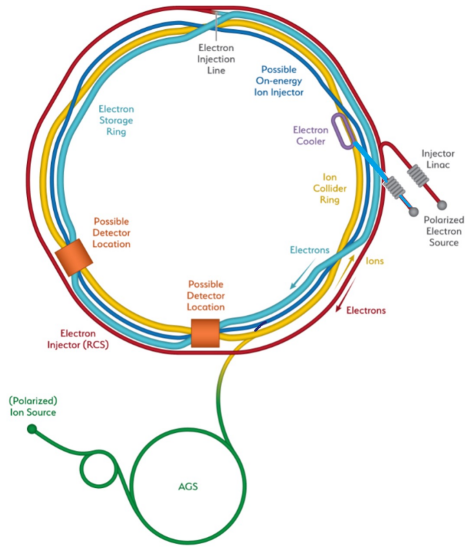
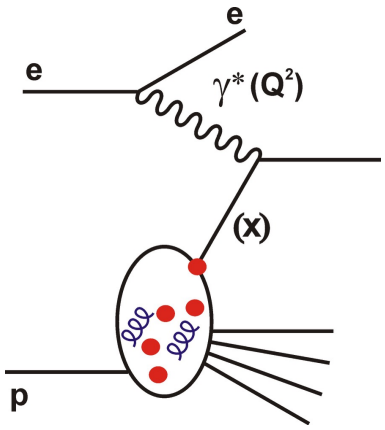
ep Collider Experiments from HERA to EIC: Synergies & Prospects

Paul Newman (Birmingham)

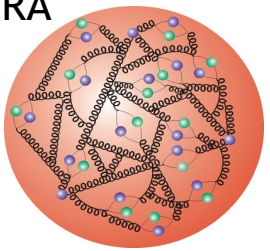




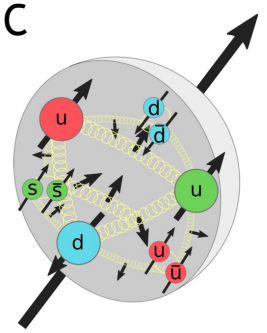
ePIC / EIC Physics Readiness Workshop, 18 March 2026

[A personal perspective driven by things I have worked on]

… the sort of talk I was giving 10 years ago,
before I started to understand how
different the EIC programme is from that of HERA



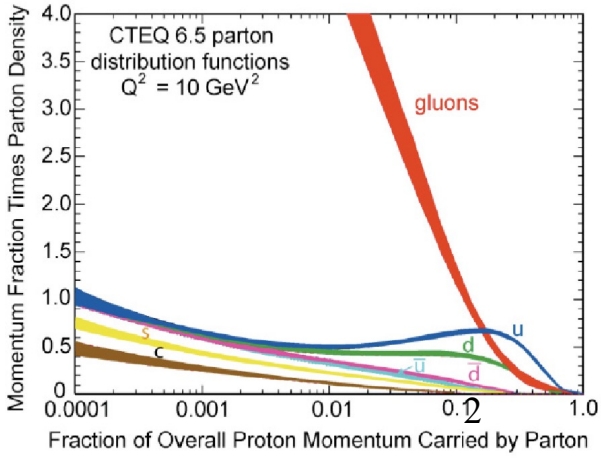
Fundamental questions for EIC



- **What does the proton look like in 3D?**
  … How is proton mass generated from quark and gluon interactions?
  … How is proton spin generated?
  … Mechanism behind confinement?

Atom: Binding/Mass = 0.00000001
Nucleus: Binding/Mass = 0.01
Proton: Binding/Mass = 100

- **How are parton properties and dynamics altered in nuclei?**
  … How do quarks and gluons interact with the nuclear medium?
  … What is the QCD-science of high density systems of gluons?
  … How is the low x growth of the gluon density tamed?



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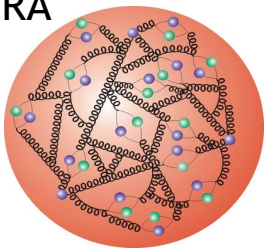

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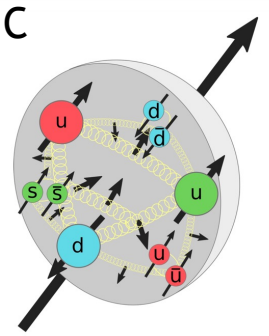

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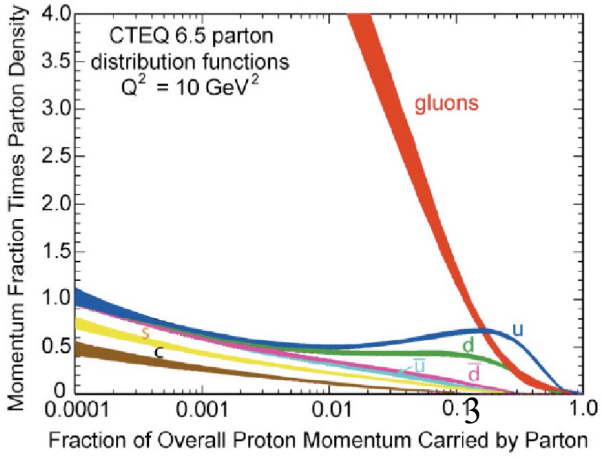
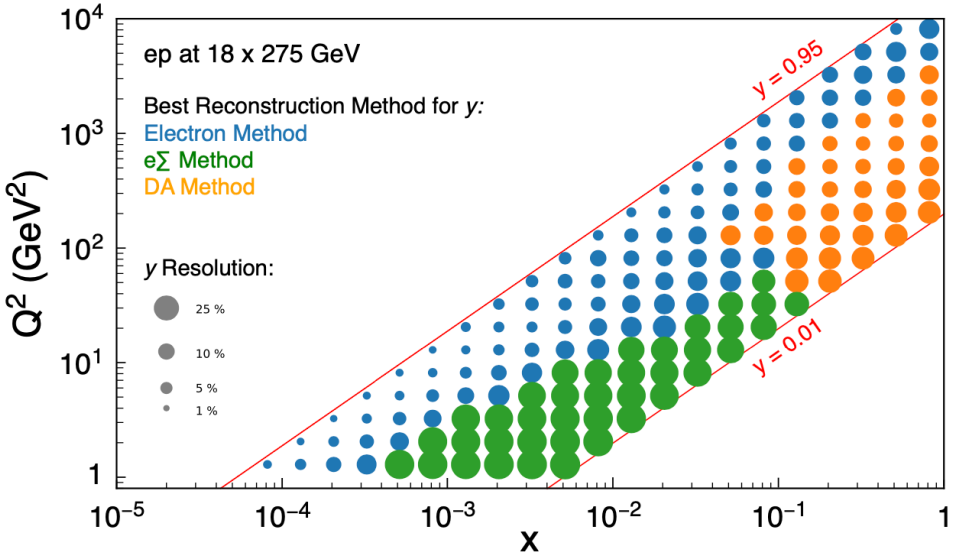


Example of Technical Evolution



- Many methods of kinematic variable reconstruction exploiting both electron and HFS developed at HERA and being applied at EIC.

