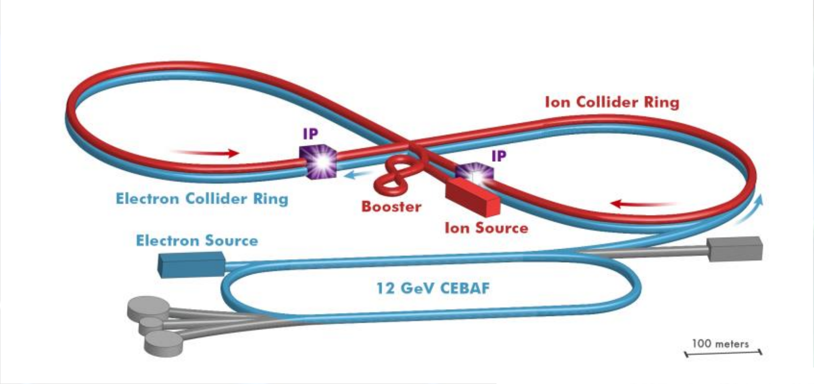
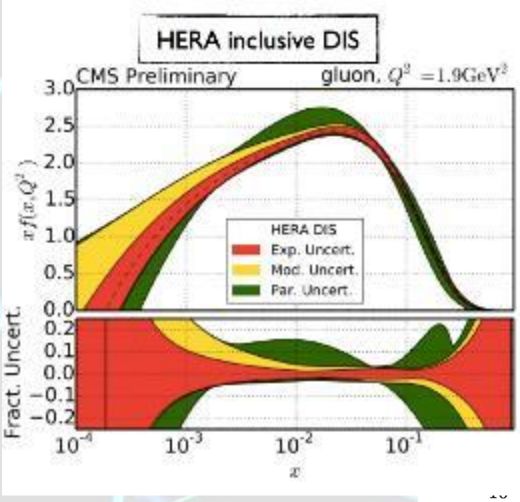
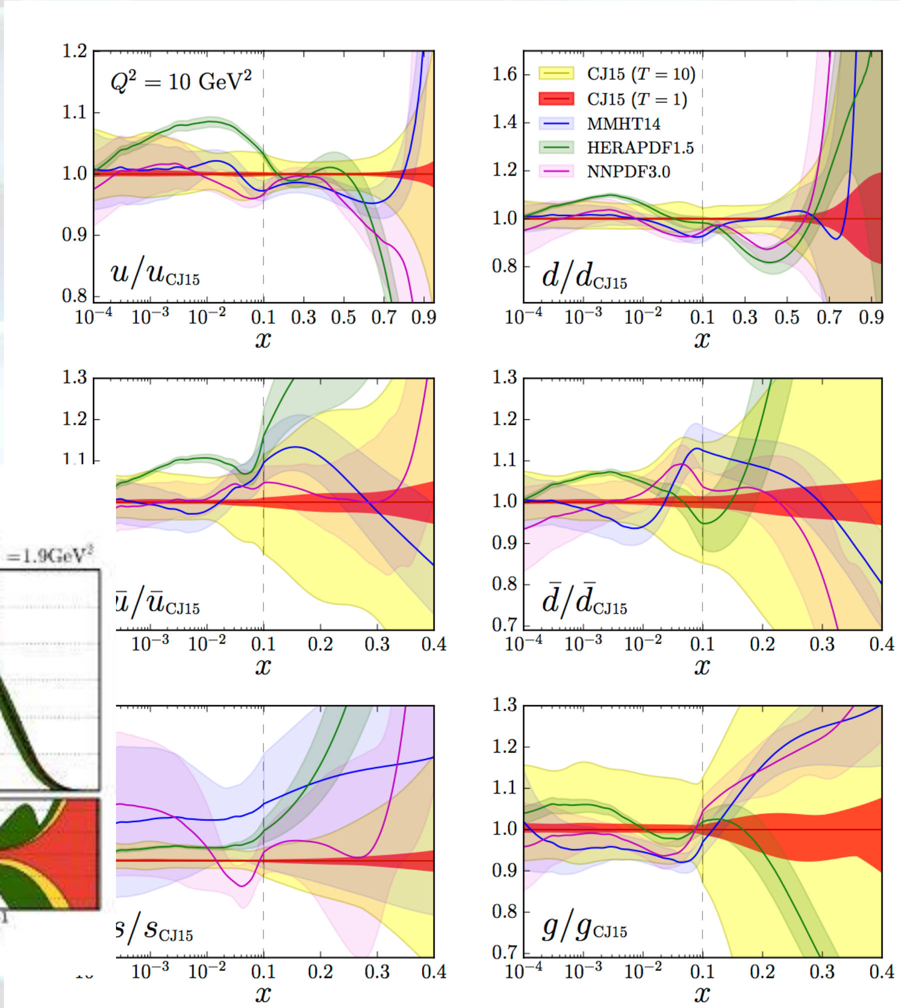
Determining Large x PDFs at JLEIC – *a work in progress*



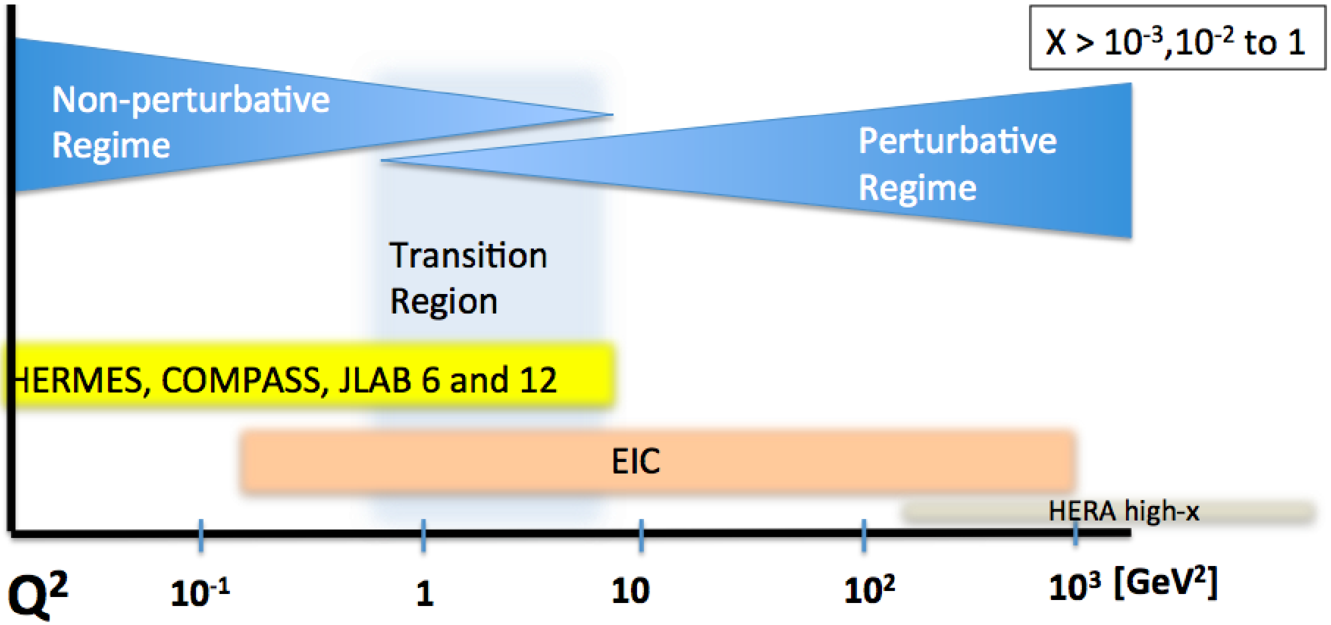




A. Accardi (Hampton),
R. Ent, J. Furletova,
C. Keppel, K. Park,
R. Yoshida (JLab),
M. Wing (UC London)

Motivation

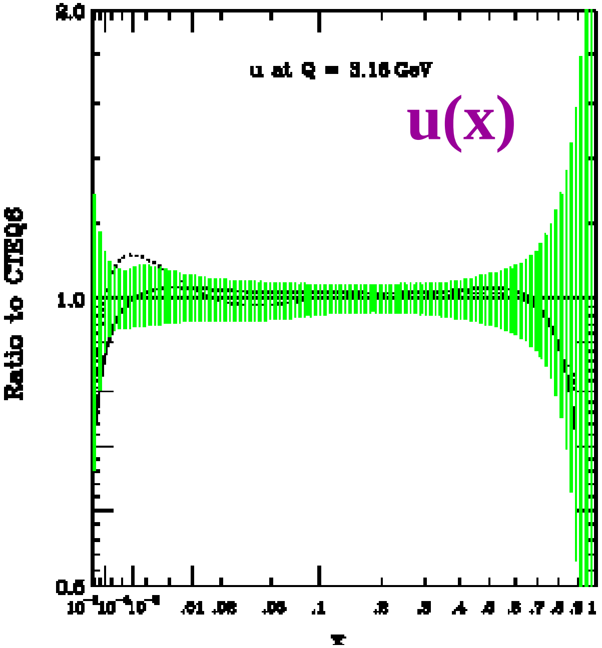
- In general, DIS experiments provides the best systematic control for PDF measurements.
- High-x (>0.1) PDFs are of interest to LHC (and HL-LHC) program for searches for new physics .
- Medium-x (0.01 to 0.001), possibly for Higgs couplings.
- Jefferson Lab 12 GeV program measures high-x at Q^2 up to ~10 GeV^2. Measurements ranging to high (up to a few 1000 $GeV^{2)}$ will enable studies of target mass, higher twist, pert/nonpert. studies)

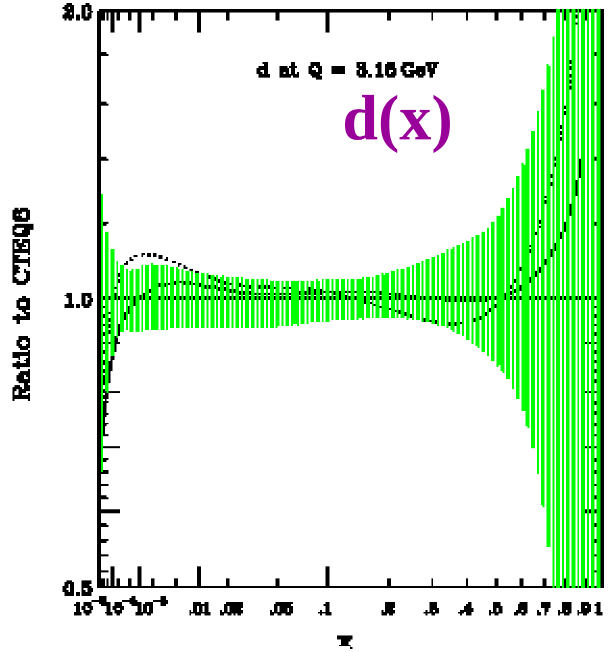


Motivation II

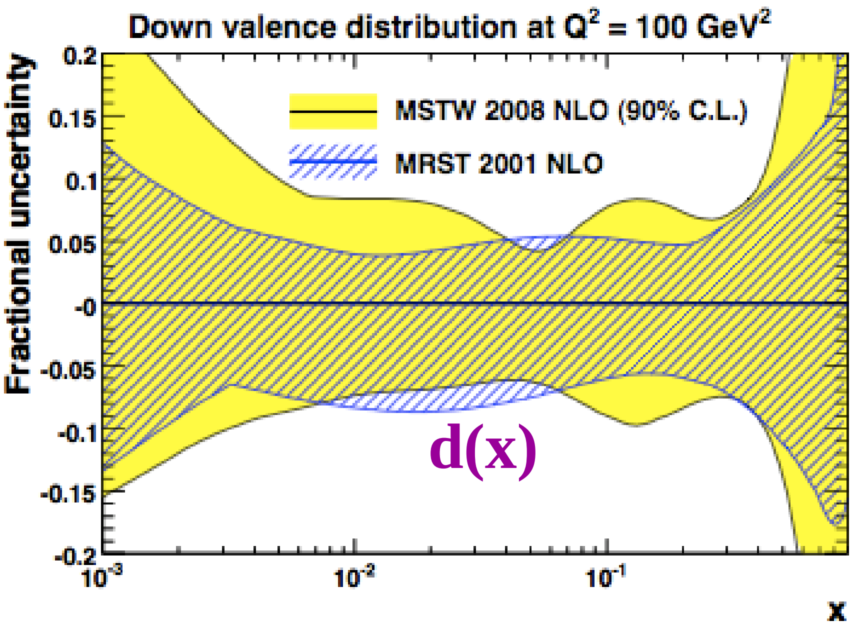
- HERA measurements at high-x tends to be statistics limited—high-x, generally means high-Q^2 (more on this later).
- Other measurements are either
  - At hadron-hadron machines with, in general, larger systematic uncertainties (Tevatron, LHC itself)
  - Fixed target experiments at lower Q^2 and/or have target corrections leading to uncertainties when used in QCD fits.
- The proposed Electron Ion Collider is kinematically between HERA and fixed-target.
  - Measure at perturbative Q^2 values and on proton target.
- EIC and HL-LHC will run concurrently (according to current projections).

