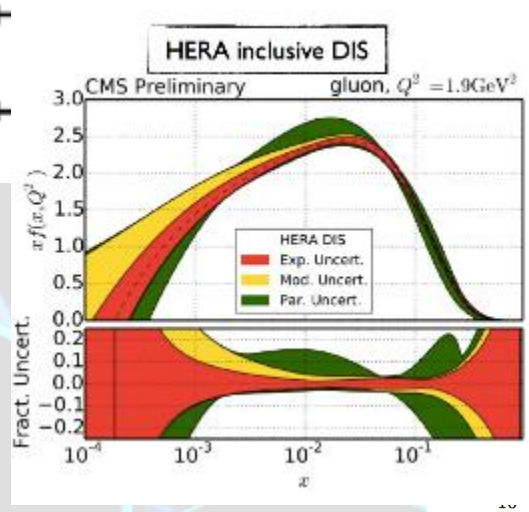
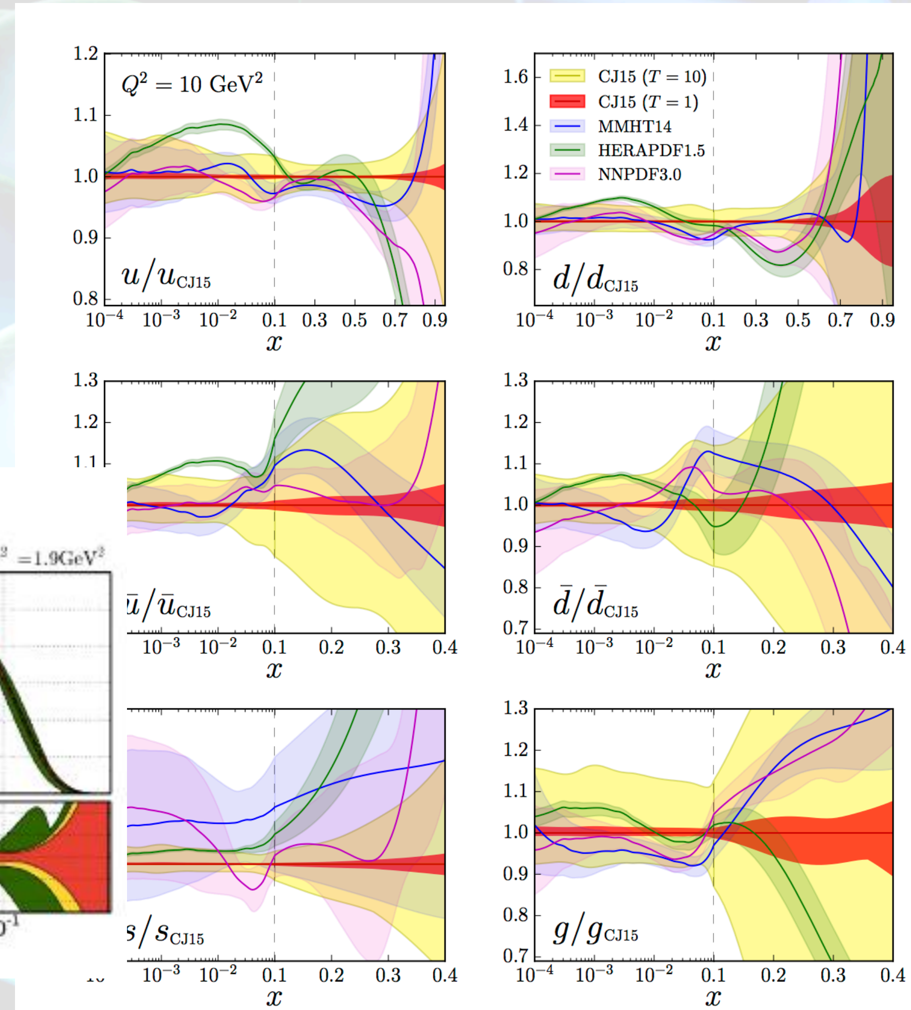
Determining Large x PDFs at JLEIC –
a work in progress





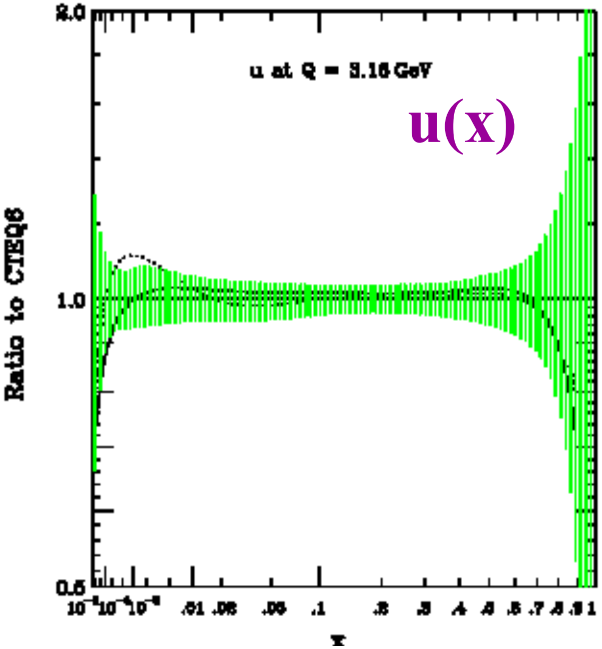


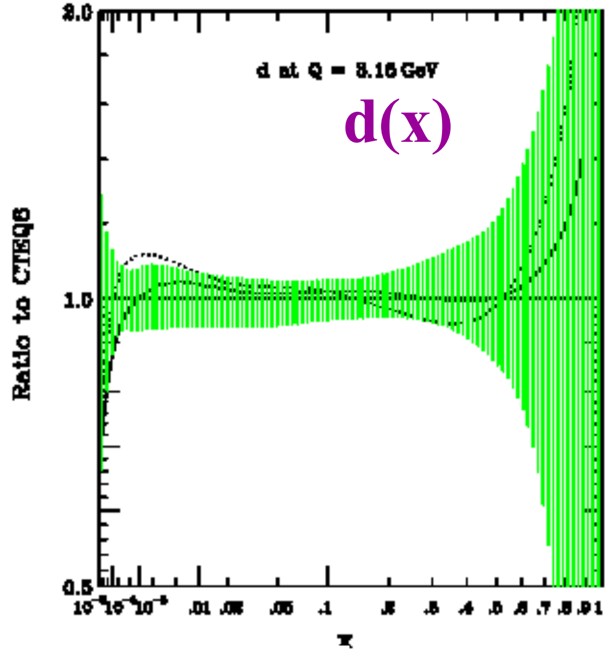
A. Accardi (Hampton),
R. Ent, C. Keppel,
K. Park, R. Yoshida (JLab),
M. Wing (UC London)

Parton Distribution Functions (PDFs)

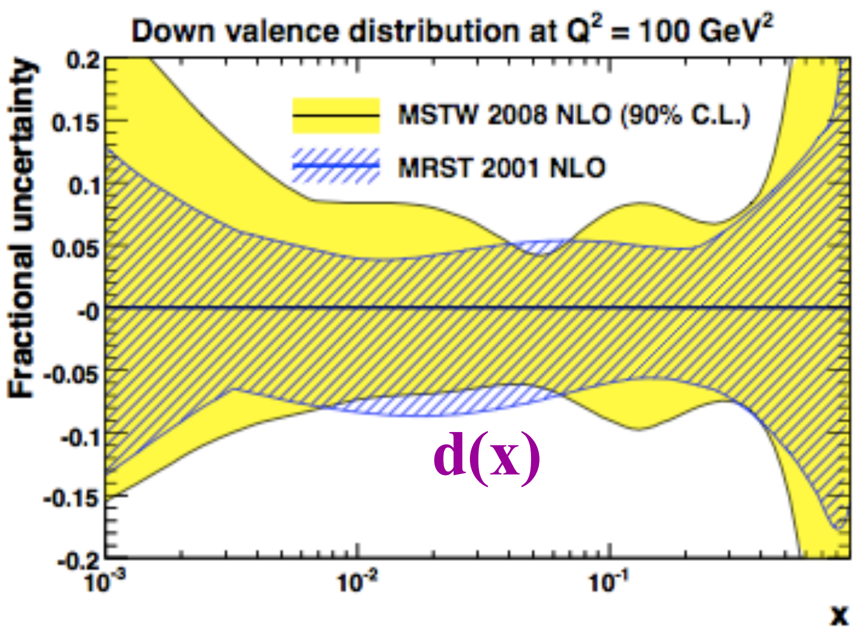
- Provide fundamental information regarding nucleon and nuclear structure
- Knowledge of the interaction initial state, and hence the PDFs, is critical to precision measurements at hadron colliders
  - Sensitivity to new physics, new heavy particles, requires better knowledge of large x PDFs