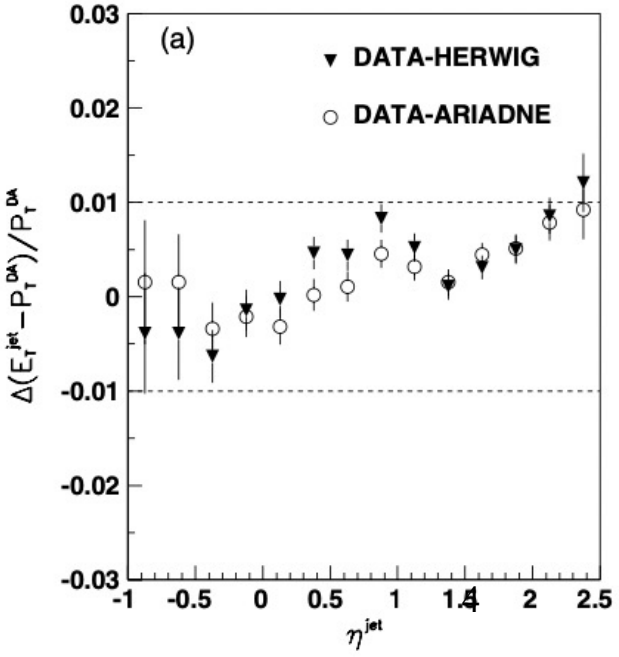
- They lead into more modern techniques involving kinematic fitting / machine learning

- This redundancy is crucial in determining systematics – eg hadronic energy scale

- <1% achieved at HERA!

- ePIC will invent ever-more clever calibration techniques, particularly at low p_T

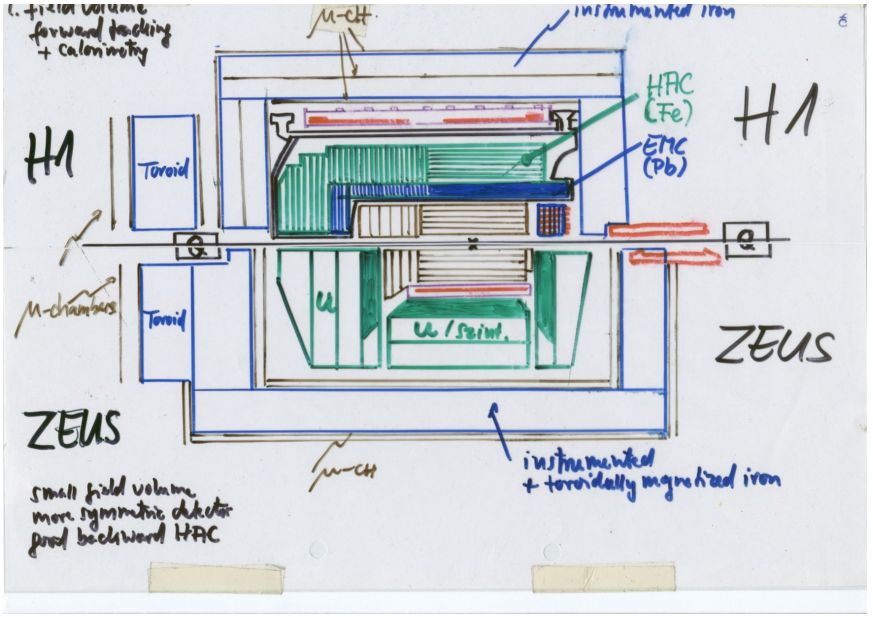
Our current assumptions on systematics are based on pessimistic extrapolations from HERA!

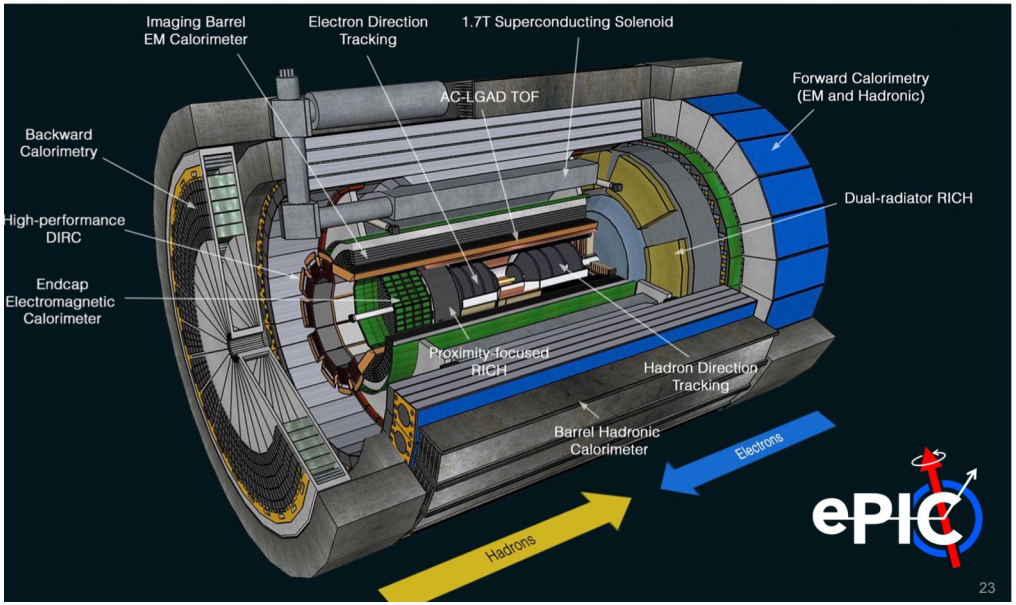


Obvious HERA - EIC Differences

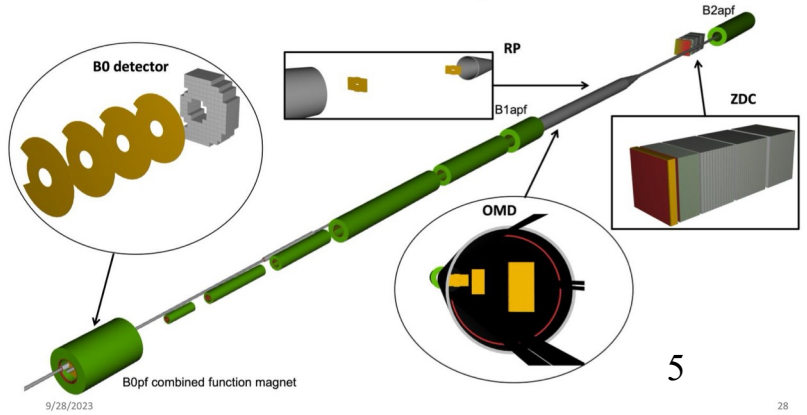
- Centre of mass energy
- Luminosity
- Polarisation of targets
- Nuclear targets
- Detector Technologies
- Forward region emphasis
- Particle ID emphasis