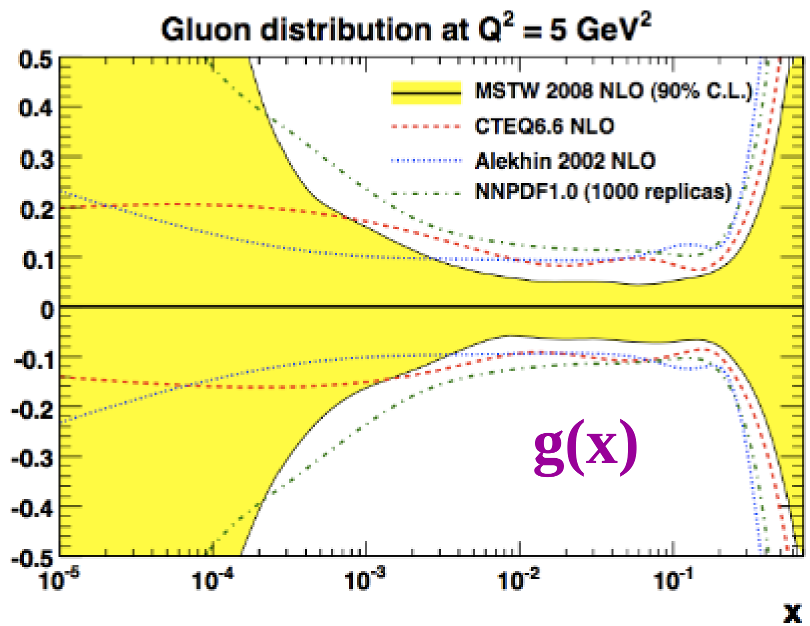
Large x (x > 0.05) -> Large PDF Uncertainties



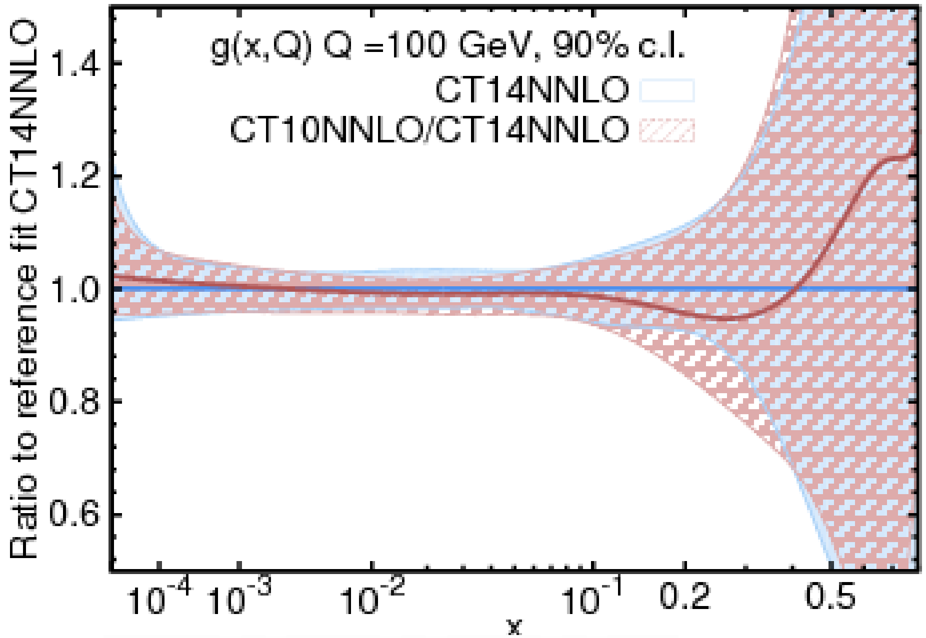


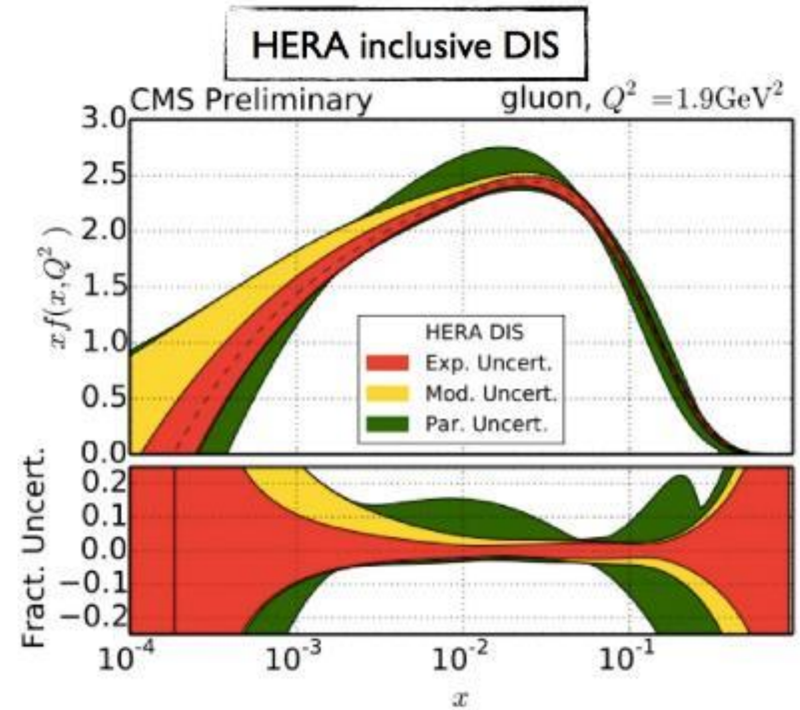
This talk will focus largely on d(x), g(x)

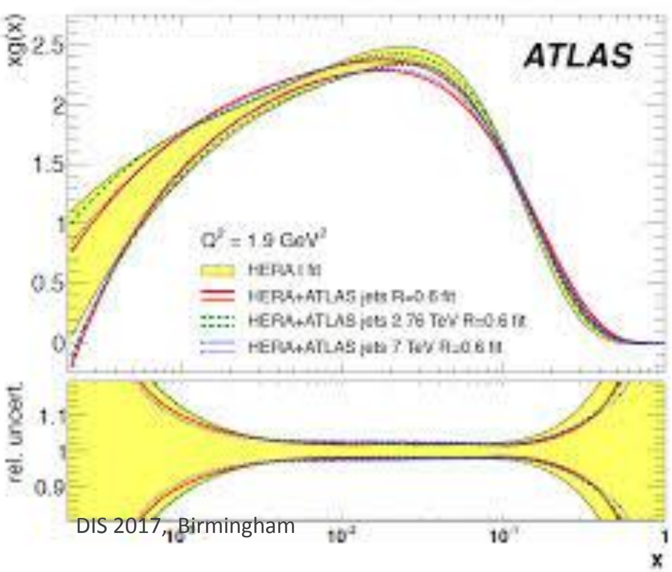




g(x) is poorly known at large (and small) x…





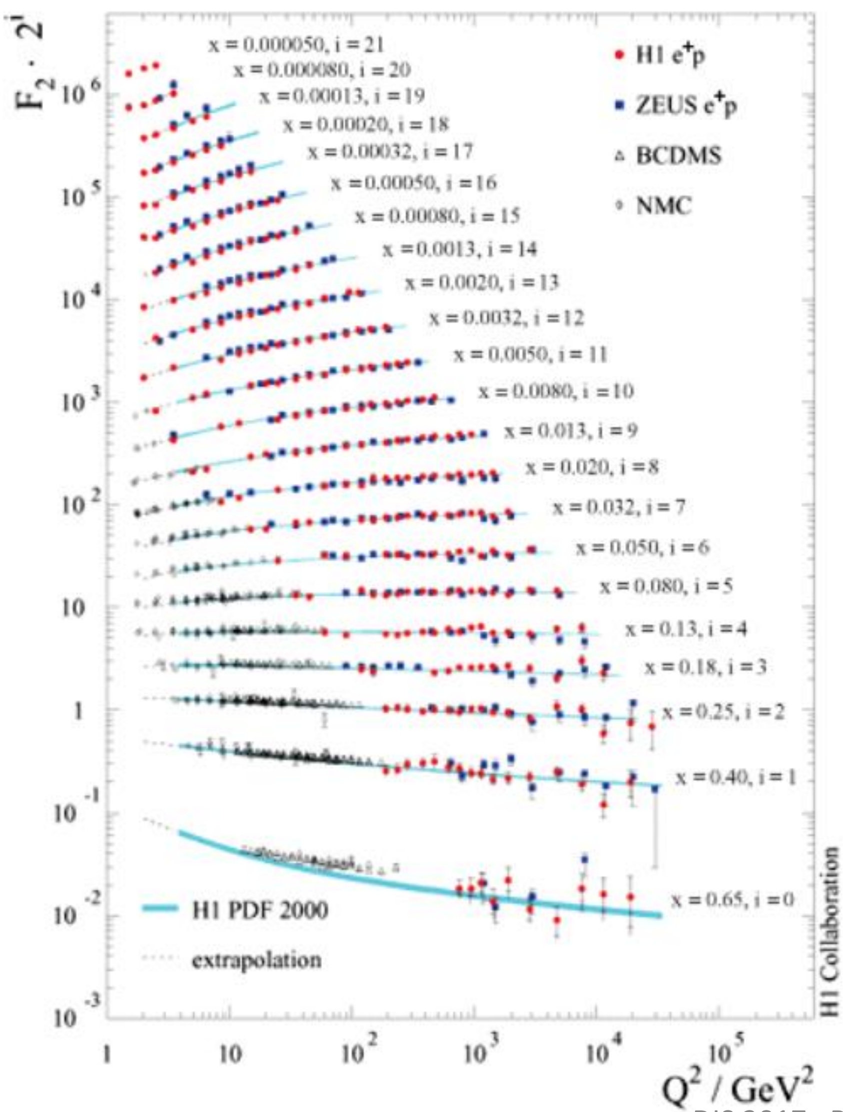


Most knowledge comes from
- (small) scaling violations in the evolution of the F_2 str. fn.
- Jets in p+p (and e+p)

Both are limited to x<~0.3

Nucleon Structure Function Measurements

F_2^p



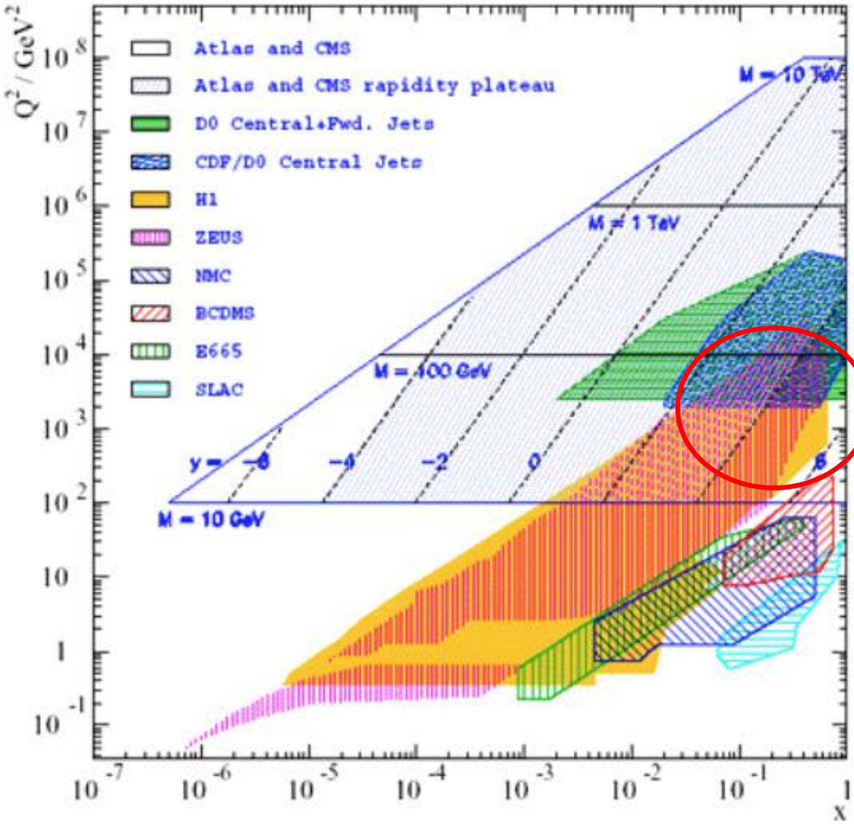
Proton –

- 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 asF_2^p
- Translates to large uncertainties on d(x)

HERA and other measurements.