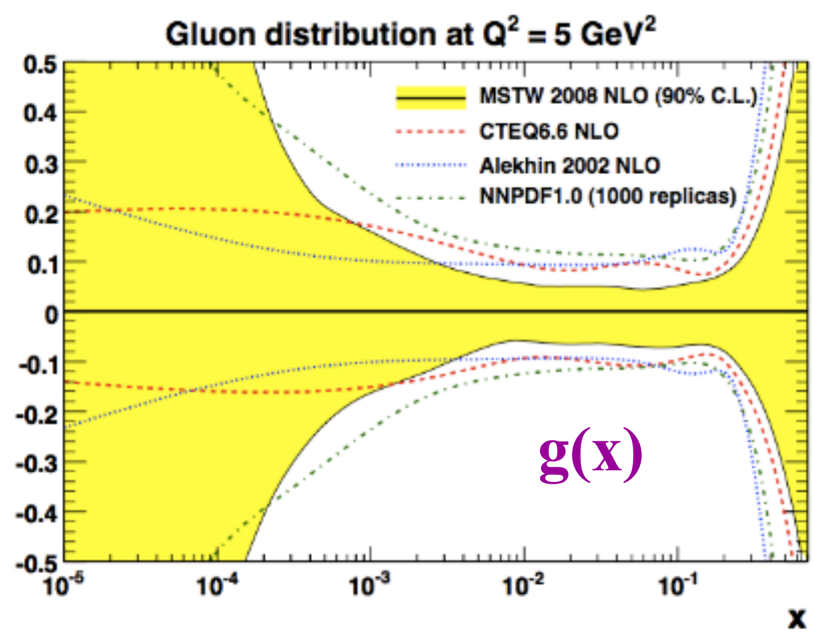
Large x (x > 0.05) -> Large PDF Uncertainties



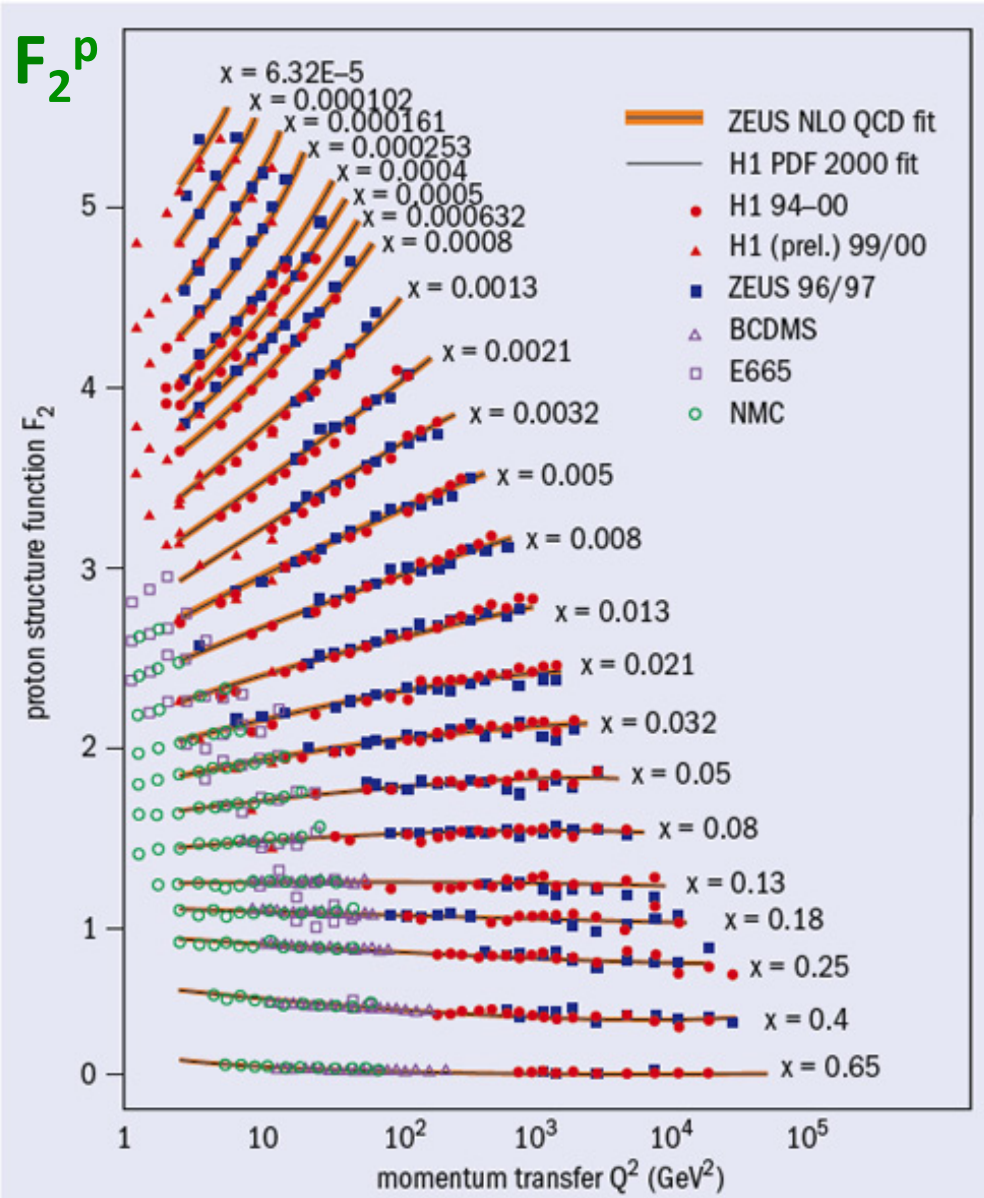


This talk will focus largely on d(x), g(x)





Nucleon Structure Function Measurements



Proton –

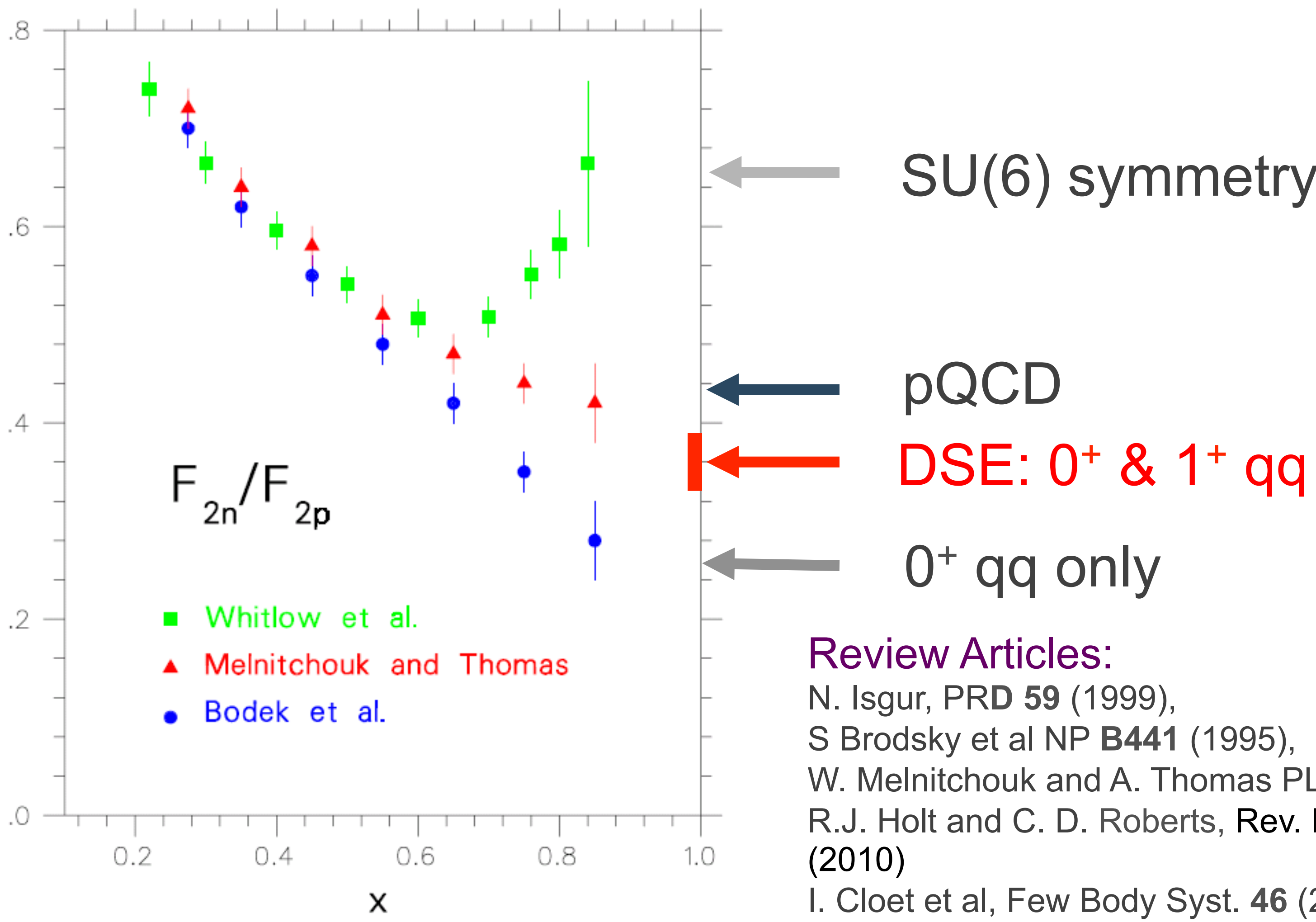
- F_2^p measured over > 5 orders of magnitude in x, Q^2 by dozens of experiments at numerous laboratories and for decades
- Well described by DGLAP, global PDF fits
- Translates to small uncertainties on u(x)

Neutron –

- No free neutron target
- Historically difficult to extract neutron from deuteron - uncertainties from nuclear corrections
- F_2^d not as well measured as F_2^p
- Translates to large uncertainties on d(x)