[F Eisele, ~ 1986]





[ePIC ~ 2026]



Crude Mapping Between Physics & Facilities

Partons with decreasing x →

[Kong Tu]

High x (Fixed Target/JLab)
Basic Structure

Intemediate x (EIC)
Emergent properties

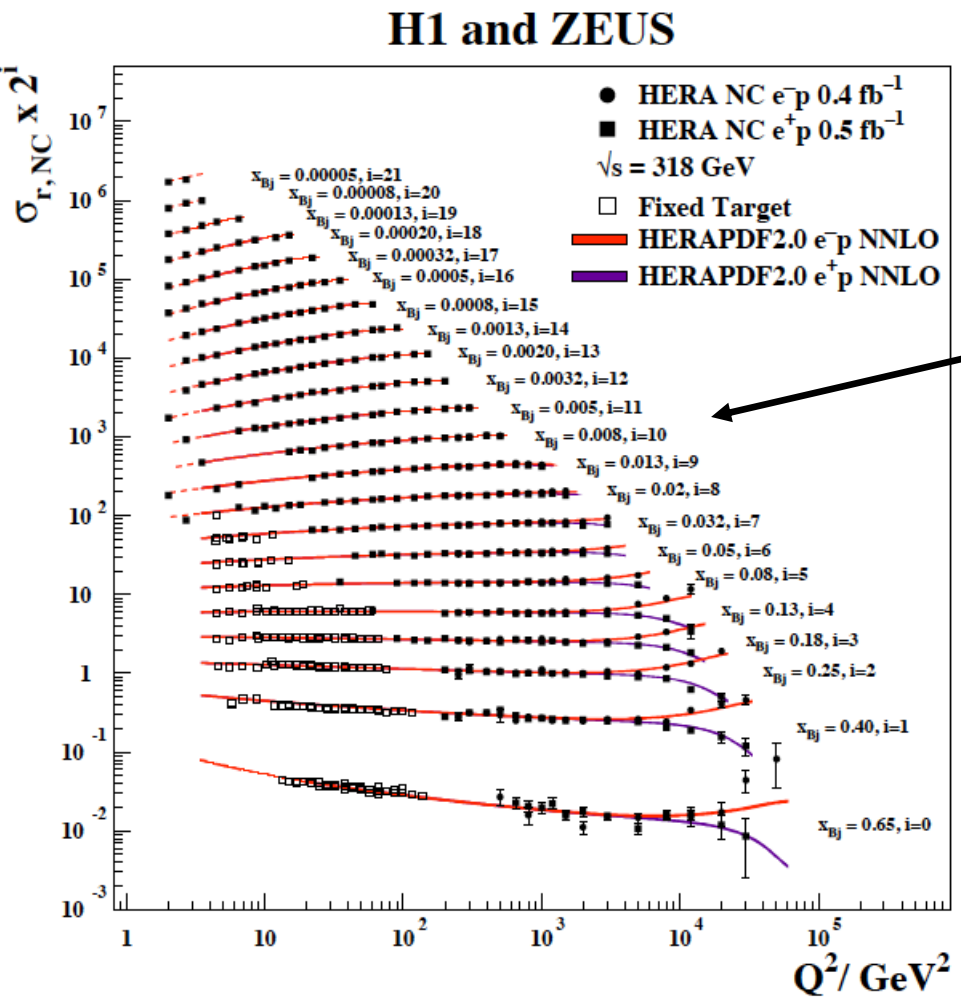
Low x (HERA / LHeC)
Non-linear dynamics

Very Low x
(LHeC,FCC-eh)
The unknown

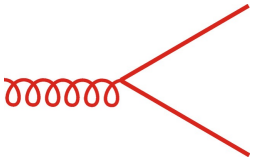
HERA Inclusive Data & Longitudinal Structure

- Photon-exchange component of NC measures quarks

$$\frac{d\sigma}{dxdQ^2} \sim F_2 = \sum_q e_q^2 \, x\,(q+\bar{q})$$



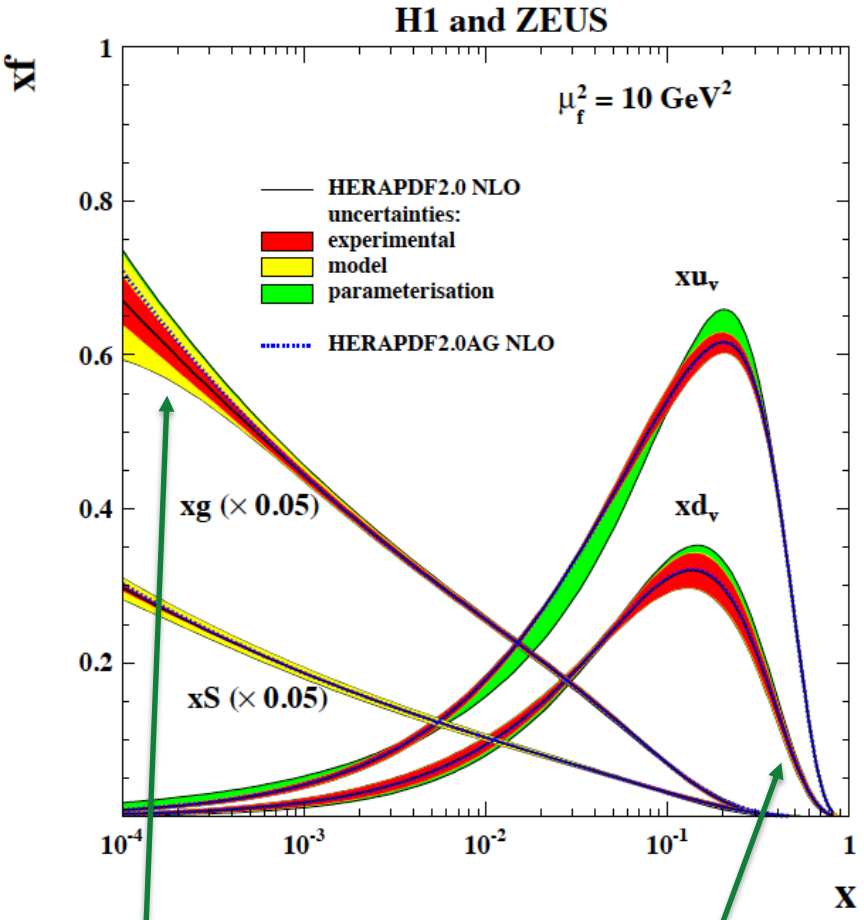
- Q^2 dependence sensitive to gluon density via splitting $g \rightarrow q\bar{q}$