HERA* measures high-x at high-Q^2

*Other HERA high-x meas. exist (not yet used in fits) Phys. Rev. D89 (2014) 072007

920 GeV Proton

27.5 GeV electron

Jet

(Falls into beampipe at high-x)

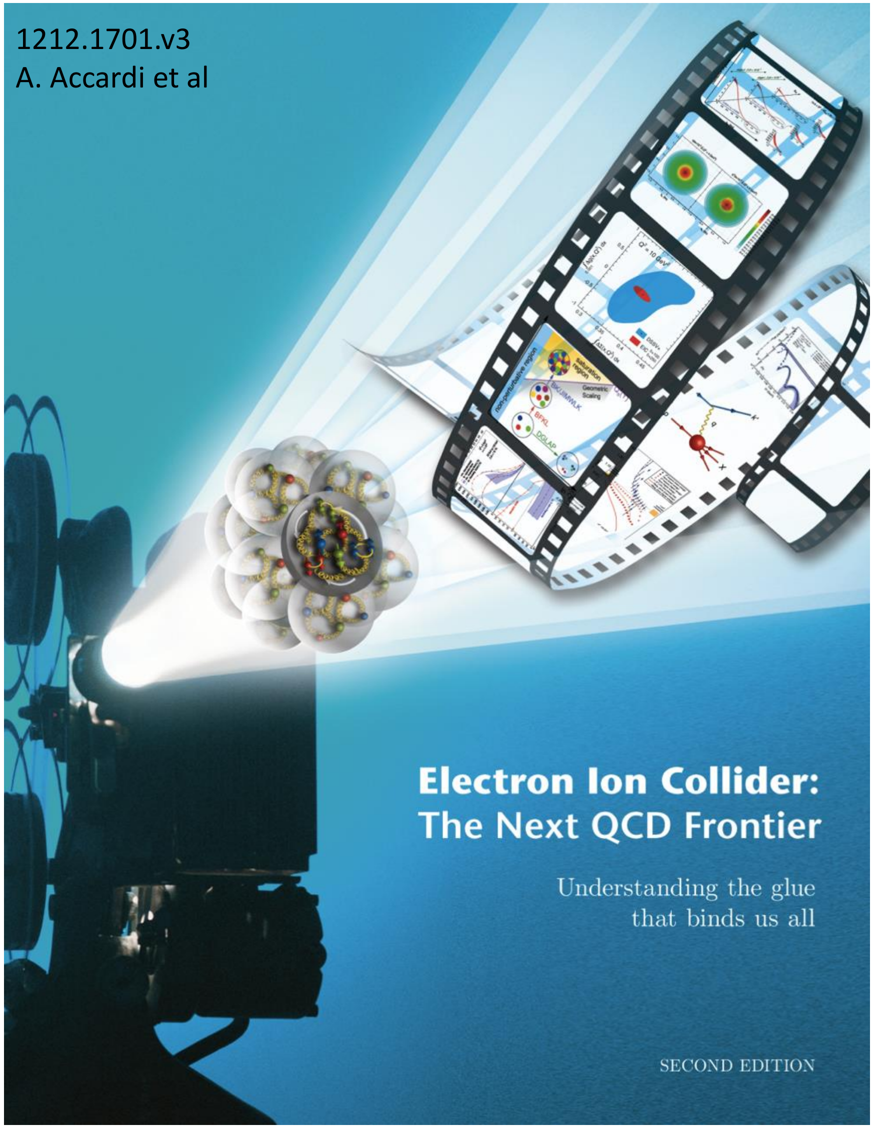
The Electron Ion Collider

For e-N collisions at the EIC:
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 3-10(20) GeV
- ✓ Luminosity L_{ep} ~ 10^{33-34} cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-~100 (~140) GeV Variable CoM

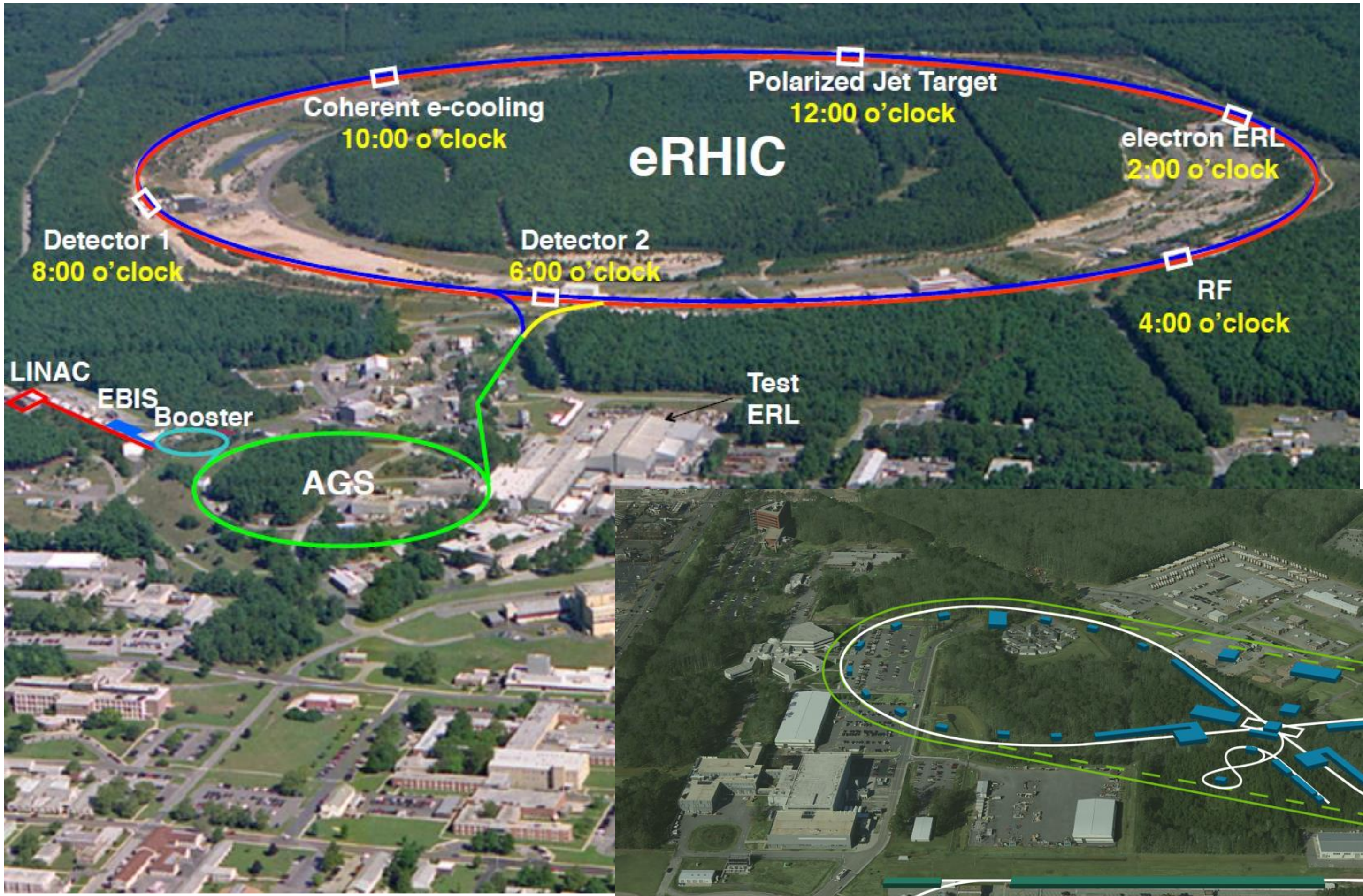
For e-A collisions at the EIC:
- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

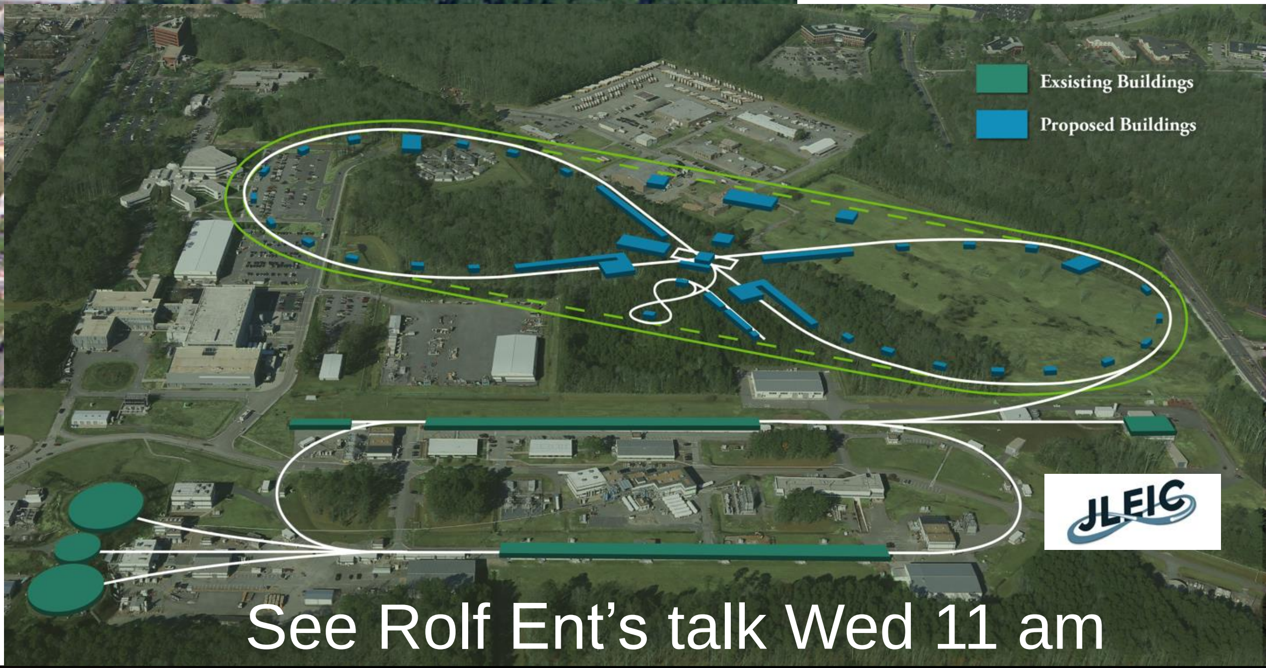
Two proposals for realization of the science case -
both designs use DOE's significant investments in infrastructure



US-Based EIC Proposals

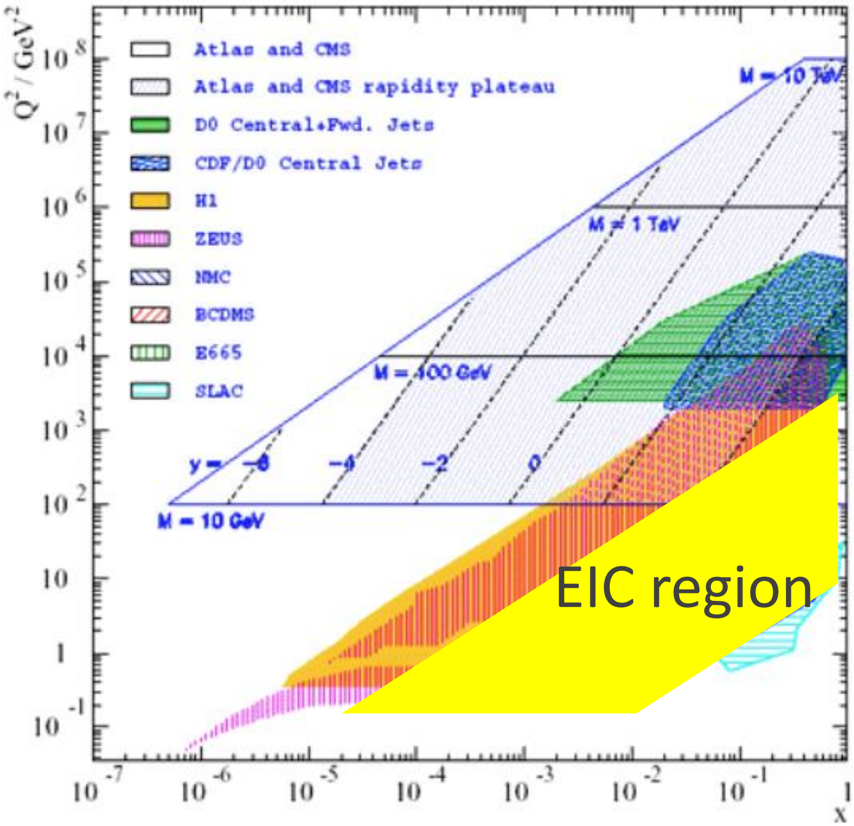


Brookhaven Lab
Long Island, NY



Jefferson Lab
Newport News, VA

EIC measurement region



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

Can EIC do better than HERA at high-x?