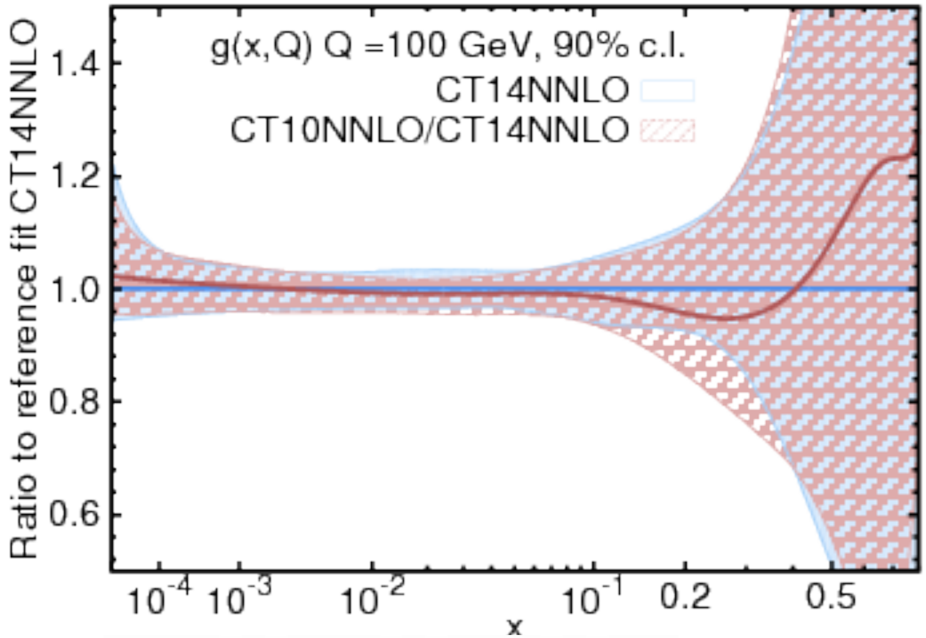
F_2^n/F_2^p (and, hence, d/u) is essentially unknown at large x:

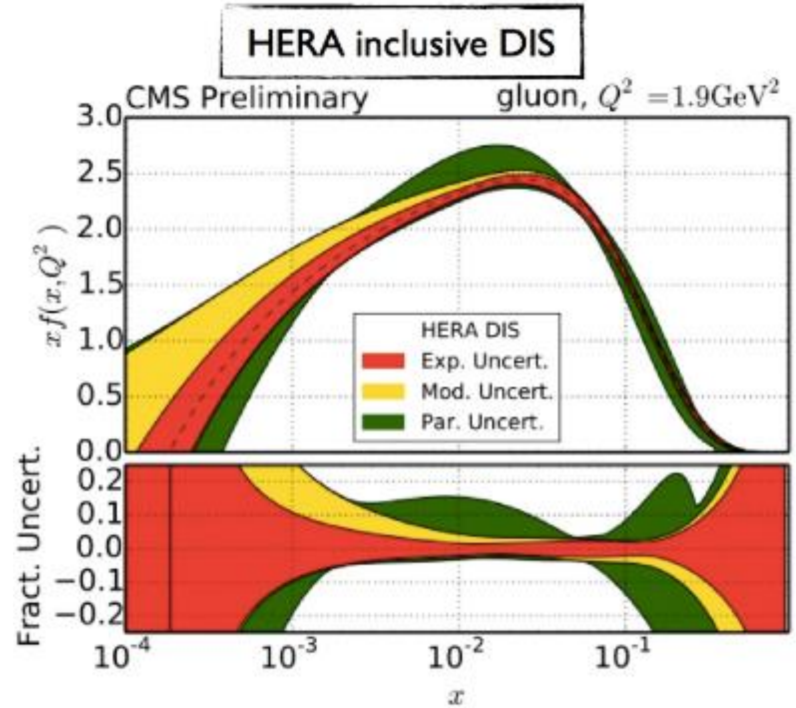
- Conflicting fundamental theory pictures
- Data inconclusive due to uncertainties in deuterium nuclear corrections
- Translates directly to large uncertainties on d(x), g(x) PDFs

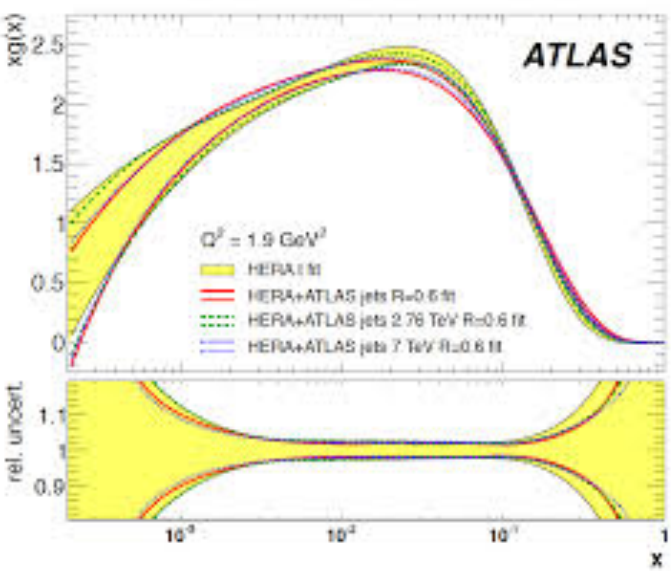


Review Articles:
N. Isgur, PRD **59** (1999),
S Brodsky et al NP **B441** (1995),
W. Melnitchouk and A. Thomas PL **B377** (1996) 11,
R.J. Holt and C. D. Roberts, Rev. Mod. Phys. 82 (2010)
I. Cloet et al, Few Body Syst. **46** (2009) 1.

g(x) is poorly known at large (and small) x…







Most knowledge comes from
- (small) scaling violations in the evolution of the F_2 str. fn.
- Jets in p+p (and e+p)

Both are limited to x<~0.3

Can the EIC help?

- Different data constrain different parton combinations at different x
- Scaling violation studies require range in both x, Q^2 – not currently possible at large x without the EIC
- Would like to have both F_2^n and F_2^p – possible with planned EIC spectator tagging capabiities

- *To begin investigating possibilities, we used projected data kinematics and uncertainties, and the “CJ” global PDF fit…*

CTEQ-Jefferson Lab “CJ” PDF Fits

Phys. Rev. D81:034016 (2010)
Phys. Rev. D87:094012 (2013)

Phys. Rev. D84:014008 (2011)
Phys. Rev. D93 114017 (2016)

PDFs at http://lhapdf.hepforge.org/lhapdf5/pdfsets

CJ collaboration: http://www.jlab.org/CJ

Goals:

- Extend CTEQ fit to larger values of x and lower values of Q^2
- Incorporate data previously subject to kinematic cuts (SLAC and JLab largely)

To accomplish this:

- Need to relax conventional cuts defining “safe” region for issues such as higher twist, target mass - will now need to take these into account
- Allow d/u to go to a constant (not just $(1-x)^a$ type form)
- *Need accurate deuteron nuclear corrections*

CTEQ-Jefferson Lab Collaboration

Improved Extraction of F_2^n from F_2^d and F_2^p

New method : employs iterative procedure of solving integral convolution equations

Y. Kahn, W. Melnitchouk, S.A. Kulagin, Phys. Rev. C 79, 035205 (2009)

- Impulse Approximation – virtual photon scatters incoherently from individual nucleons

(Beyond IA: FSI not addressed in present analysis)

$$\tilde{\mathcal{F}}^n(x) = \mathcal{N}\,\mathcal{F}^n(x) + (\delta f \otimes \mathcal{F}^n)(x)$$

$$\underbrace{\boxed{F_2^A(x,Q^2)}}_{\text{nuclear } F_2} = \sum_{N=p,n} \int_x^{M_A/M} dy\, \underbrace{\boxed{f_0^{N/A}(y,\gamma)}}_{\text{light-cone momentum distribution of nucleons in nucleus (smearing function)}} \underbrace{\boxed{F_2^N\left(\frac{x}{y},Q^2\right)}}_{\text{nucleon } F_2} \qquad \gamma = \sqrt{1+\frac{4M^2x^2}{Q^2}}$$