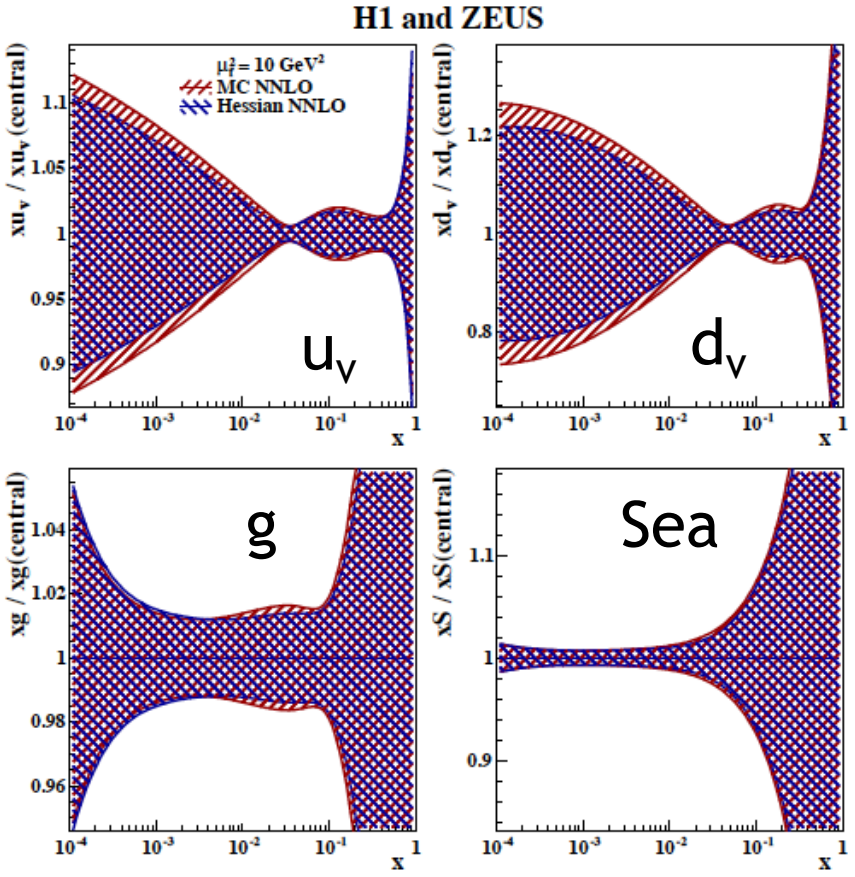


- DGLAP equations describe QCD evolution (to NNLO and approximate N³LO accuracy)

- EW effects give different quark sensitivities (Z-exchange separates e^+p v e^-p, W-exchange gives charged current ($ep \rightarrow \nu X$)

Proton PDFs from HERA only (HERAPDF2.0)



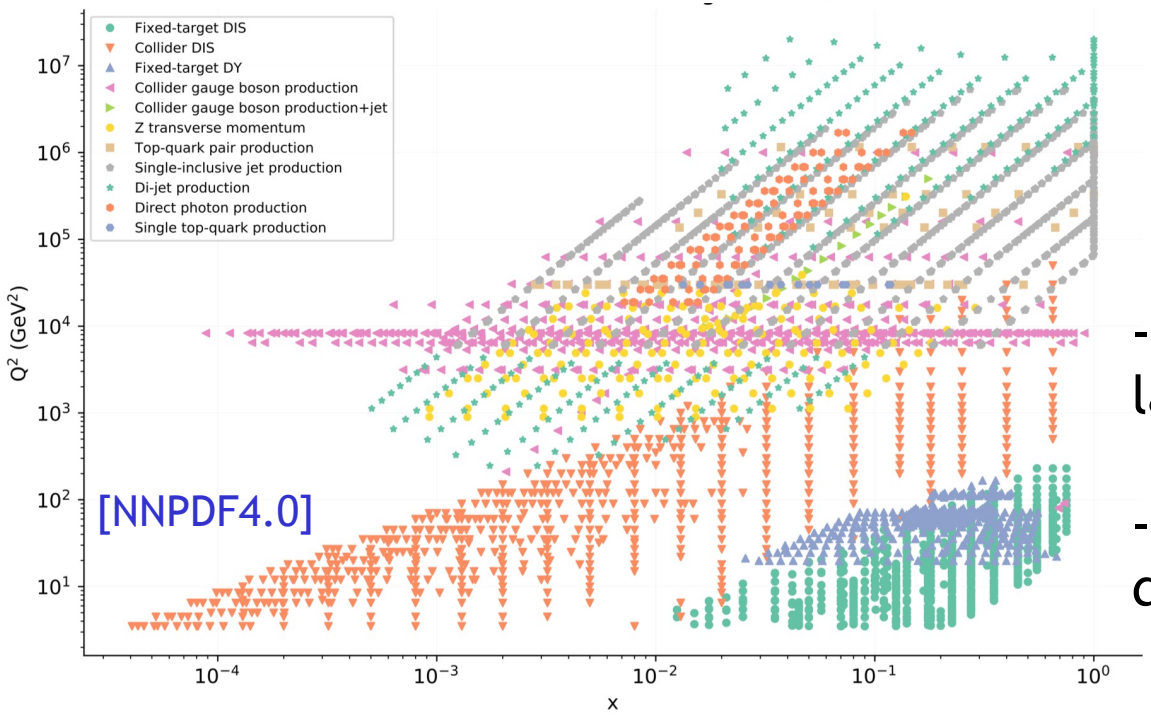


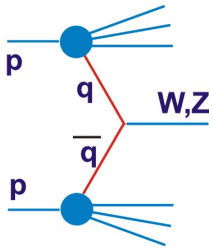
Strong interaction dragons?

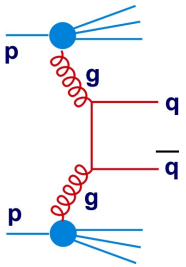
Input to energy frontier discovery?

- At x ~ 10^{-2} : ~2% gluon, 1% quark precision
- Uncertainty explodes:
  - below x=10^{-3} (kinematic limit)
  - above x=10^{-1} (limited lumi)