There are several advantages:

- Much higher luminosity (2 to 3 orders of magnitude)
- Run deuterons (measure neutrons)
- Access to lower angle jets. (large crossing angle for the beams)—see Rolf Ent's talk WG7 Wed. 16:00
- Better flavor tagging.

Also at least one disadvantage:

- Lower energies mean lower energy jets—worse calorimetric resolution.

(at high-x, Q^2~10 GeV^2: essentially x is measured by jet energy)

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 $(1\text{-}x)^a$ type form)
- *Need accurate deuteron nuclear corrections*

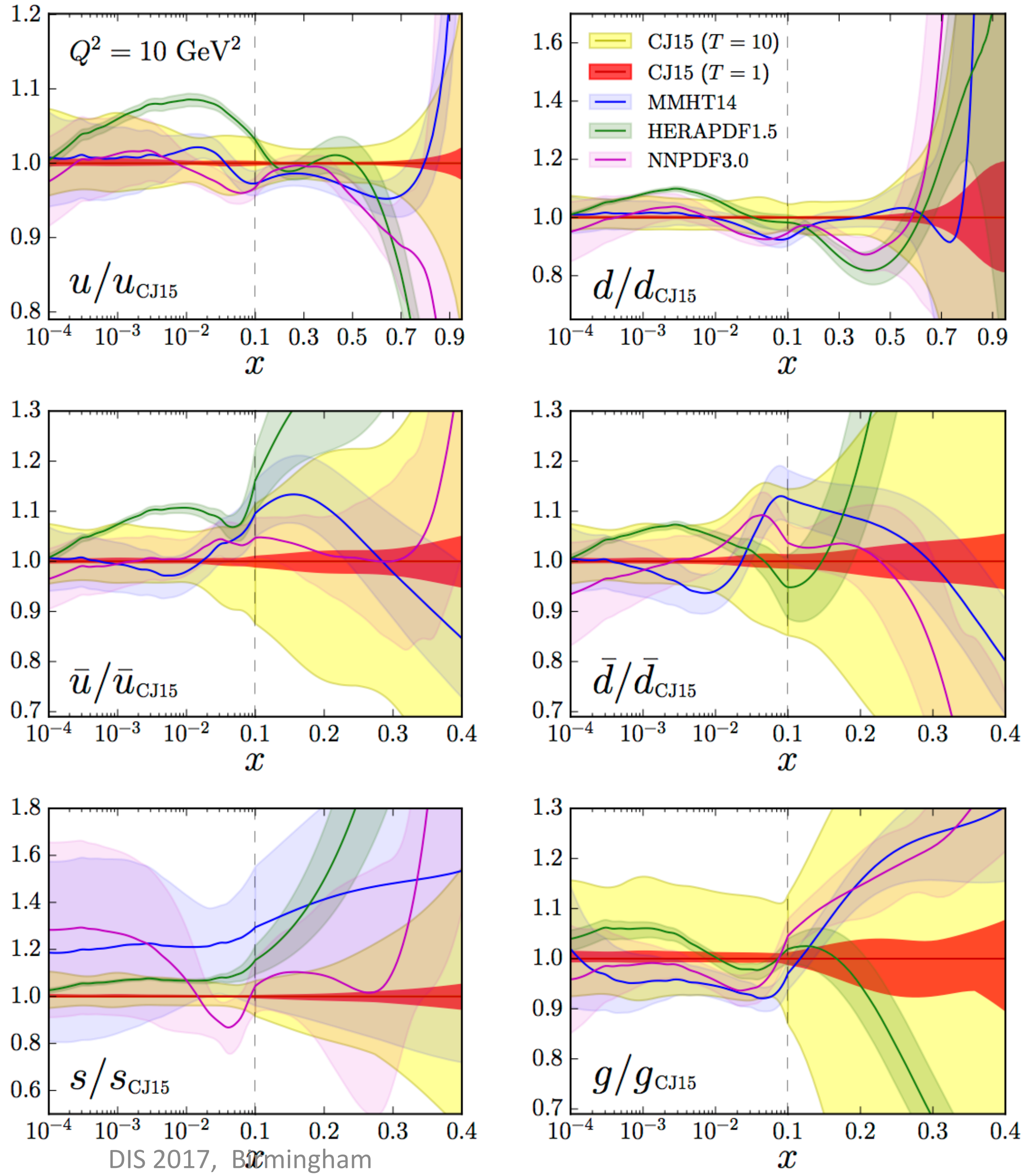
CTEQ-Jefferson Lab Collaboration

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



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

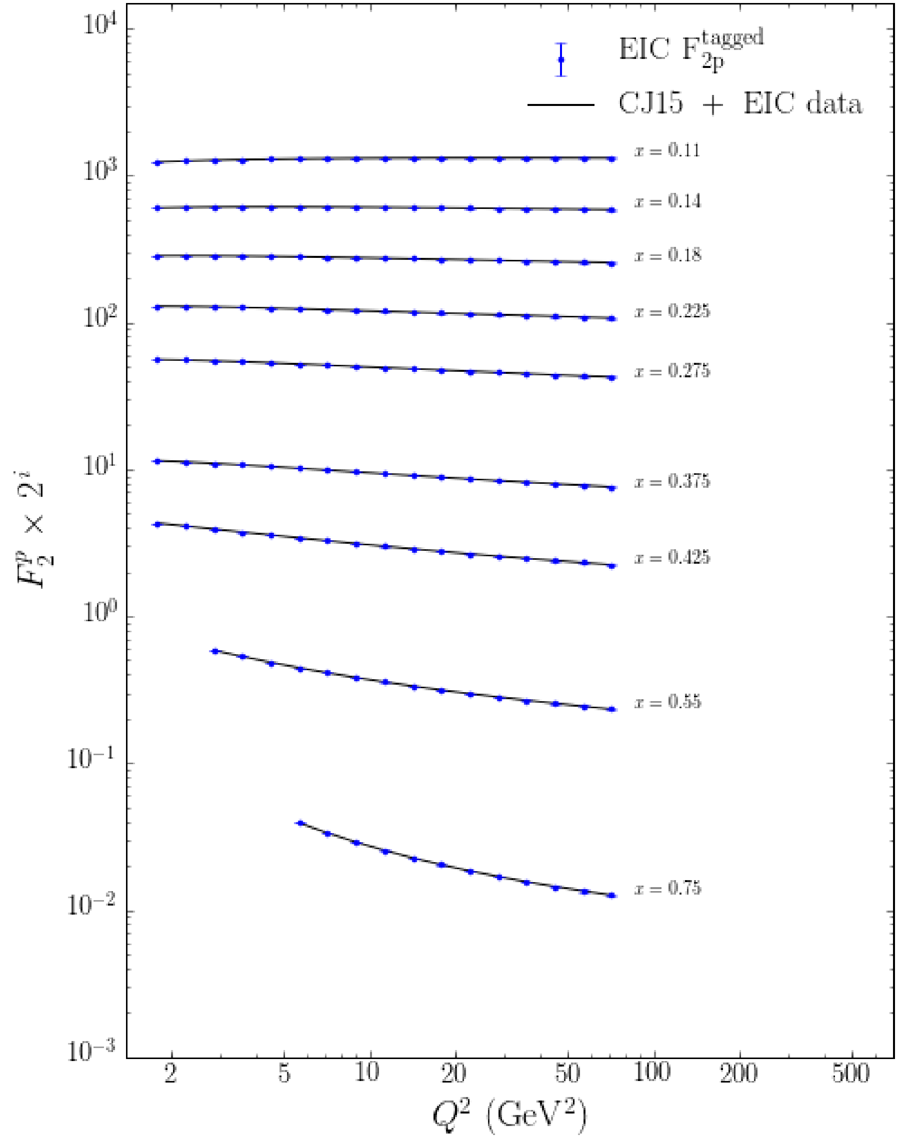
Can check on-shell extrapolation by measuring F_2^p from deuterium with tagged neutron spectator, comparing to proton target data

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..***

F_2^p (tagged) pseudodata vs x

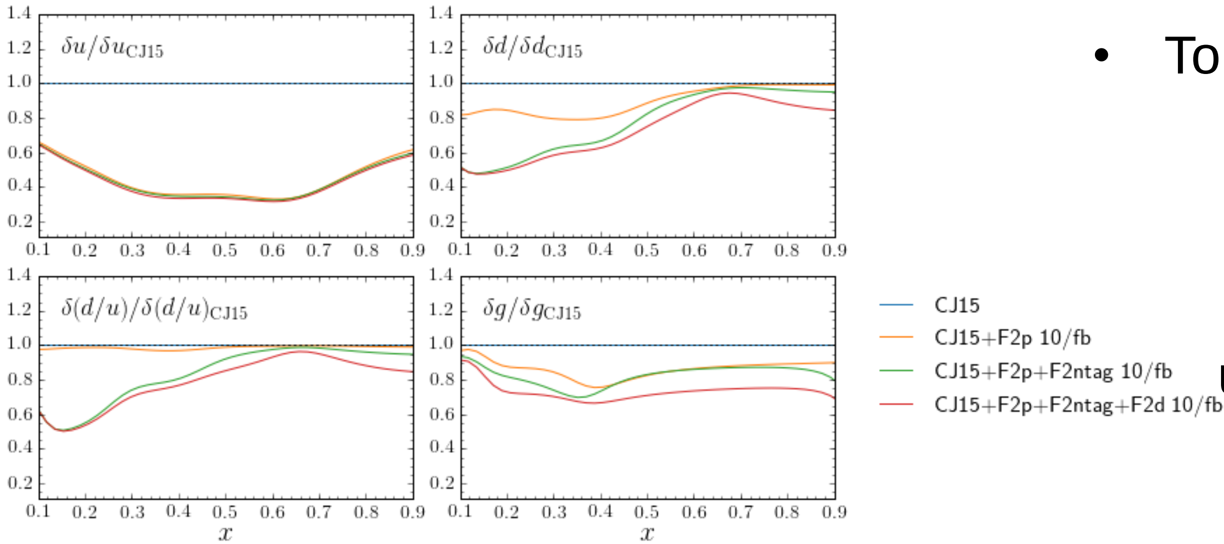


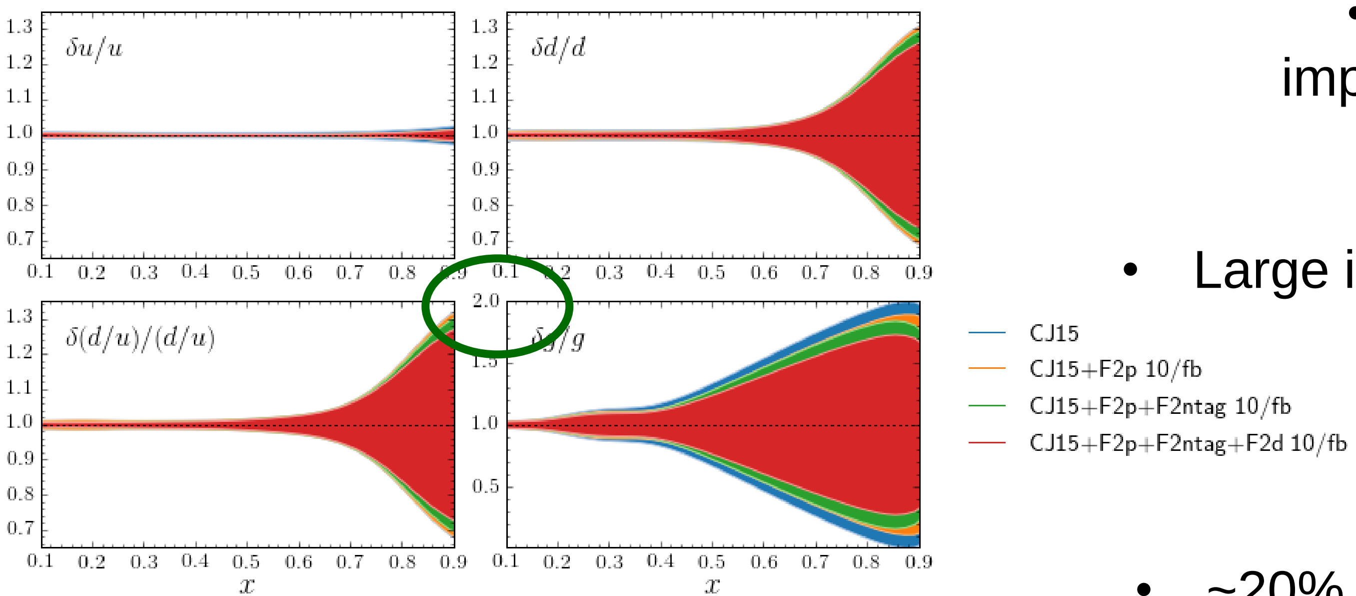
Compressed scale makes it somewhat difficult to see the experimental and fit uncertainties