$$\left(f_0^{N/A} \otimes F_2^N\right)(x,Q^2)$$

Convolution of light cone momentum distribution on nucleons in nucleus

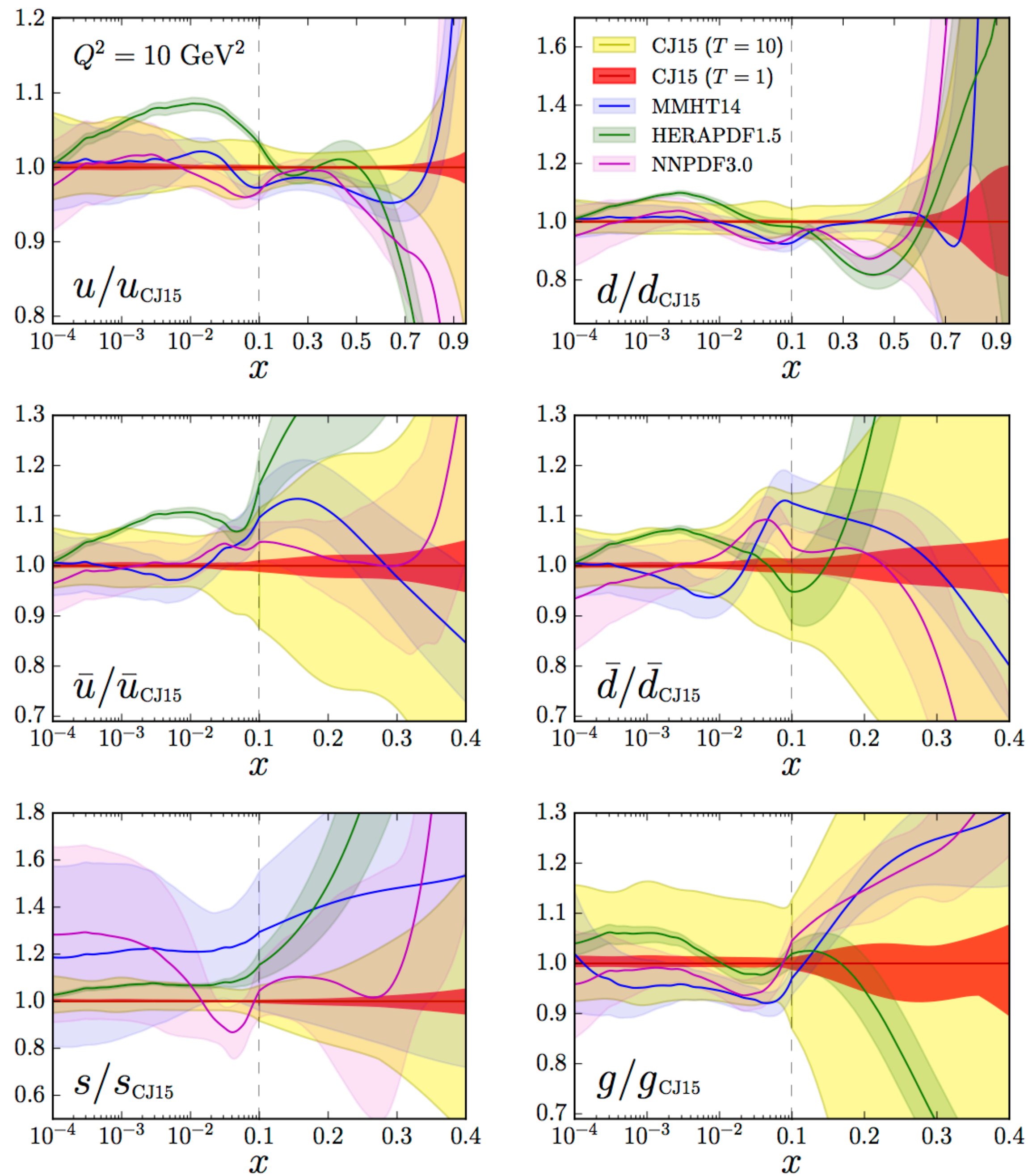
Application to Deuterium…

CJ15 Global Fit

Phys. Rev. D93 114017 (2016)

State-of-the-art in large x PDFs

- > 50% uncertainty on d(x) above x ~ 0.6
- > 50% uncertainty on g(x) above x ~ 0.2

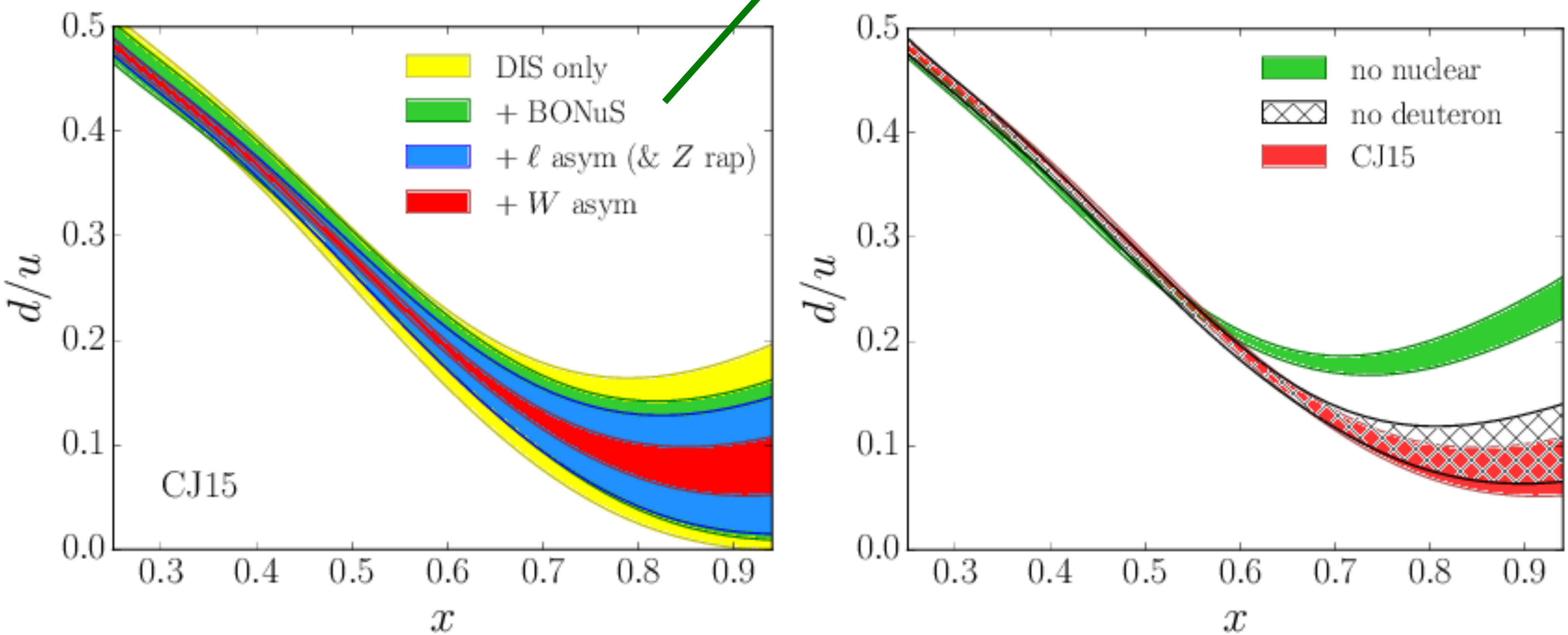


$F_2^{\mathbf{n}}$ better constrained

Resulting CJ uncertainty bands

- **Nuclear corrections** still dominant
- **Constrained by p+p → W + X !**

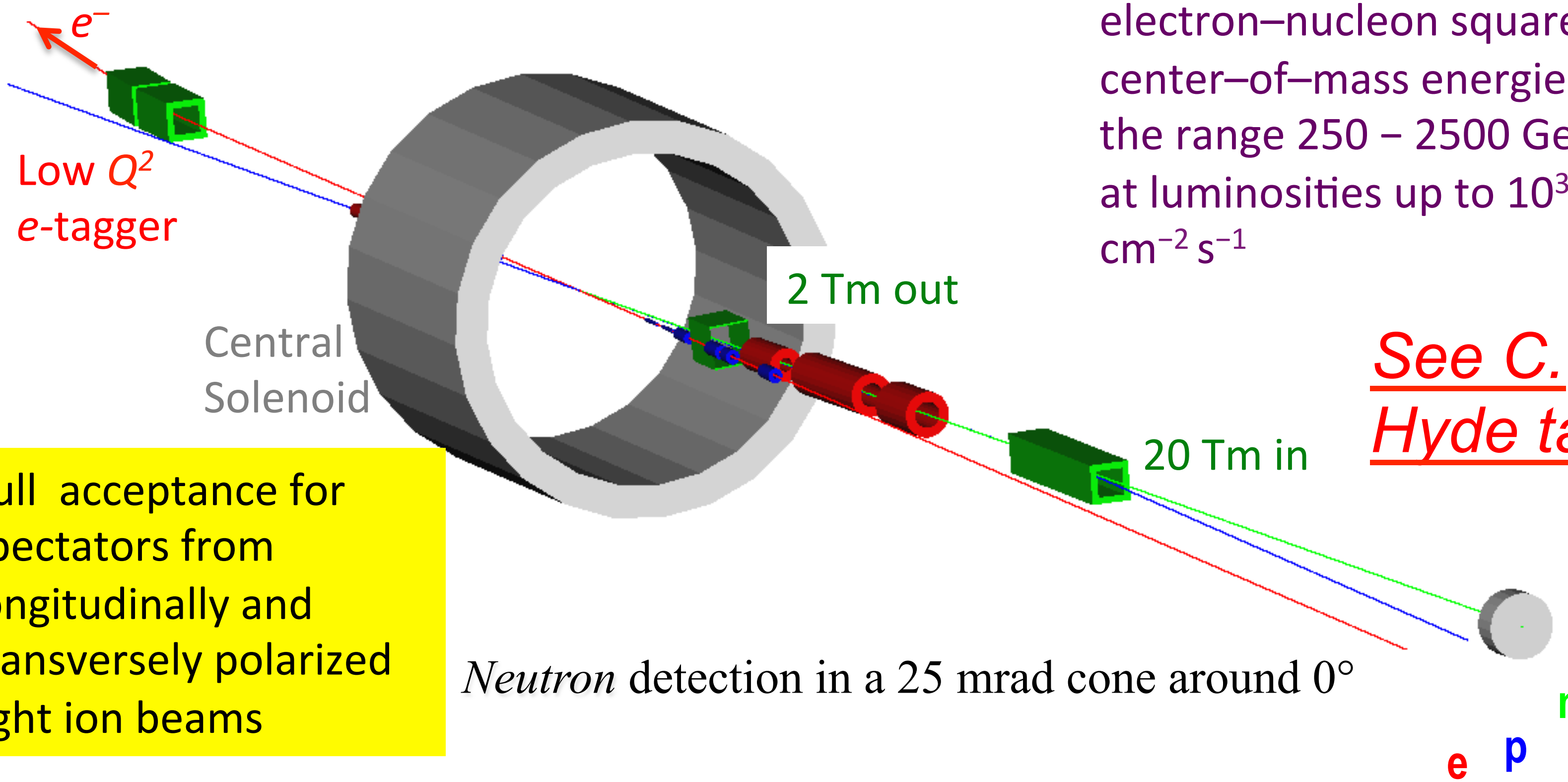
Effective neutron target via spectator tagging experiment at JLab