Constraining PDFs with LHC Data



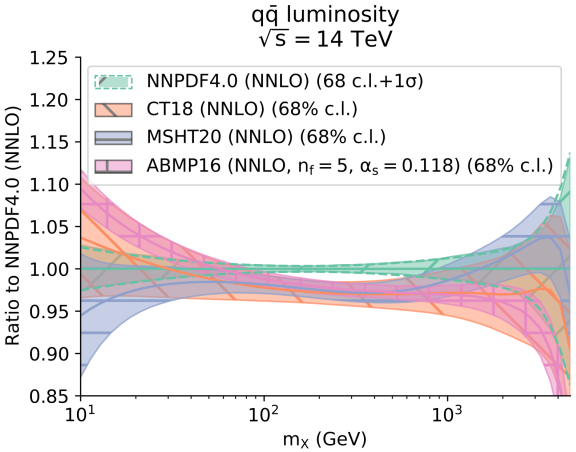


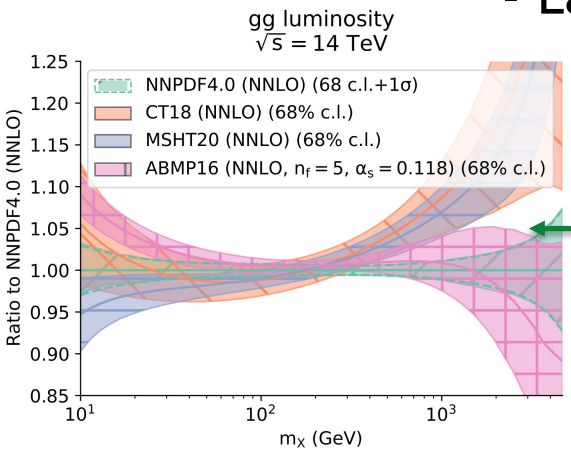


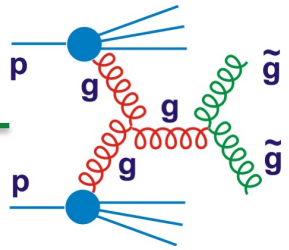
- LHC impacts PDFs mainly at large x & helps flavour decomp

- Not fully convergent between different global fitting groups

- Large x BSM effects can hide

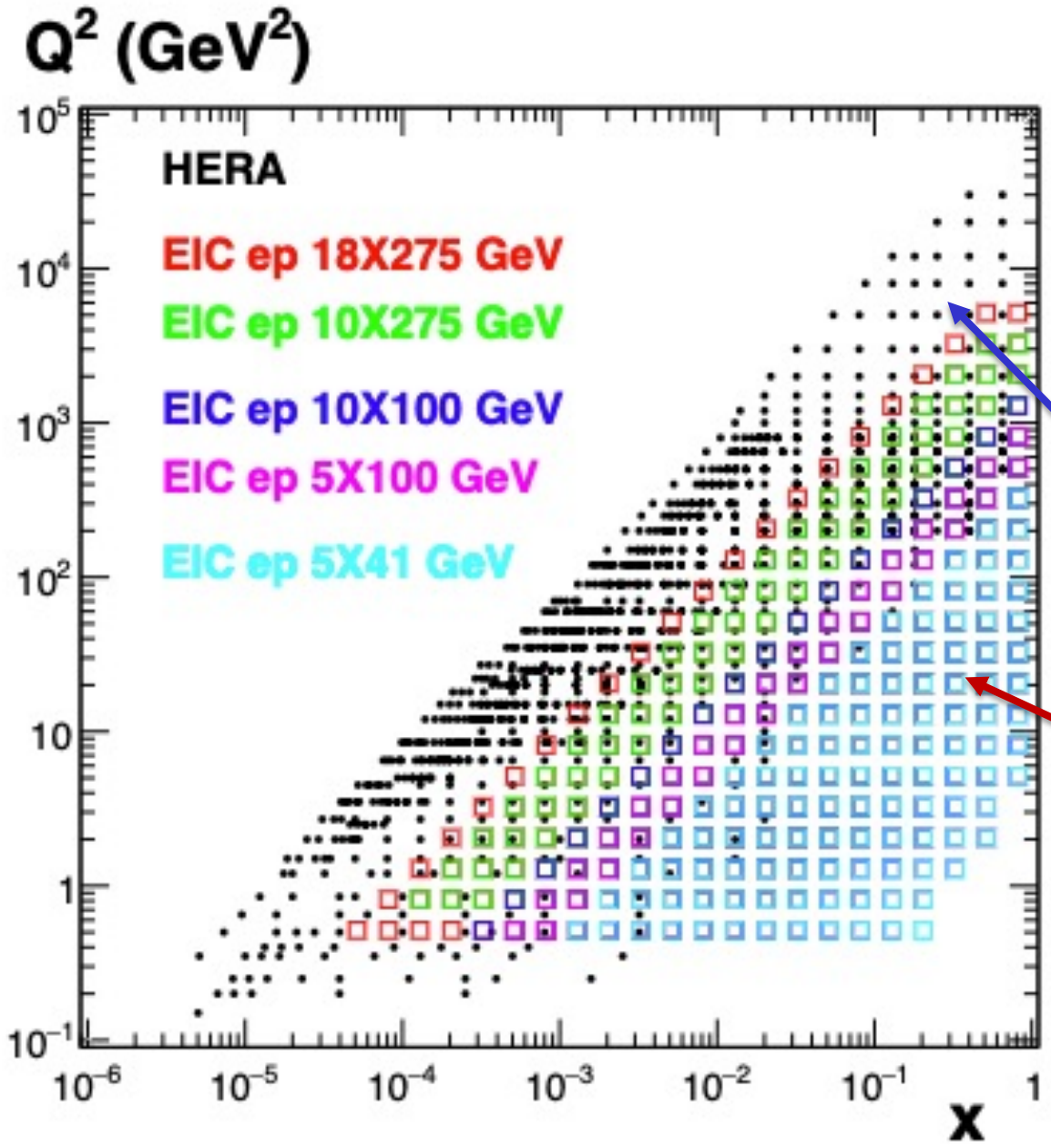






… could many of the tensions between data sets / methodologies be avoided if it were possible to constrain PDFs from DIS data only?..

Inclusive EIC Simulated Data v HERA



- Overlapping kinematic ranges at different √s fill broad x,Q^2 kinematic region without needing extreme (low y) measurements

HERA data have limited high x sensitivity due to $1/Q^4$ factor in cross section and kinematic x / Q^2 correlation

EIC data (especially lower √s configurations) fill large x, modest Q^2 region with high precision

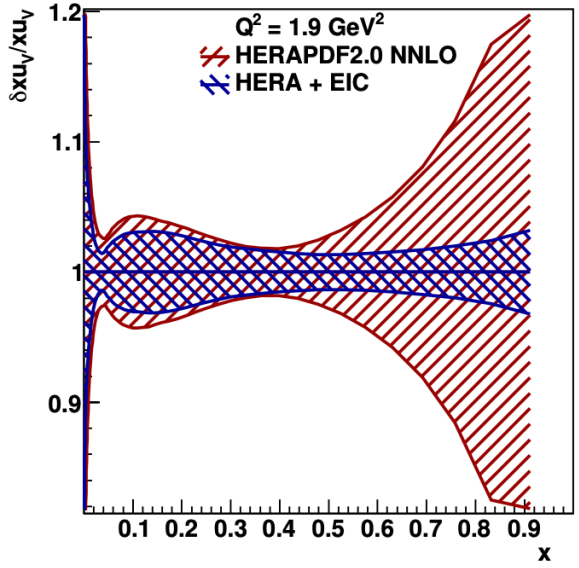
EIC Impact on DIS-only Proton Parton Densities