Currently no cut in y:

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

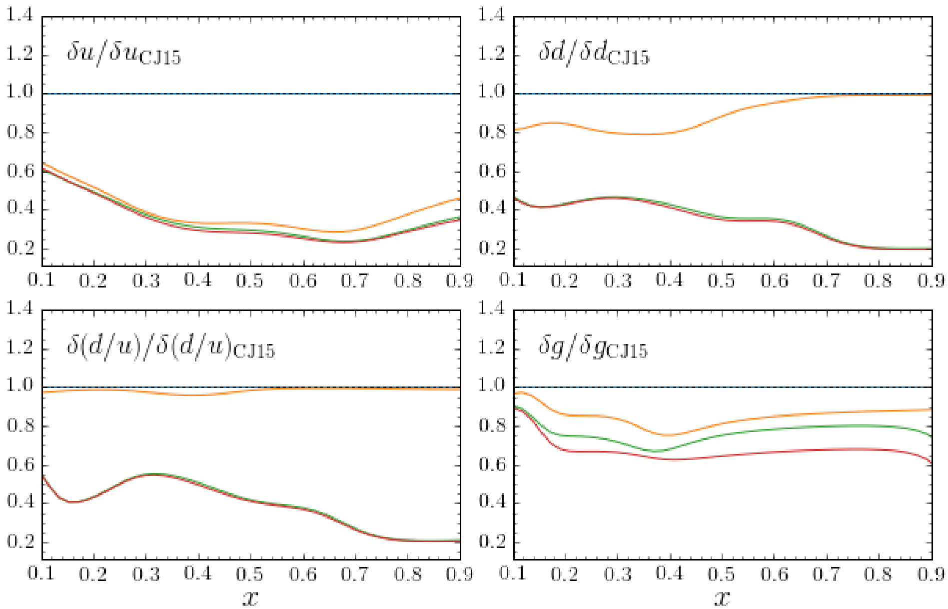
10/fb luminosity



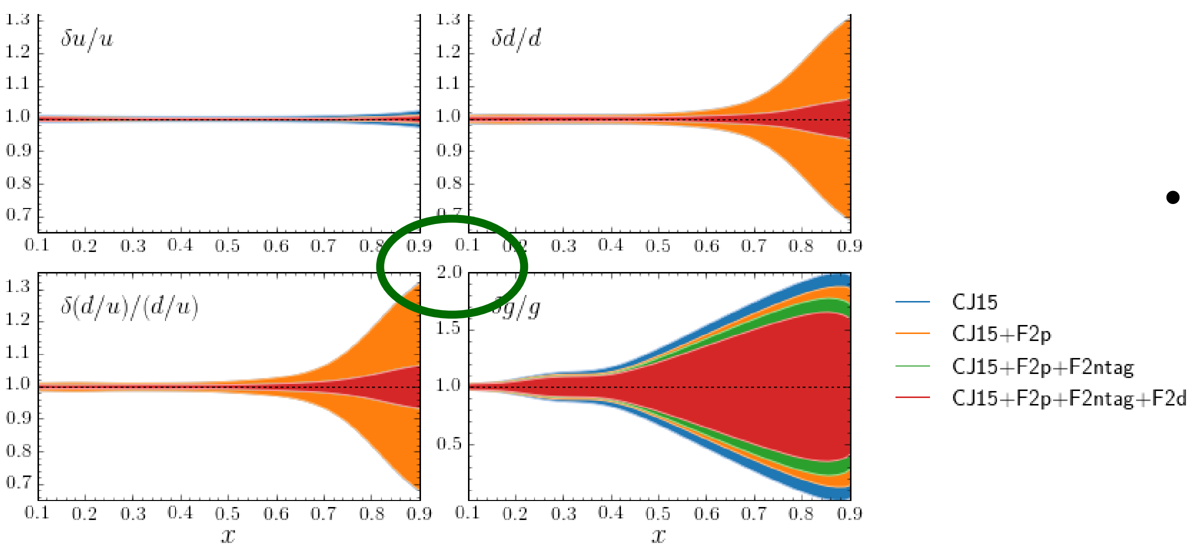


- Top: improvement in relative PDF uncertainties compared to CJ15
- Bottom: relative uncertainties compared to CJ15
- Improvement in u impressive, but already small uncertainty
- Large improvement in d(x), ~50%
- d/u tracks d
- ~20% improvement in g(x)

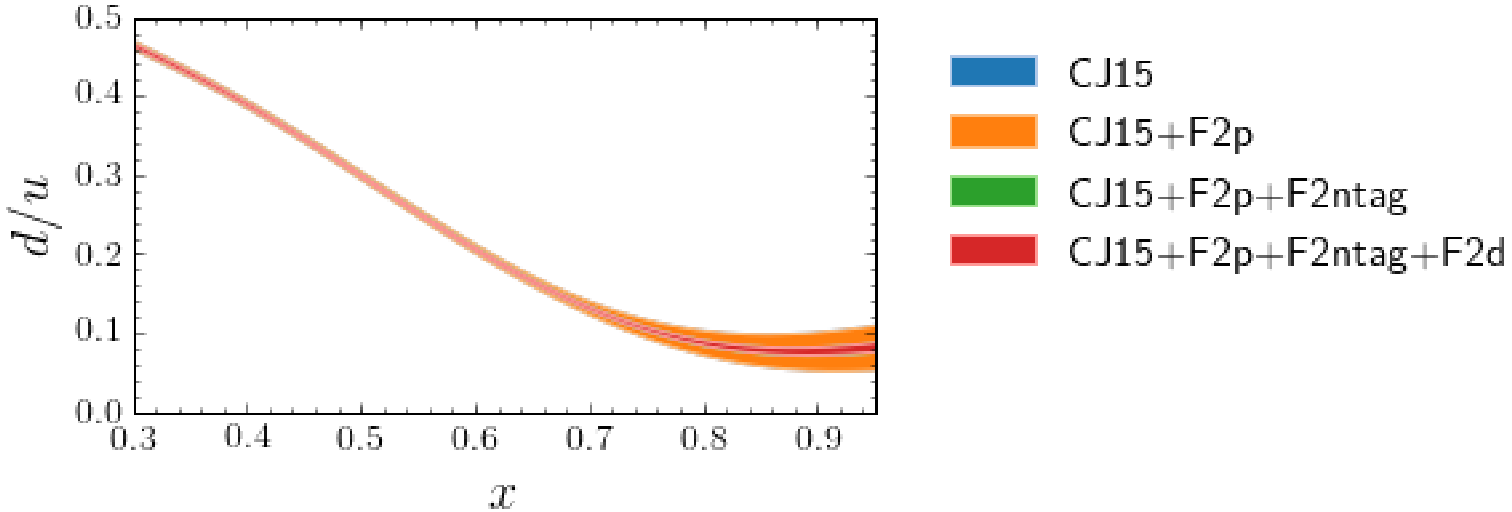
100/fb luminosity



- *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

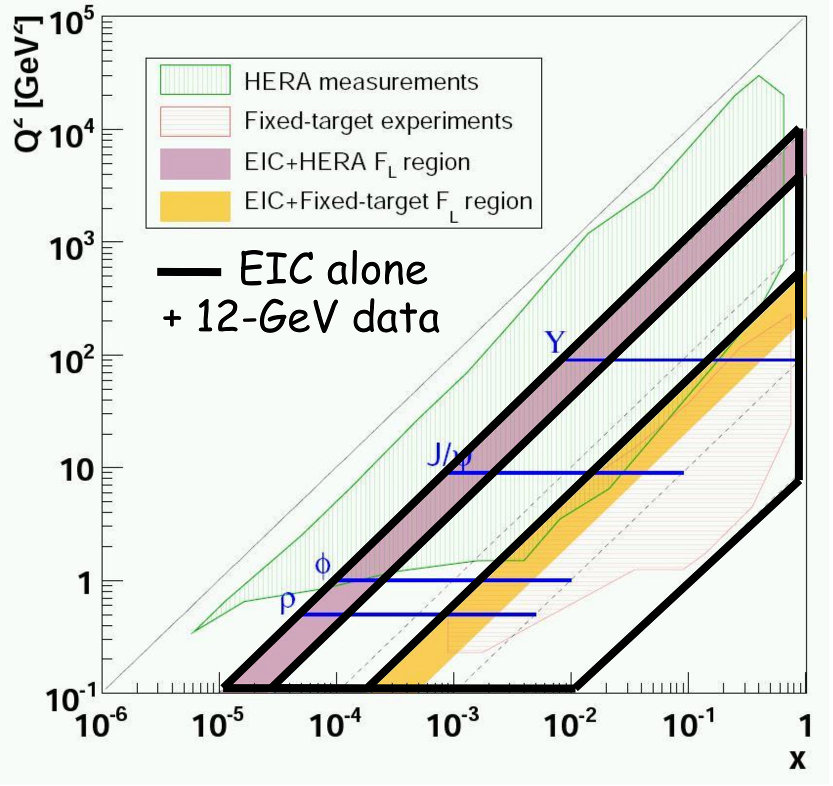
Next Steps

- Currently looking at adding other constraints.
  - Data sets with different cms energies (30, 50, 56, 60). --Add F_L constraint. (see next slide)
  - Add charged current data (electron and positron) add constraints on u and d.
- Other possibilities (using particle ID):
  - Charm production in NC. Gluon constraint from BGF
  - Charm production in CC: strange content.

F_L at EIC: Measuring the Glue Directly

Longitudinal Structure Function F_L $\propto \frac{\alpha_s}{2\pi} x \int_x^1 \frac{d\xi}{\xi} \xi(1-\xi)\, g\left(\frac{x}{\xi}, Q^2\right) + \ldots$

- Experimentally can be determined directly IF VARIABLE ENERGIES!
- Highly sensitive to effects of gluon



How to measure Gluon distribution $G(x,Q^2)$:

- Scaling violation in F_2: $\delta F_2/\delta \ln Q^2$
- $F_L \sim \alpha_s\, G(x,Q^2)$
- inelastic vector meson production (e.g. J/ψ)
- diffractive vector meson production $\sim [G(x,Q^2)]^2$

$$\frac{d^2\sigma^{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2} F_L(x,Q^2)\right]$$

Summary

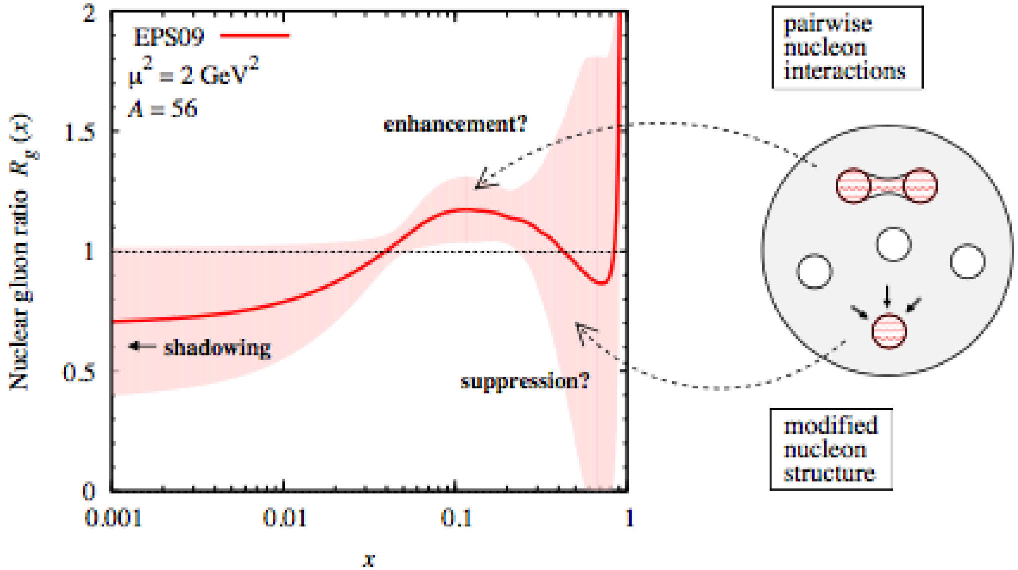
A 10/fb e-p run and an 100/fb e-d run (*with e-*n_{tag}*!*) reduces the u uncertainty to better than 1% and the d uncertainty down to 5% at x = 0.9.

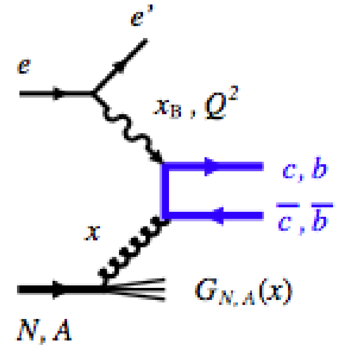
The gluon can also likely be improved significantly.