Tagged Structure Functions at the EIC

The technique is uniquely suited to colliders: no target material absorbing low-momentum nucleons

The JLEIC design provides electron–nucleon squared center–of–mass energies in the range 250 – 2500 GeV^2 at luminosities up to 10^{34} cm^{-2} s^{-1}



See C. Hyde talk!

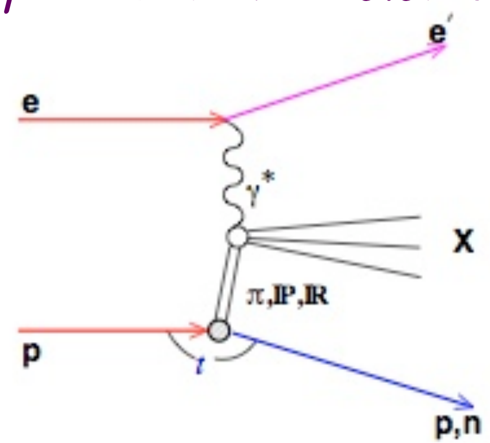
- Full acceptance for spectators from longitudinally and transversely polarized light ion beams

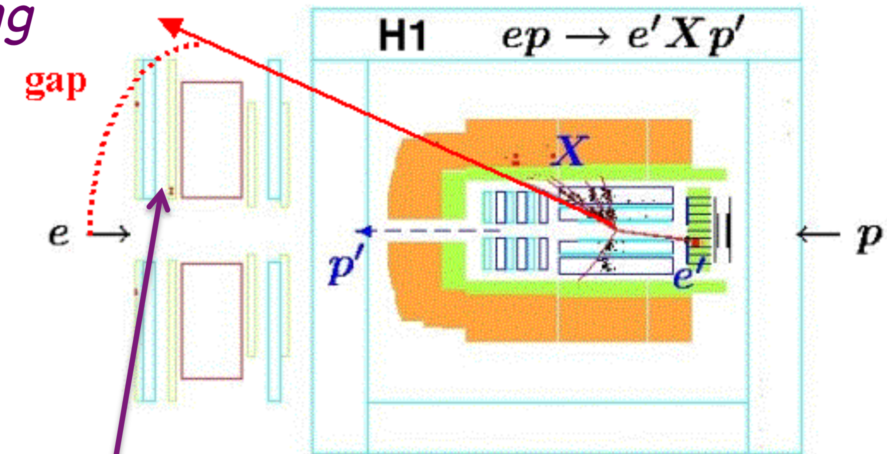
Neutron detection in a 25 mrad cone around 0°

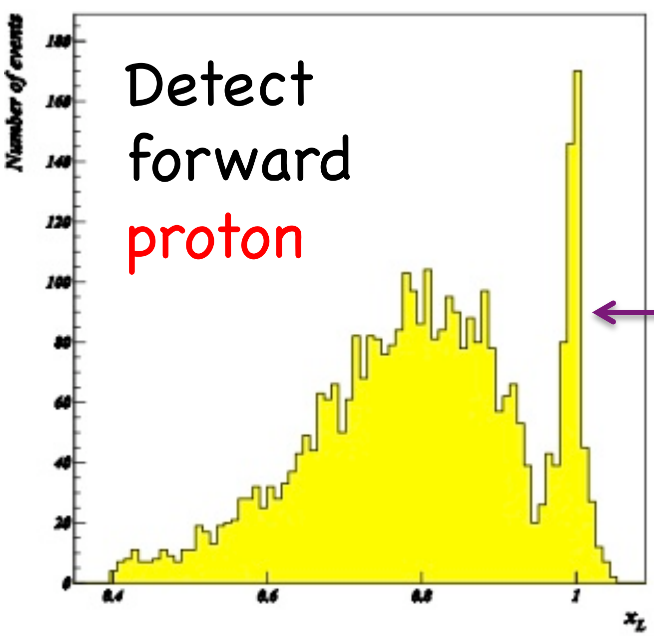
Secondary high dispersive ion focus ~40 m downstream of IP

Tagged Structure Functions at HERA – Example: proton tag

- *Tag leading baryon production*
- *ep → eXN via color singlet exchang*







Detect forward proton

Diffractive Scattering:

Large rapidity gap

$x_L = E^p/E^p_{beam} \sim 1$

Also tagged neutron

X_L

DESY 10-095 Eur.Phys.J. C71 (2011) 1578

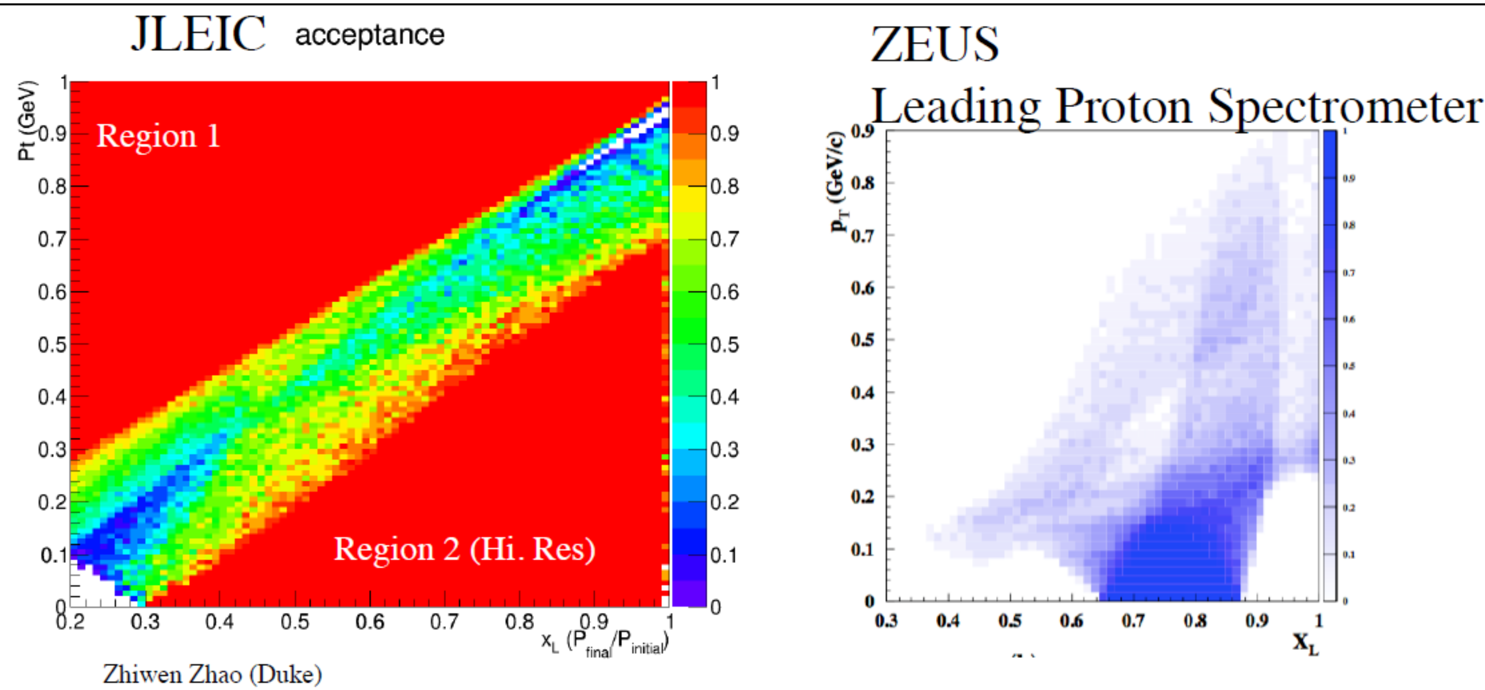
$$F_2^{D(4)} = f_{I\!P}(x_{I\!P}, t) F_{I\!P}(\beta, Q^2) + n_{I\!R} \cdot f_{I\!R}(x_{I\!P}, t) F_{I\!R}(\beta, Q^2)$$

Pomeron contribution Reggeon contribution

The Pomeron diverges as $1/(1-x_L)$, the f-Reggeon is flat

EIC: Full Acceptance for Forward Physics!