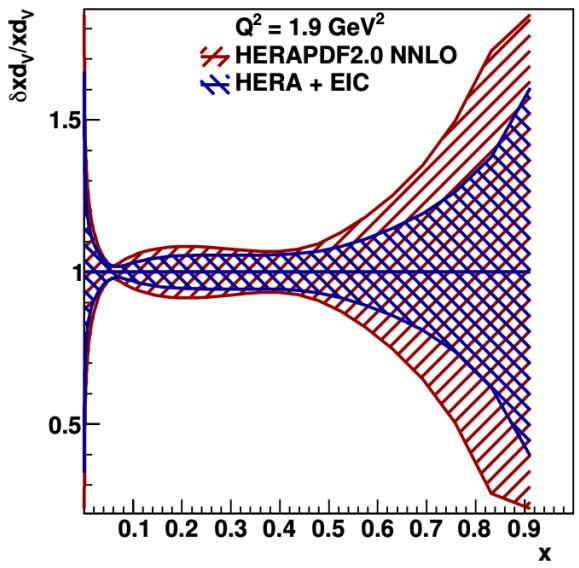
Fractional total uncertainties with / without simulated EIC data added to HERA (lin-x scale)

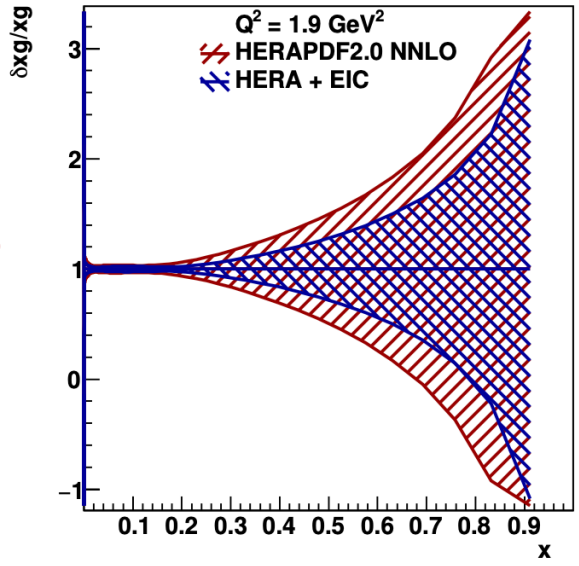
… EIC brings reduction in large x uncertainties copared with HERA for all parton species

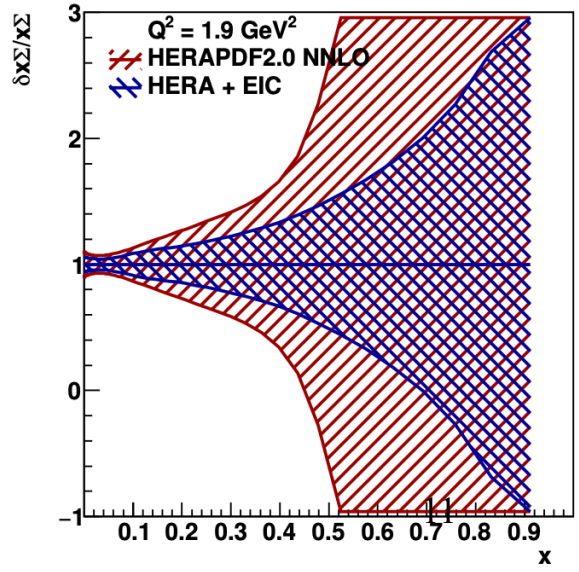
Up quarks improve relative to global fits including LHC (not shown)

This can still be relevant in (late) LHC interpretation

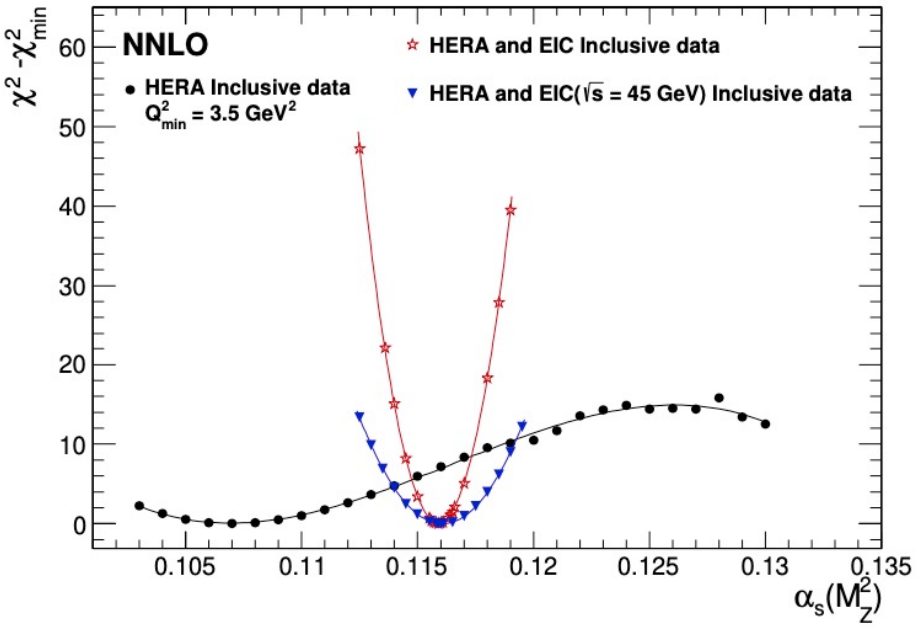








Taking α_s as an additional free parameter



- HERA data alone (HERAPDF2.0) shows only limited sensitivity when fitting inclusive data only.

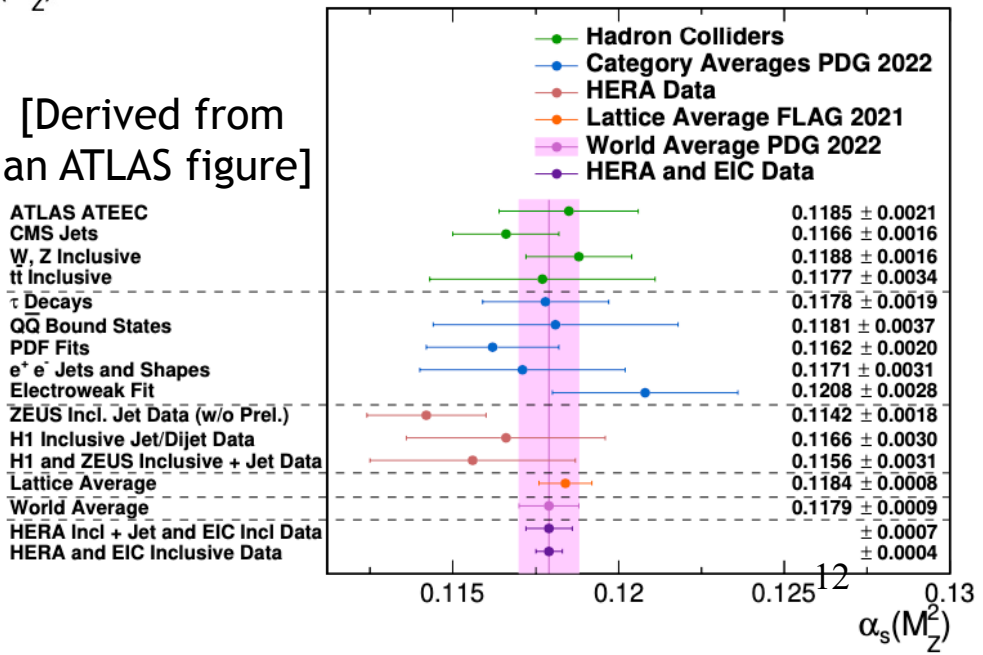
- Adding EIC simulated data has a remarkable impact

$$\alpha_s(M_Z^2) = 0.1159 \pm 0.0004\ (\text{exp})\ {}^{+0.0002}_{-0.0001}\ (\text{model} + \text{parameterisation})$$