These are the first naïve studies: if convinced that there will be sizable improvements, we need to move to more careful estimates.

Large-x nuclear gluons with charm at EIC

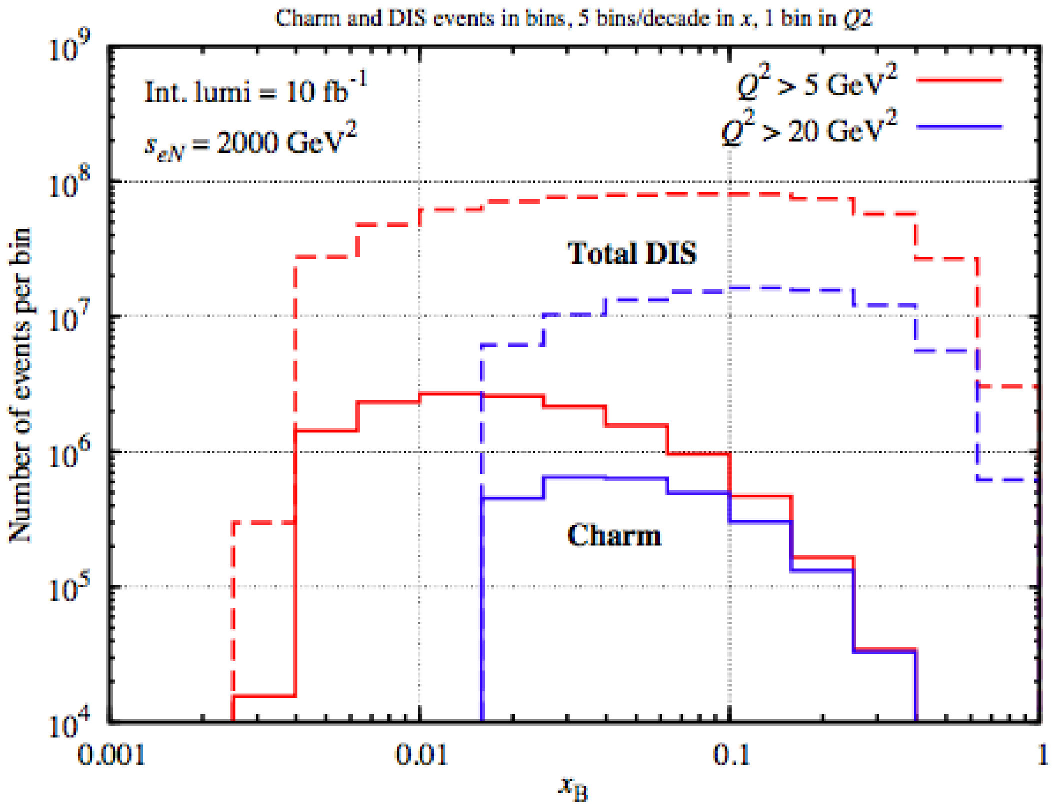
S. Furletov, Yu. Furletova, Ch. Hyde, N. Sato, M. Strikman, C. Weiss, prepared for DIS2017

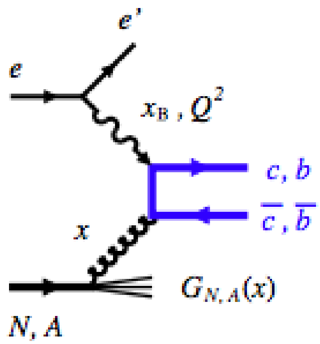




- Nuclear modification of gluons gives insight into NN interactions in QCD
  $x > 0.3 \leftrightarrow$ modified single-nucleon structure, $x \sim 0.1 \leftrightarrow$ pairwise NN interactions
- Nuclear modification at large x poorly constrained by present data
- EIC: Limited information from inclusive F_{2A}, F_{LA}
- EIC: Heavy quark production as direct probe

Charm production rates at large x

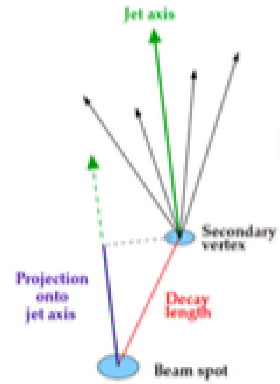




- Charm production rates drop rapidly at large x
- Charm production rates $\sim 10^5$/bin at $x \sim 0.1$ (int. lumi 10 fb^{-1})
- Charm/DIS ratio $\sim$ 2–3 % at $x \sim 0.1$, increases with Q^2

Charm reconstruction methods at large x

h_c	f	Decay	BR
D^0	59%	$K^-\pi^+$	3.9%
		$K^-\pi^+\pi^+\pi^-$	8.1%
D^+	23%	$K^-\pi^+\pi^+$	9.2%
D^{*+}	23%	$(K^-\pi^+)_{D0}\,\pi^+_{\rm slow}$	2.6%
		$(K^-\pi^+\pi^+\pi^-)_{D0}\,\pi^+_{\rm slow}$	5.5%
D_s^+	9%	$(K^+K^-)_\phi\,\pi^+$	2.3%
Λ_c^+	8%	$pK^-\pi^+$	5.0%



- Charm reconstruction using exclusive D-meson decays

  $D^{*+} \to \pi^+(\text{slow}) + (K^-\pi^+)_{D0}$ used at HERA w/o PID, efficiency $< 1\%$.

  EIC PID + vertex detection allow use of other exclusive channels (D^0, D^+)

  Total efficiency estimated $\sim 6\%$

- Charm reconstruction using inclusive modes with displaced vertex

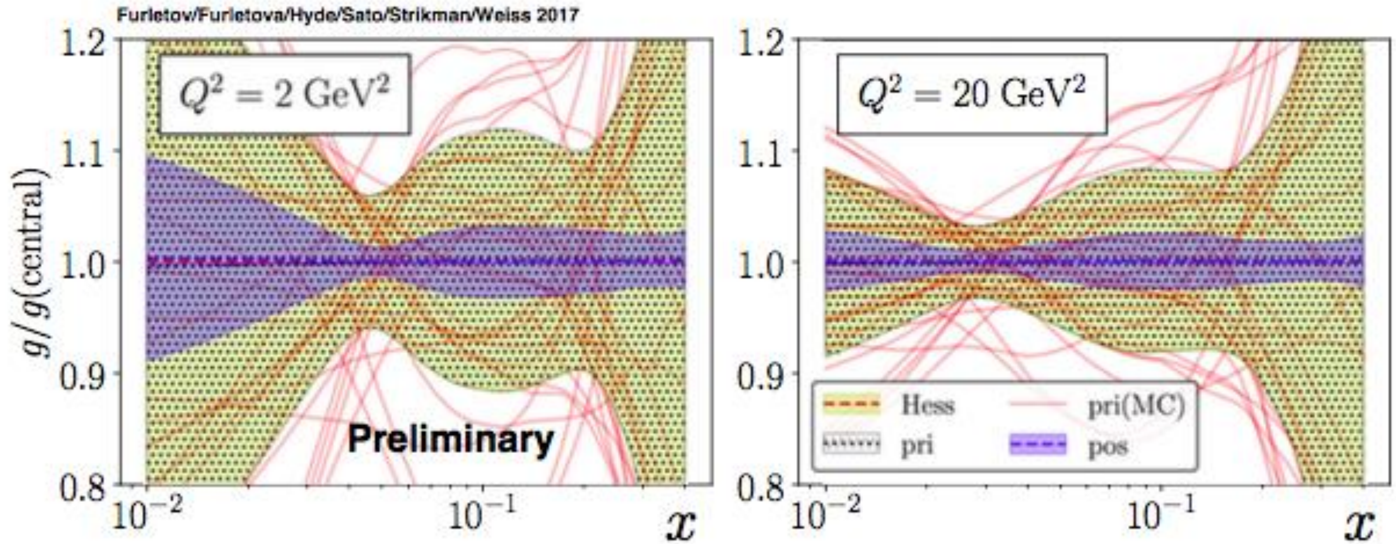
  D–meson decay length significance distribution used at HERA with vertex detector

  Efficiency estimated at ~30% (E. Aschenauer et al., 2016)

  Sys error estimate with simulations of track fitting & vertex reconstruction, in progress

- Charm reconstruction using high–p_T $c\bar{c}$ pairs

Charm impact on large–x nuclear gluon



- Impact of F_{2c} pseudodata on EPS09 studied quantified using MC reweighting
  Method of CJ15 analysis. Verified equivalence with Hessian reweighting.

- Here: Assumed 10% total error, dominated by systematics, point-to-point

- Substantial impact on large–x nuclear gluons

- Possible to constrain large–x nuclear gluons with charm at EIC!

Conclusions

- EIC has been so far discussed as a low-x machine.
- However, EIC will cover high-x at Q^2 between HERA and Jlab 12.
- The potential for EIC for high-x measurements is being explored.
  - Study nuclear effects
  - Constrain PDFs for searches at (HL-)LHC.
- The first studies look promising. Continuing on with exploratory studies.