Example: acceptance for p' in e + p → e' + p' + X



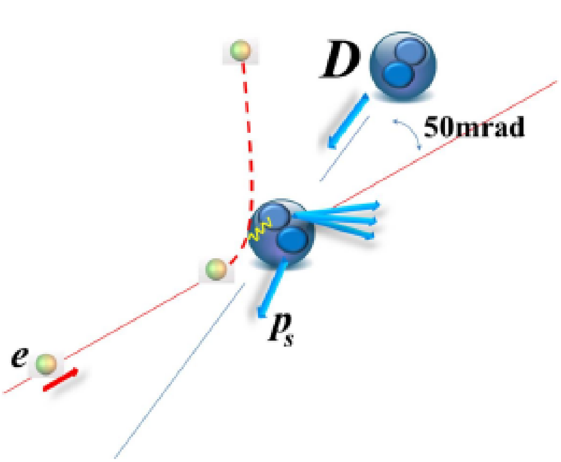
Acceptance in diffractive peak (X_L>~.98)

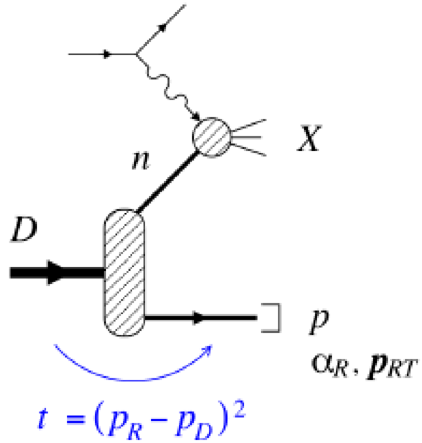
ZEUS: ~2%

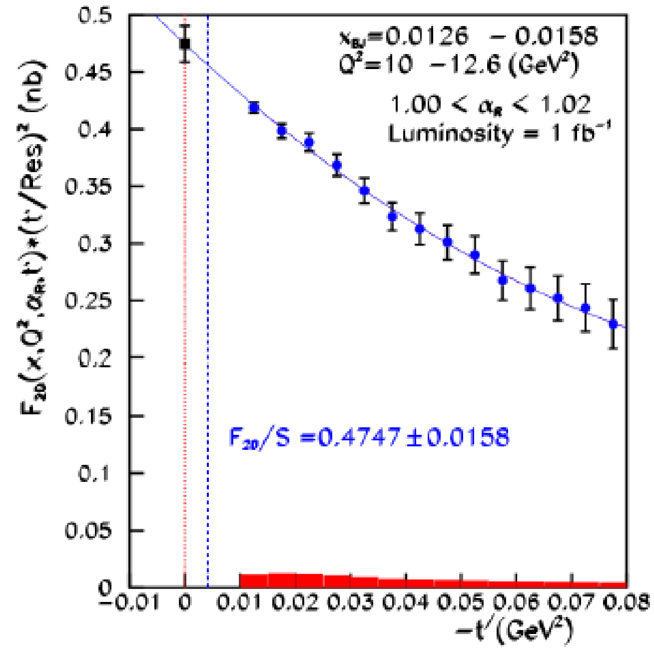
JLEIC: ~100% (also covers much higher X_L than ZEUS)

Huge gain in acceptance for forward tagging to measure F_2^n and diffractive physics!!!

(Tagged) Neutron Structure Extrapolation in t



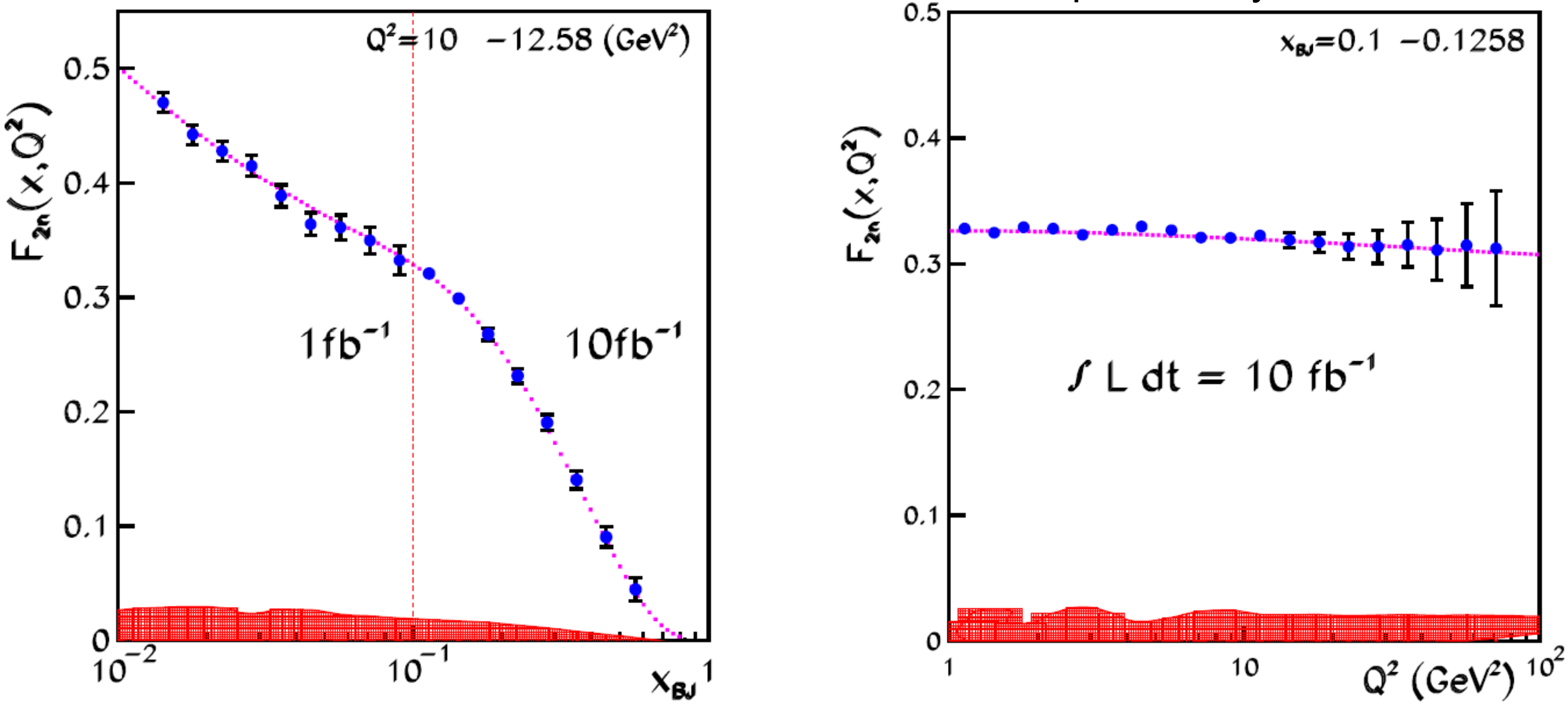




- t resolution better than 20 MeV, < fermi momentum
- Resolution limited/given by ion momentum spread
- Allow precision extraction of F_2^n neutron structure function

(Tagged) Neutron Structure Extrapolation in t

Preliminary examples (courtesy Kijun Park)
Uncertainties include on-shell neutron extrapolation systematics



- 1 year of EIC @ luminosity of 10^{32} gives about 1 fb^{-1}
- 1 year of EIC @ luminosity of 10^{33} gives about 10 fb^{-1}
- 1 year of EIC @ luminosity of 10^{34} gives about 100 fb^{-1}

Data so far being considered in CJ fit projection study….

So far, have used JLEIC 10x100 GeV^2 projections in bins $0.1 < x < 0.9$ for:

- ✓ F_2^p
- ✓ F_2^n from deuterium with tagged proton spectator
- F_2^d

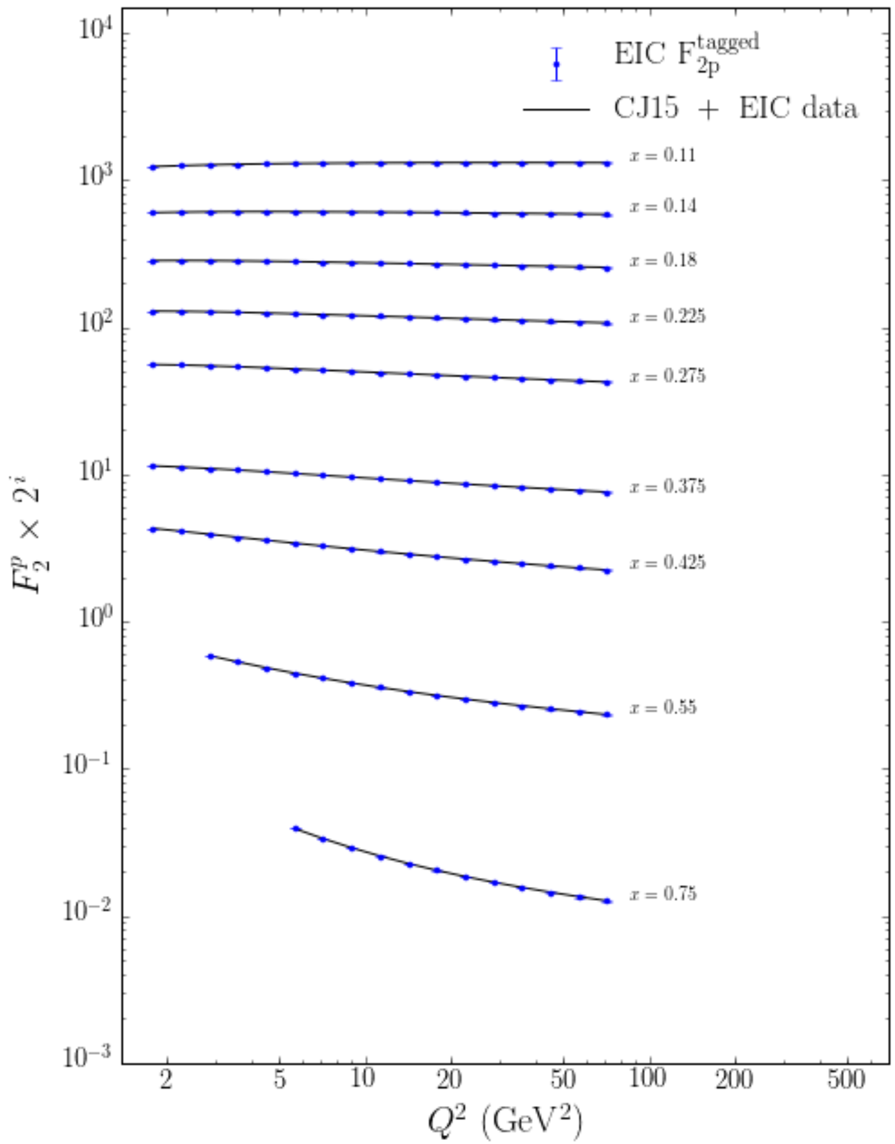
Can check on-shell extrapolation by measuring F_2^p from deuterium with tagged neutron spectator, comparing to proton target data