Adding EIC (precision high x) data to HERA can lead to α_s precision a factor ~2 better than current world experimental average, and than lattice QCD average

Scale uncertainties remain to be understood (ongoing work)

[Derived from an ATLAS figure]



F_L as a powerful additional observable

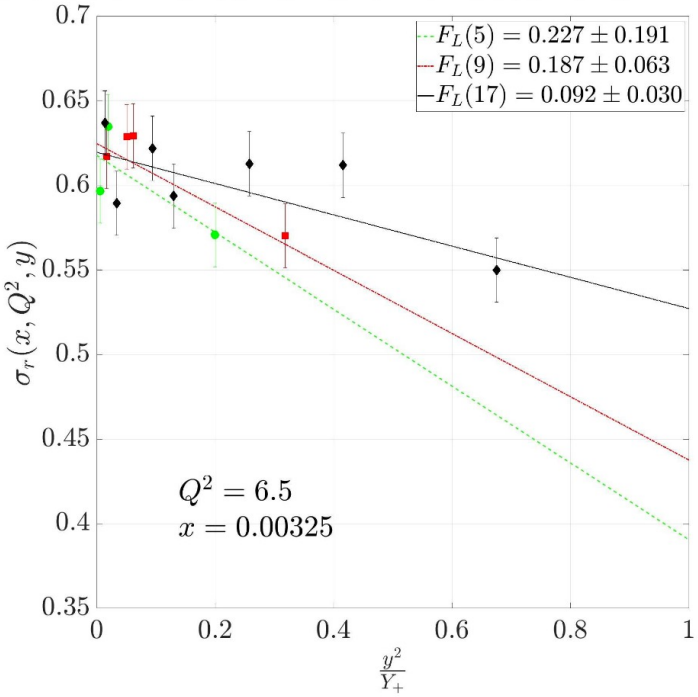
$$\sigma_r(x, Q^2, y) = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

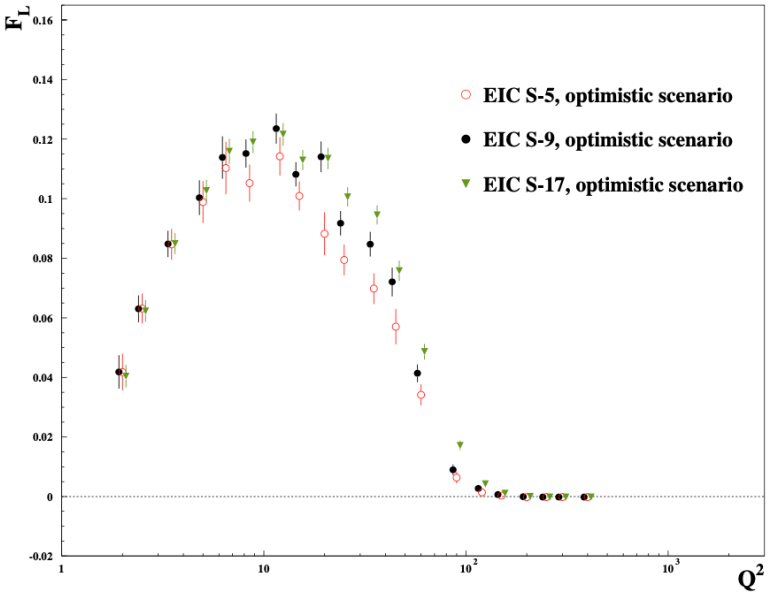
- Cross section measurements at high y are sensitive to F_L as well as F_2

- F_L vanishes in QPM
- Sensitive to low x gluon density in QCD
- Complementarity / opportunity to see tensions in theory eg due to saturation (applying to eA will be very interesting)

- Measurement at same (x,Q^2) but varying $\sqrt{s}$ (hence y) sensitive to F_L (Rosenbluth)
- Precision strongly dependent on statistical uncertainties and systematics that are uncorrelated between different $\sqrt{s}$

- Experimentally challenging, but multiple beam energy configurations at EIC





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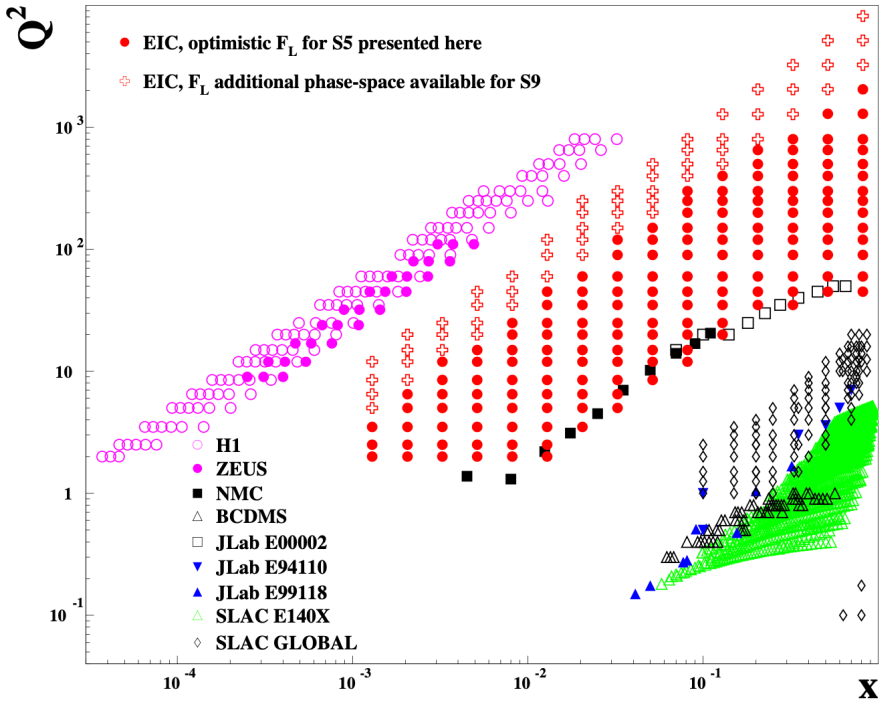
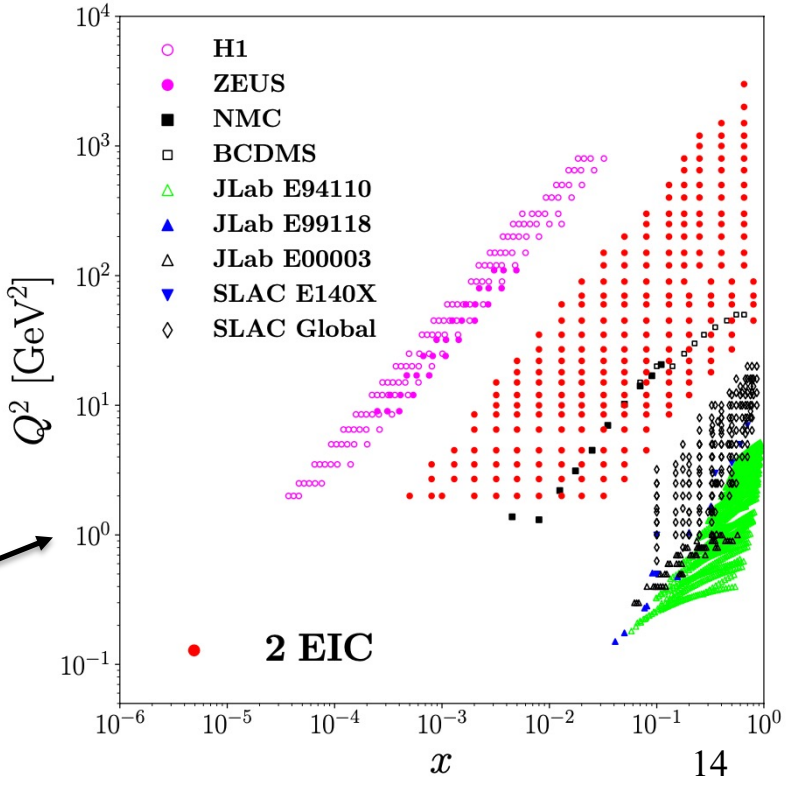