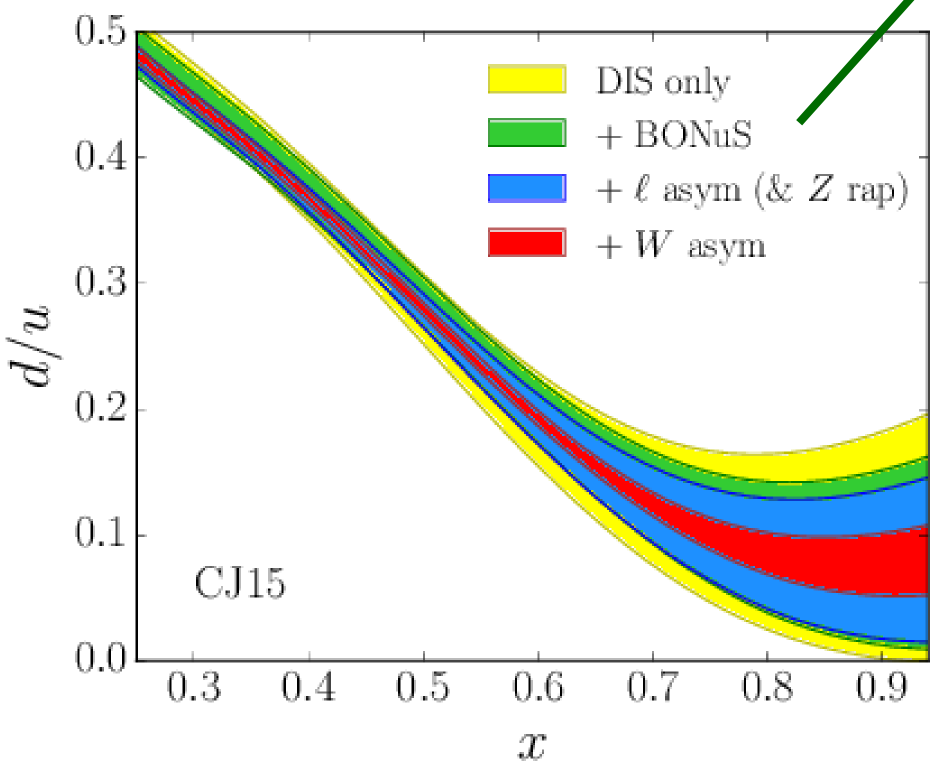
Backups

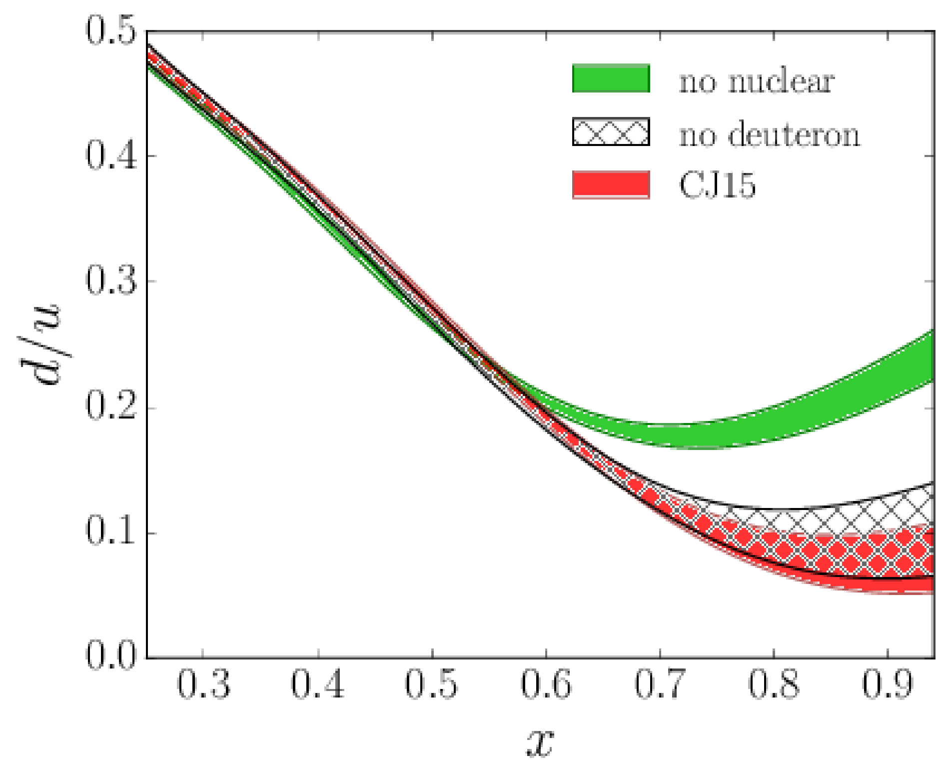
F_2^n better constrained

Resulting CJ uncertainty bands

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

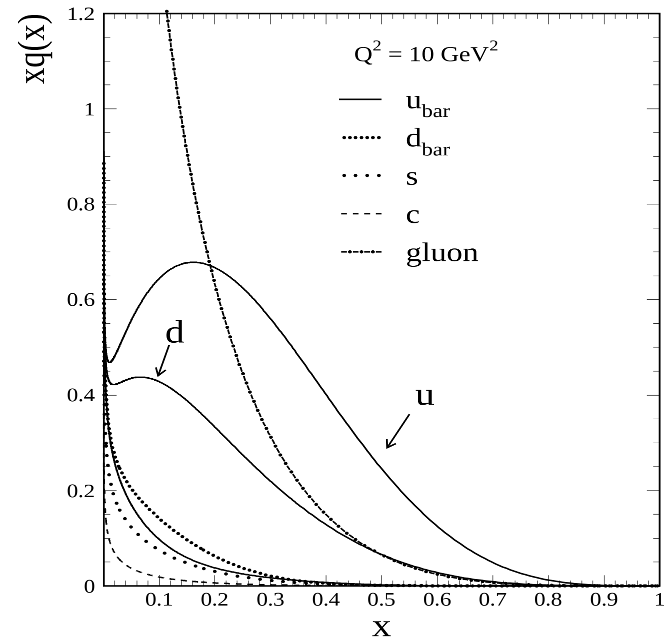
Effective neutron target via spectator tagging experiment at JLab





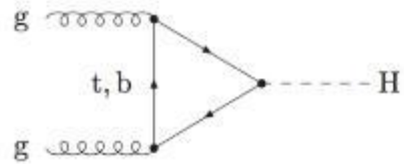
$F_2^p - F_2^n$ yields non-singlet distribution

- 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

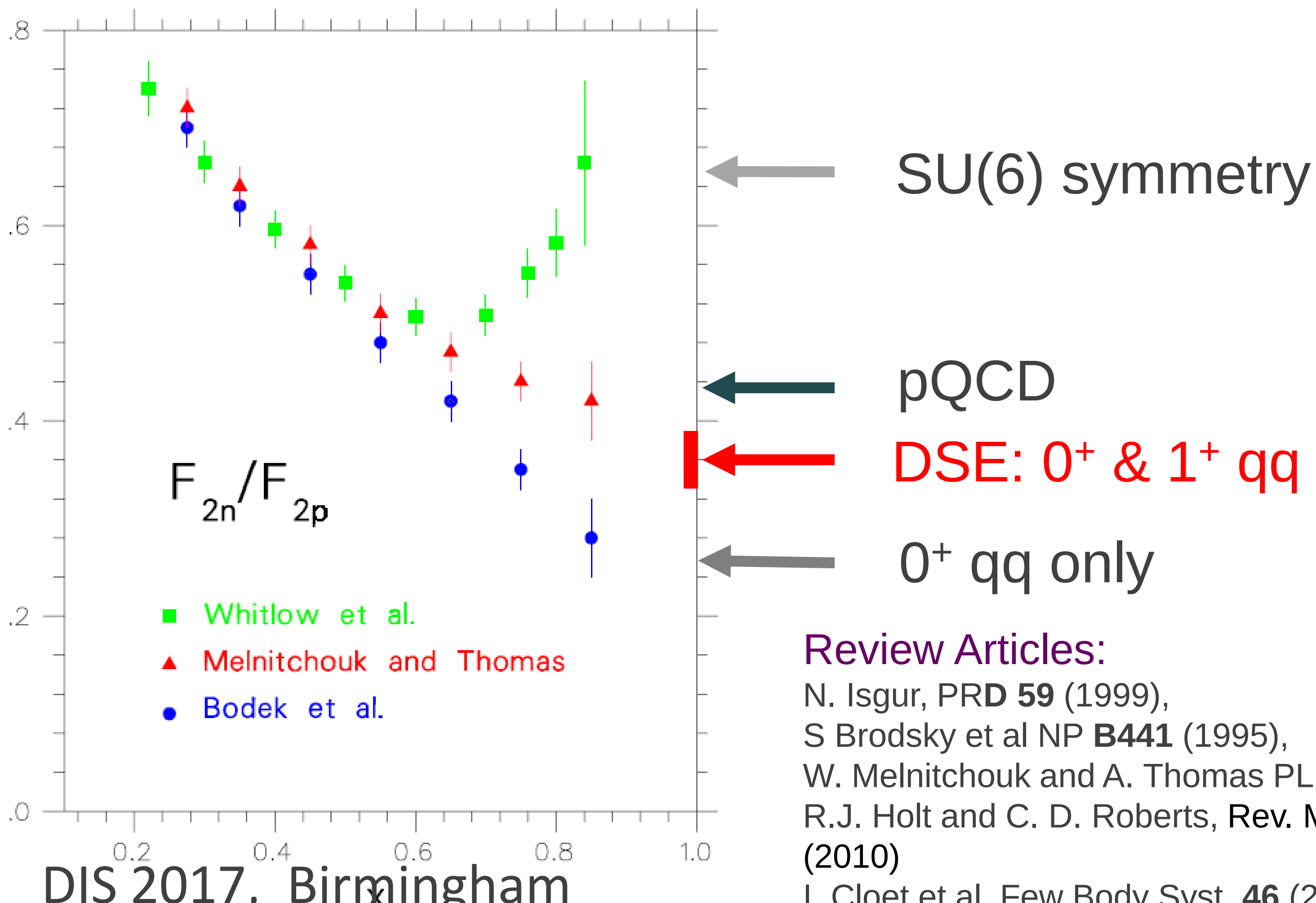
– This is the main production mechanism for a Higgs at the LHC



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

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, PR**D 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.

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

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)

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

$$\boxed{F_2^A(x,Q^2)} = \sum_{N=p,n} \int_x^{M_A/M} dy\, \boxed{f_0^{N/A}(y,\gamma)}\, \boxed{F_2^N\left(\frac{x}{y},Q^2\right)} \qquad \gamma = \sqrt{1+\frac{4M^2x^2}{Q^2}}$$

nuclear F_2

light-cone momentum distribution of nucleons in nucleus (smearing function)

nucleon F_2

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

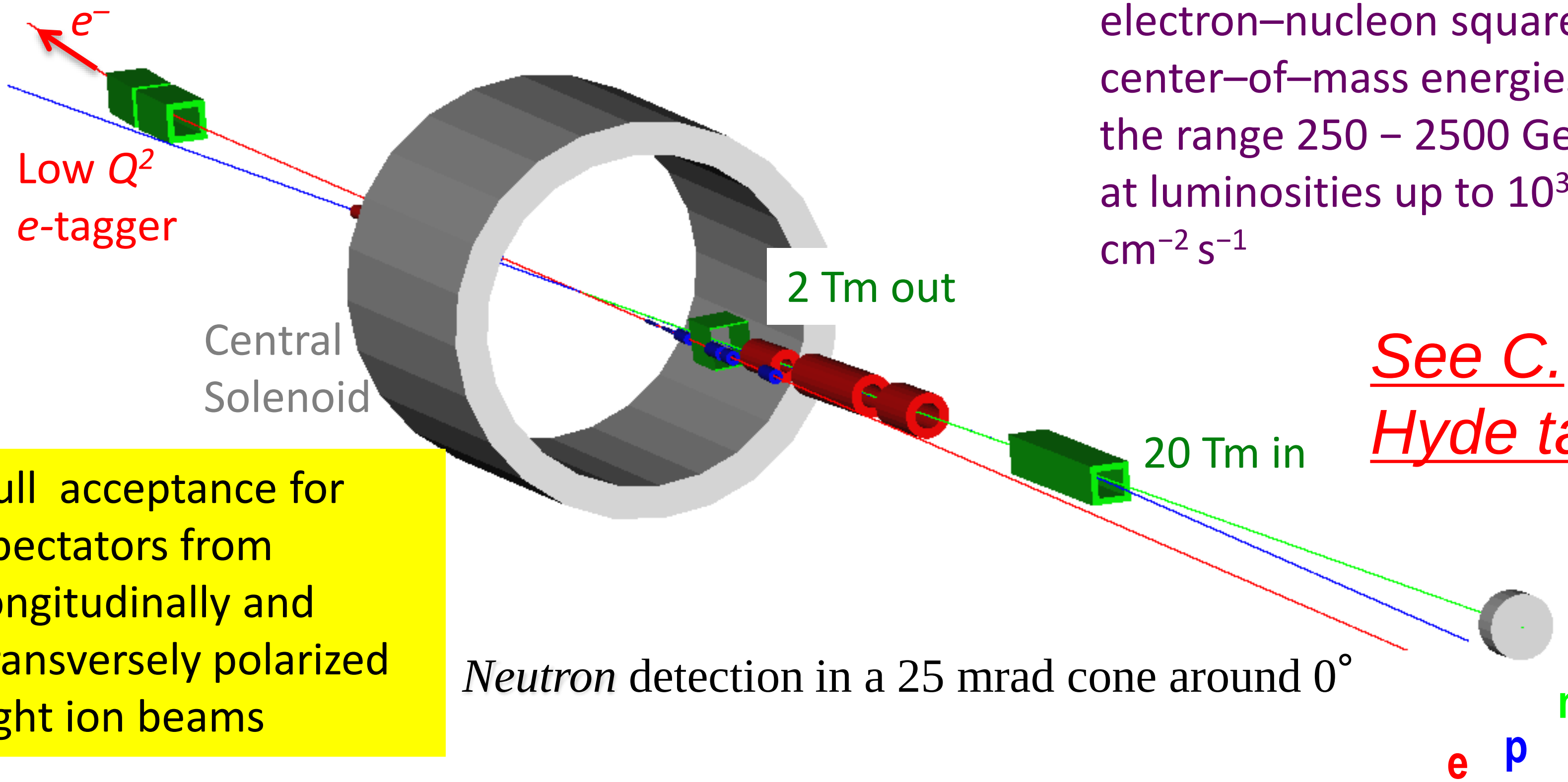
Convolution of light cone momentum distribution on nucleons in nucleus

Application to Deuterium…

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!