Can check nuclear corrections to F_2^d against $F_2^{n\,\text{(tagged)}}$

  - *Finally will be able to distinguish between models!*

- *Assume 1% systematic uncertainty*
- $W^2 > 3.5$ GeV^2 and $Q^2 > 1.69$ GeV^2 (standard CJ15 cuts)
- ***A simple study so far (first results hot off the press)…***

F_2^p (tagged) pseudodata vs x

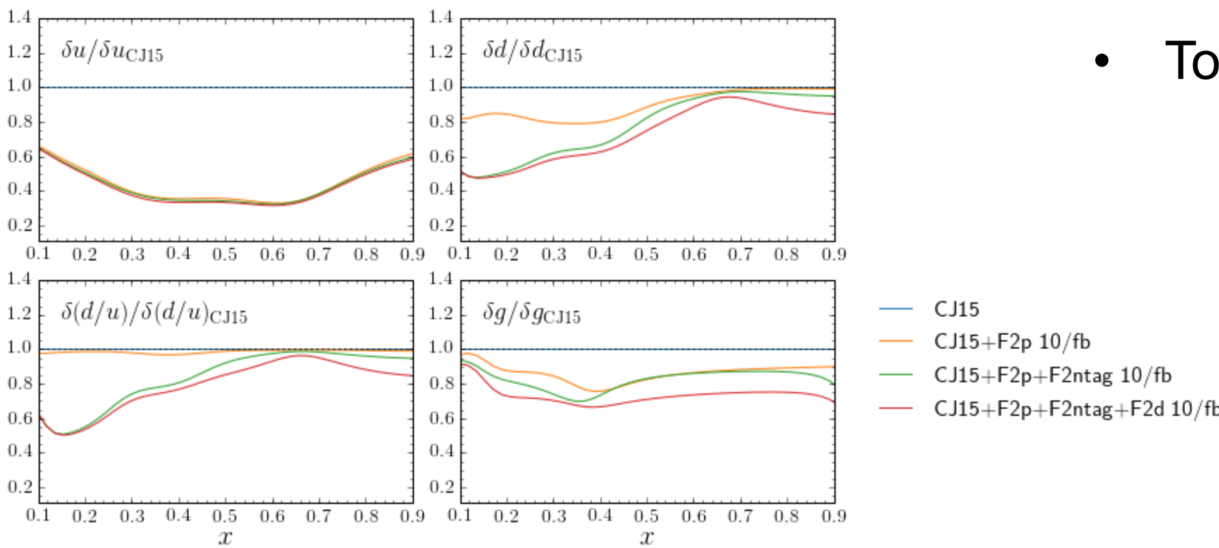


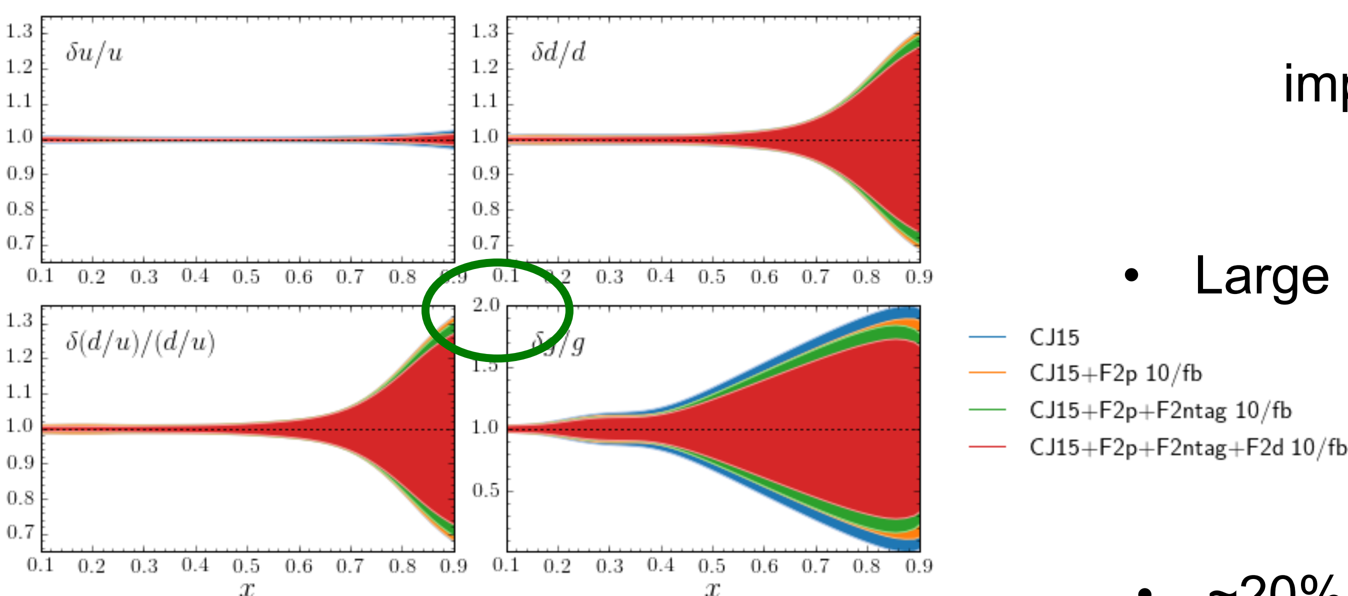
Compressed scale makes it somewhat difficult to see the experimental and fit uncertainties

Currently no cut in y:

- would loose a little bit in the high Q^2 range from y<ymax, unlikely a problem since ymax ~0.85.
- would loose some low Q^2 leverage at large x from a y_min cut, might have impact on the gluon fits
- requires more careful simulations