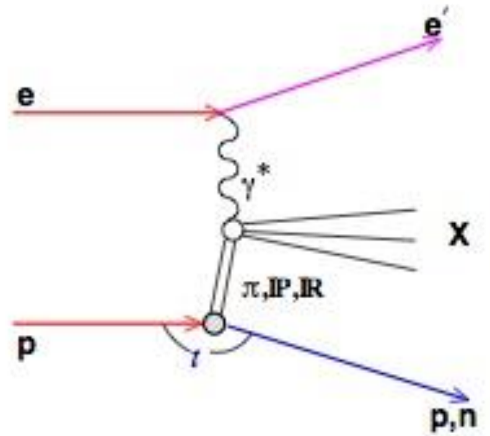
- Full acceptance for spectators from longitudinally and transversely polarized light ion beams

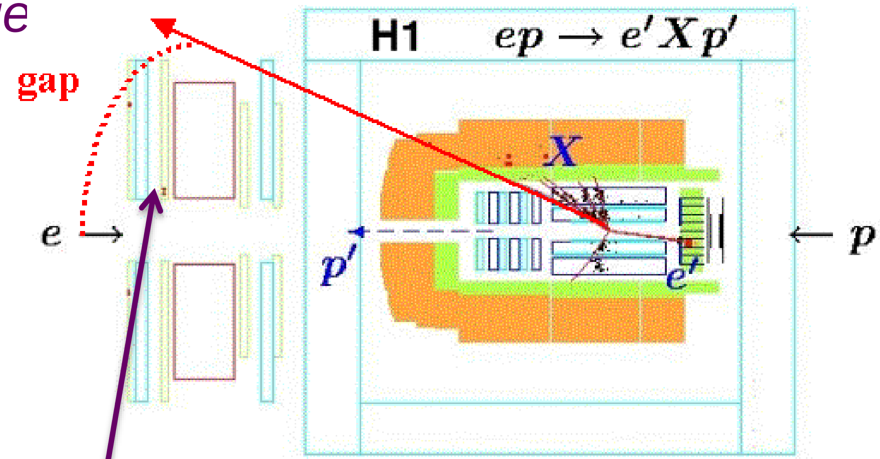
Neutron detection in a 25 mrad cone around 0°

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 exchange*



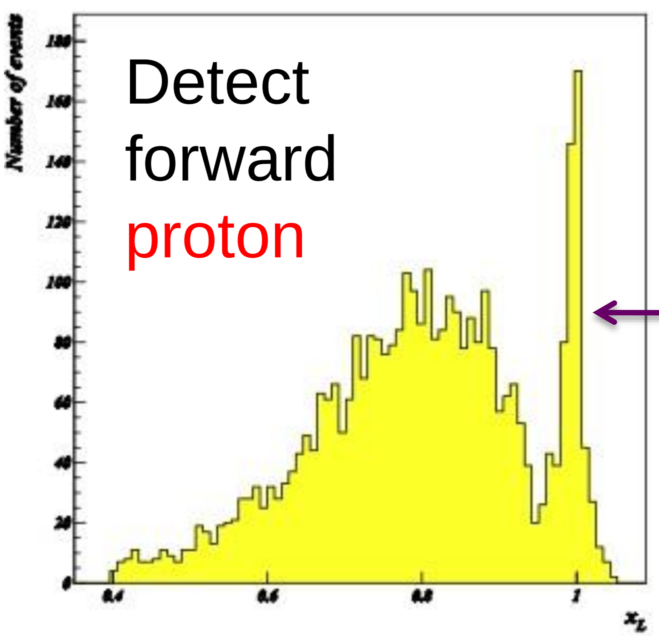


Diffractive Scattering:

Large rapidity gap

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

Also tagged neutron



Detect forward proton

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

Pomeron contribution　　Reggeon contribution

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

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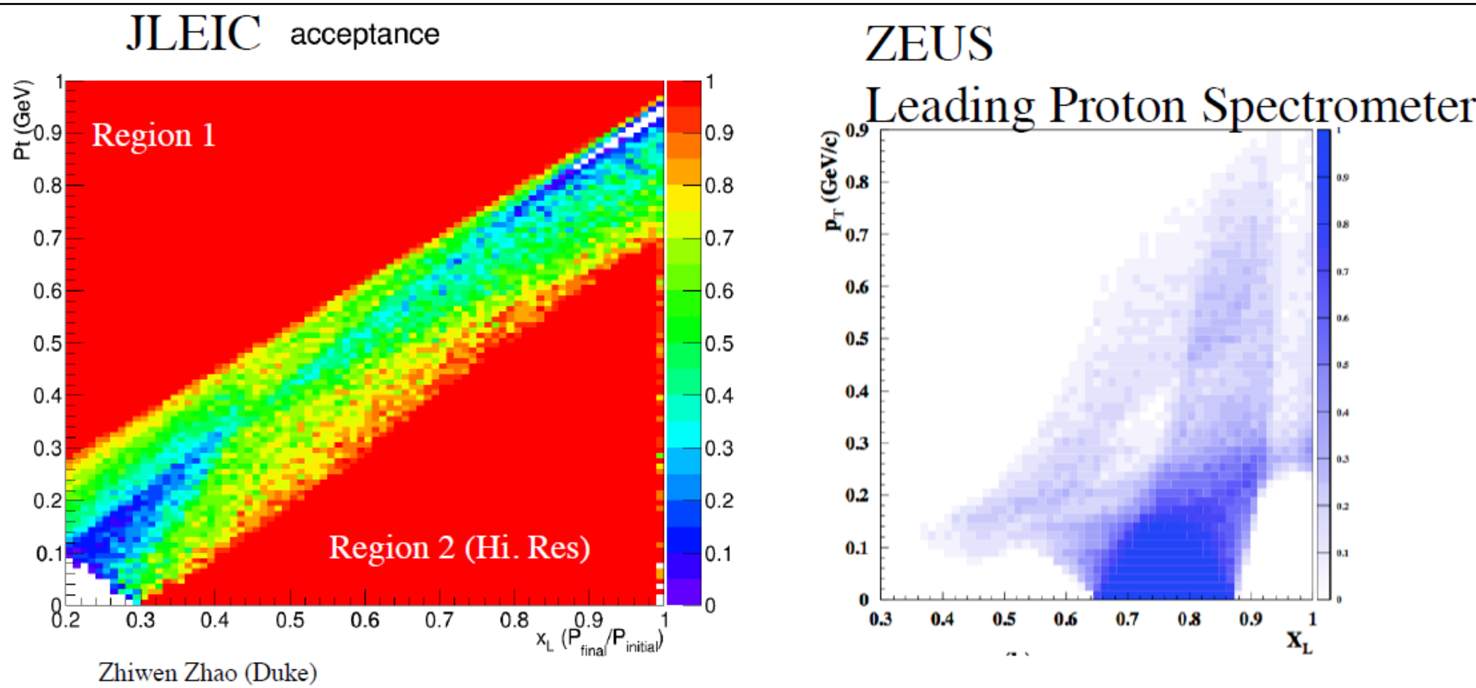
EIC: Full Acceptance for Forward Physics!

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



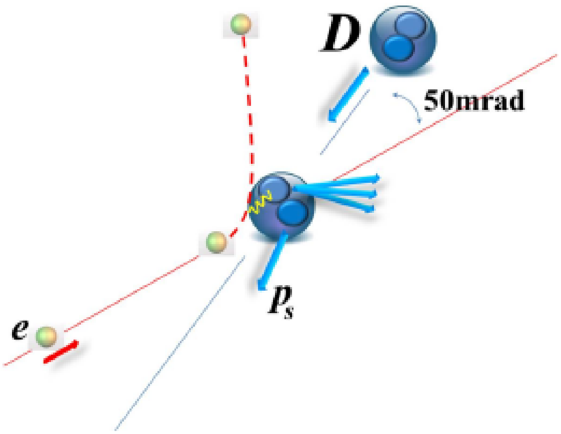
Acceptance in diffractive peak (X_L>~.98)

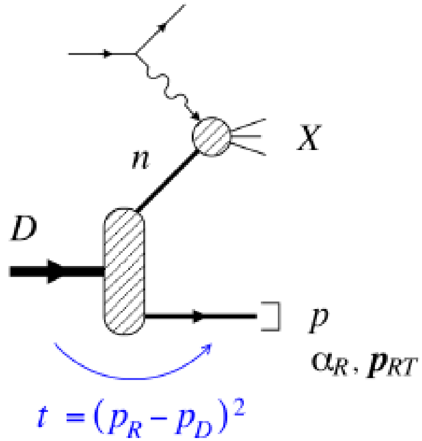
ZEUS: ~2%

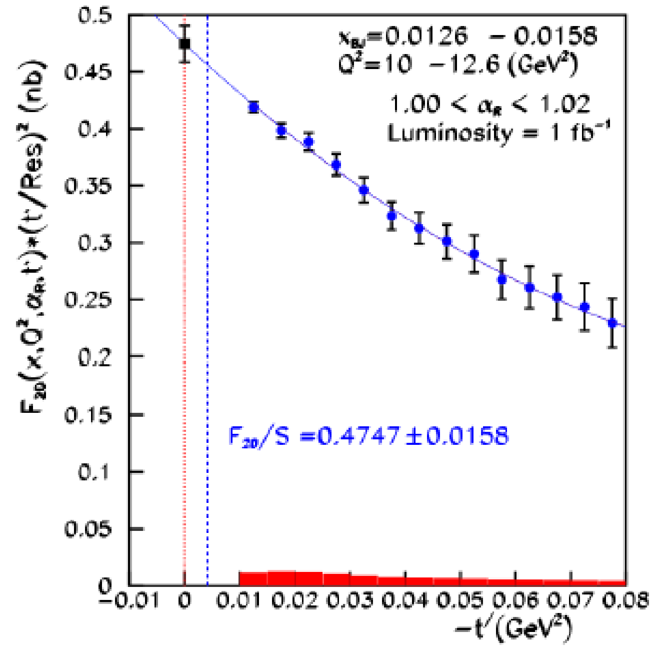
JLEIC: ~100% (also covers much higher X_L than ZEUS)

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

(Tagged) Neutron Structure Extrapolation in t



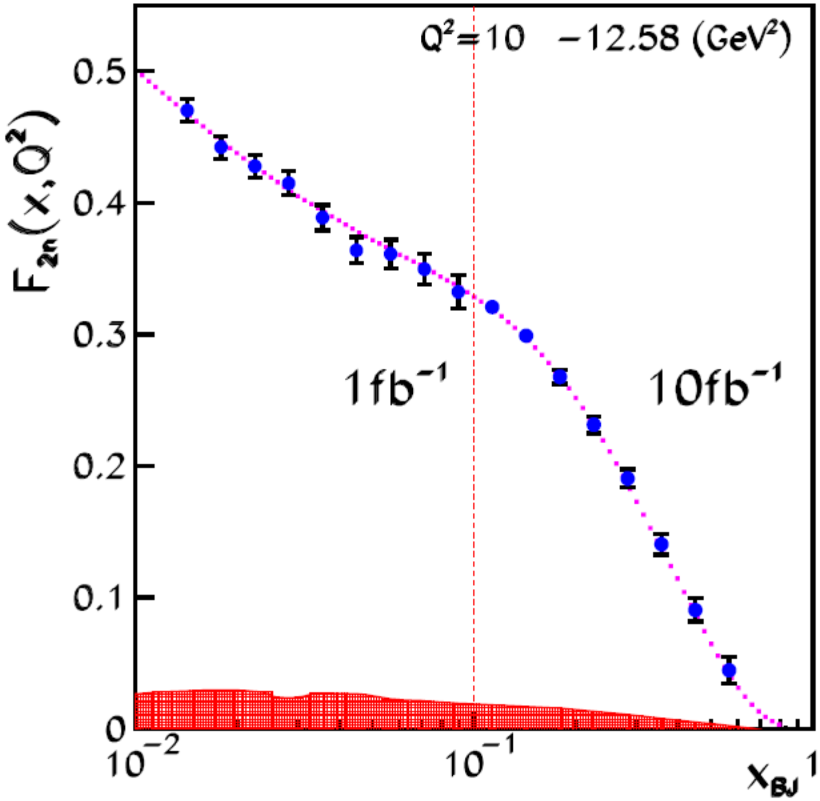


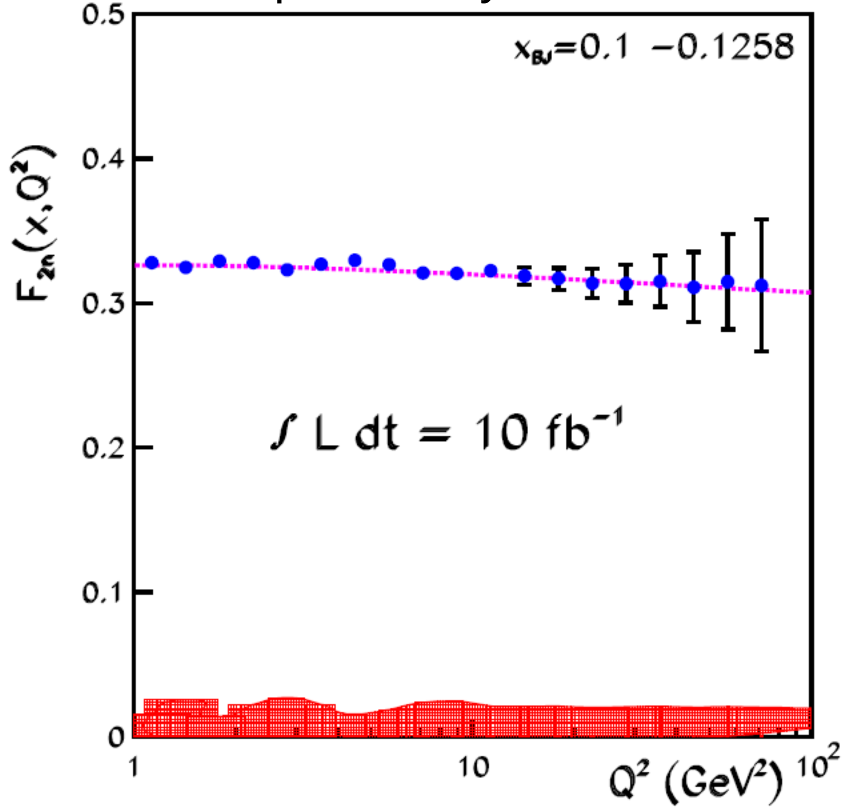


- t resolution better than 20 MeV, < fermi momentum
- Resolution limited/given by ion momentum spread
- Allow precision extraction of F_2^n neutron structure function

(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}