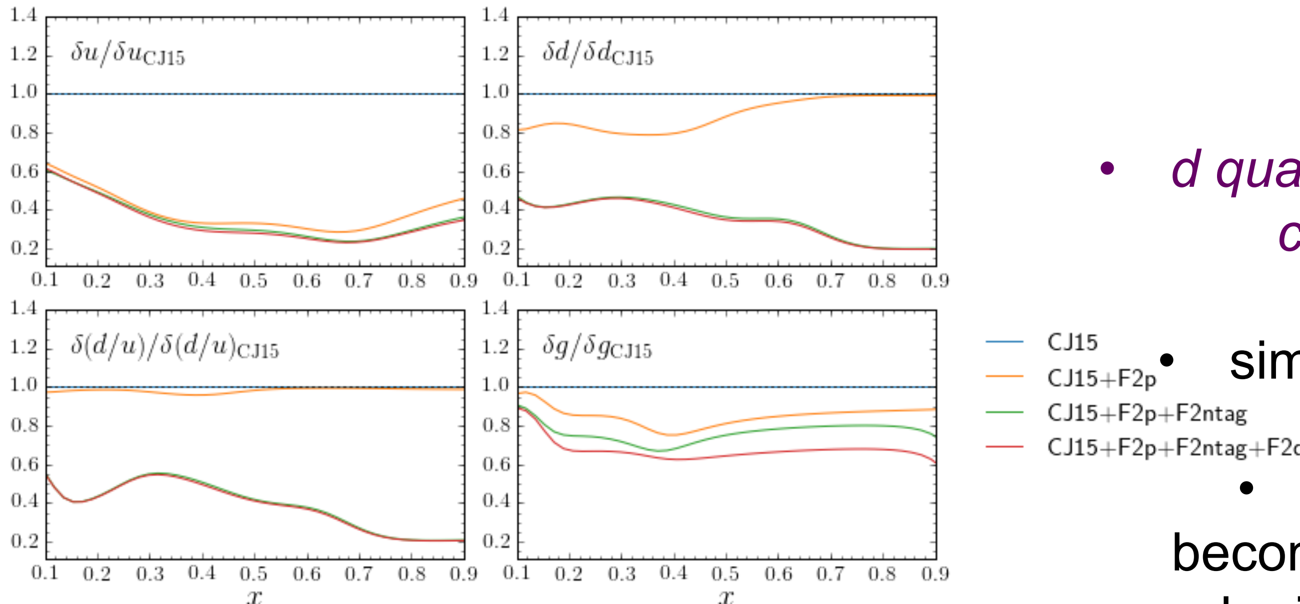
10/fb luminosity

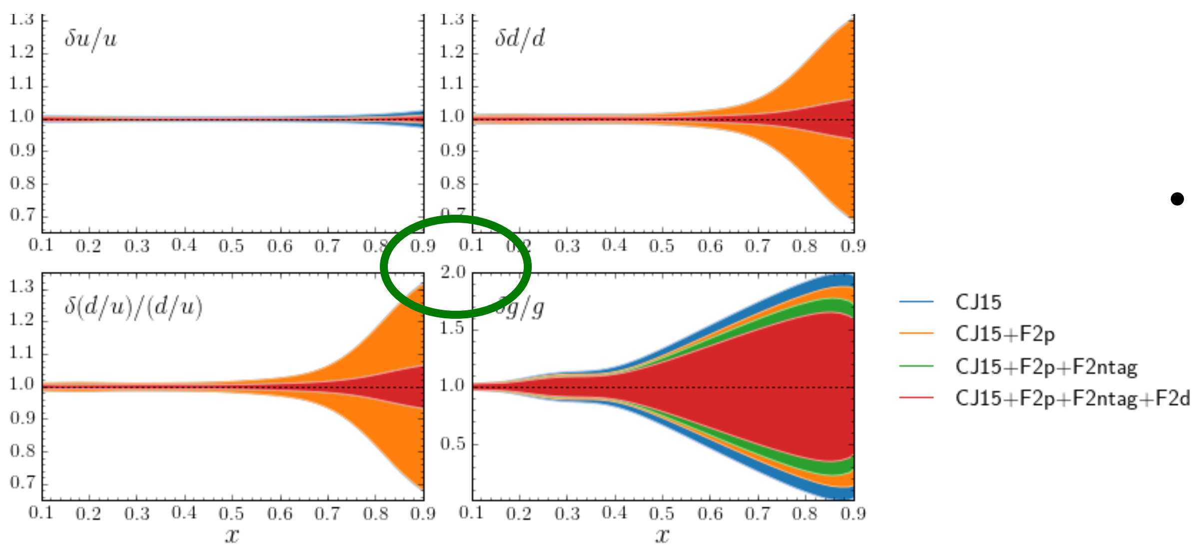




- Top: improvement in relative PDF uncertainties compared to CJ15
- Bottom: relative uncertainties compared to CJ15
- Improvement in u impressive, but already small uncertainty
- Large improvement in d(x), ~50%
- d/u tracks d
- ~20% improvement in g(x)

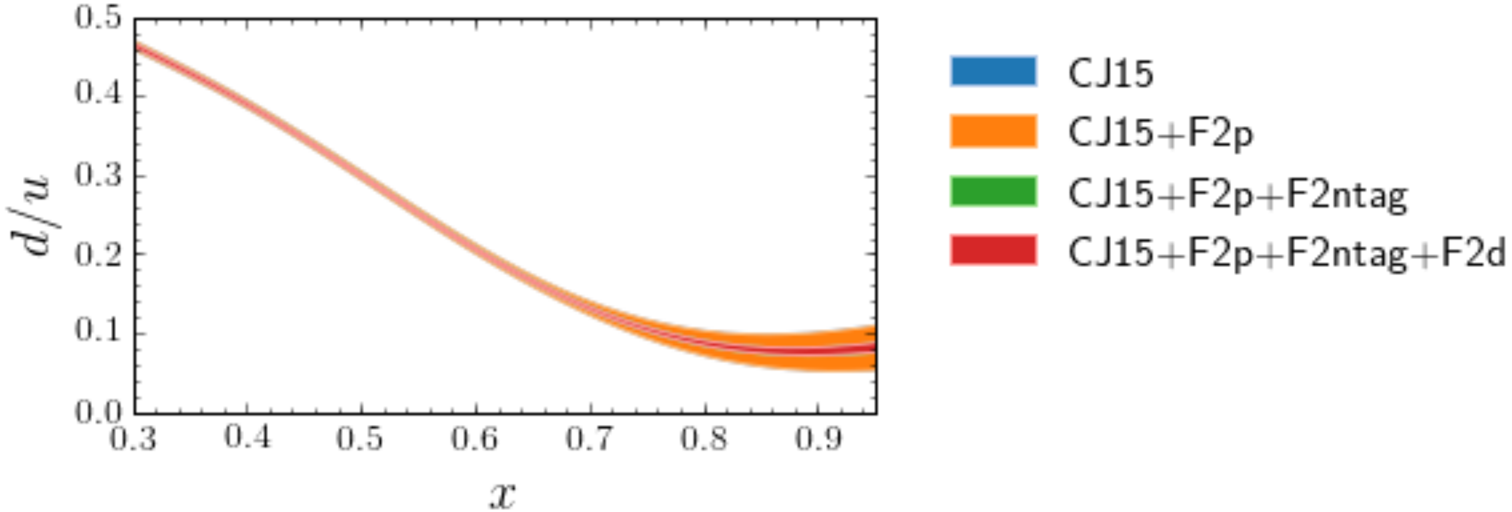
100/fb luminosity





- *d quark precision will become comparable to current u!!*
- similar improvement in g(x)
- The u quark uncertainty becomes less than ~1%; may be important for large mass BSM new particles.
- With d quark nailed by F_2^n, fitting F_2^d data will explore details of nuclear effects

Improved d(x) precision is good news



- The d-quark goes from a few 10% to ~1% percent level
- Resolve long-standing mystery of d/u at large x, bell-weather for fundamental models of nucleon structure
- D/(p+n) in one experiment for the first time – unprecedented handle on nuclear medium modifications
- Facilitate accurate neutron excess/isoscalar corrections
  - Important also for neutrino physics and nuclear PDFs

Improved g(x) precision also good news

- The gluons improve by a bit less than 10% per data set included, with the improvement seemingly independent of luminosity
  - Possibly gluons are accessed by the F_2 shape in Q^2, so that the precision of each data point is not very important, while the lever arm in Q^2 matters most

- If true, expect that adding new measurements we will continue to improve the gluons: for example, adding energy scans at 3+100 and 6+100 may reach a global improvement in the large-x gluons closer to 80%.

- Energy scans could also allow for direct access of gluons from F_L.

- Need more work to confirm above

Summary

A 10/fb e-p run and an 100/fb e-d run (*with e-n_{tag}!*) reduces the u uncertainty to better than 1% and the d uncertainty down to 5% at x = 0.9.

The gluon will also be significantly improved, but…

Still a work in progress, need to:

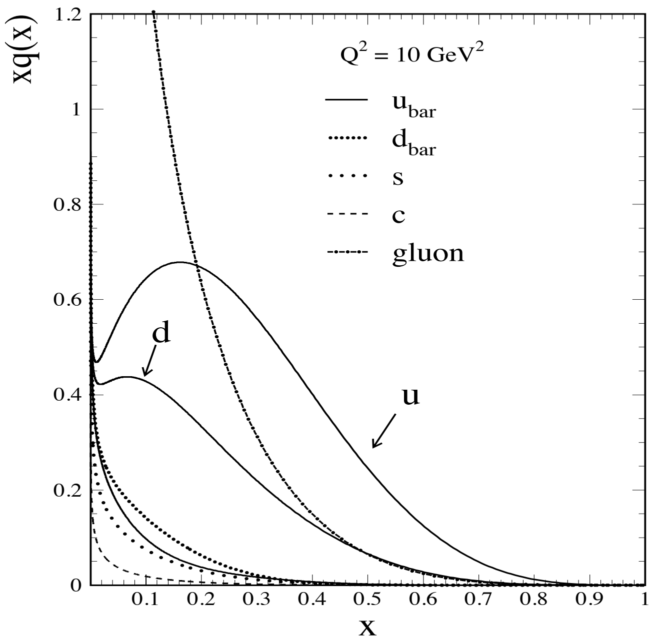
- Study more energy combinations
- Study y cut
- Evaluate also F_L
- Expand x binning
- Optimize grid

Thank you!

Backups

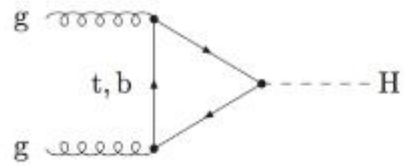
$F_2^p - F_2^n$ yields non-singlet distribution

- At moderate x (~0.3), singlet comparable to non-singlet
- Large uncertainties on singlet distribution - - in structure function measurements, comes from (small) scaling violations in F_2
- Q^2 evolution is simpler for the non-singlet (reduced number of splitting functions)
- Assuming a charge-symmetric sea, p-n isolates the non-singlet
- Such measurements provide a direct handle on the quark structure of the nucleon
- Also, need to pin down non-singlet (p-n) to extract singlet (complementary to F_L)



Example: Higgs production by gluon fusion

– This is the main production mechanism for a Higgs at the LHC



To calculate the cross section for this process in pp collisions, we need to know the gluon PDF