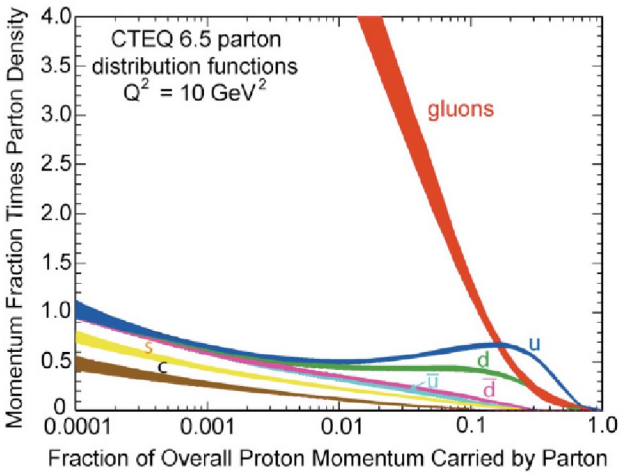
Full EIC assumptions

Complementary ep phase space to HERA and fixed target studies

ESR studies (Stephen Maple's talk)



New Dynamics in Dense Parton Systems?



- HERA just about saw ln 1/x effects?
- Large effects in inclusive EIC ep unlikely, but possibly from tension with F_L or final states

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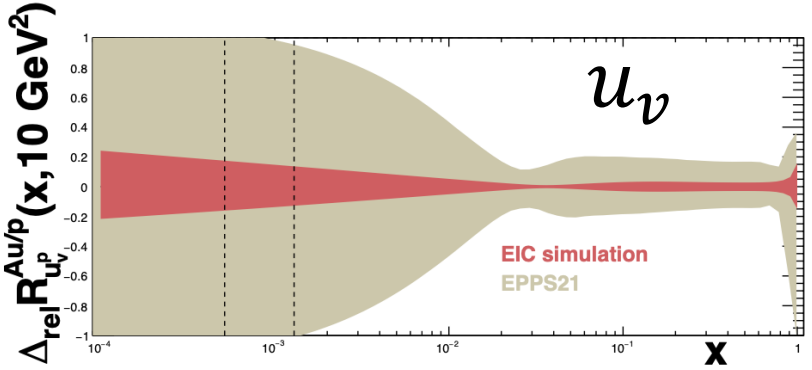
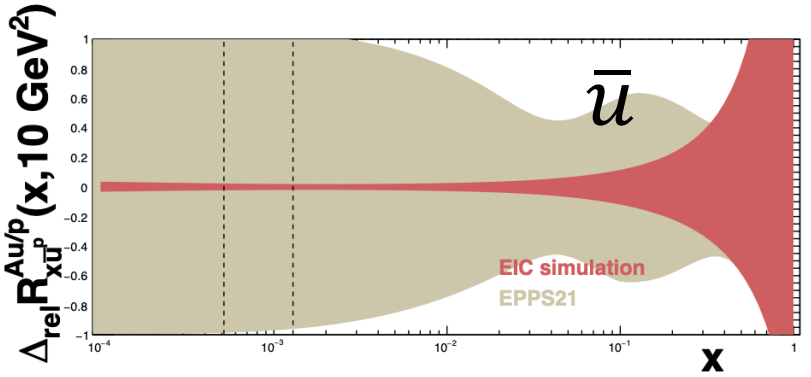
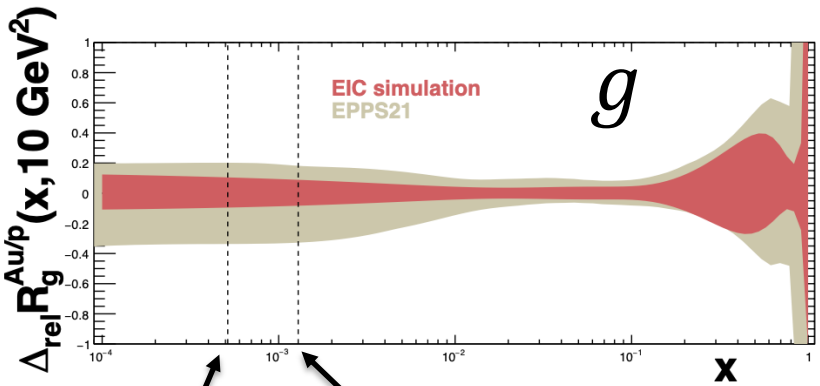
- Much more promising in nuclei

Sensitivity of EIC-alone relative to EPPS21 global fits (include LHC pA)

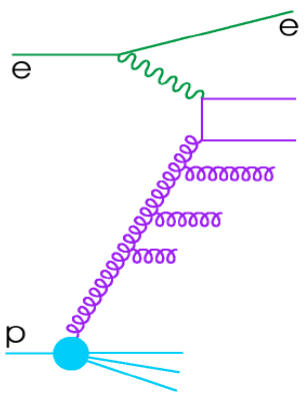
→ Factor ~ 2 improvement at x~0.1
→ Very substantial improvement in newly accessed low x region

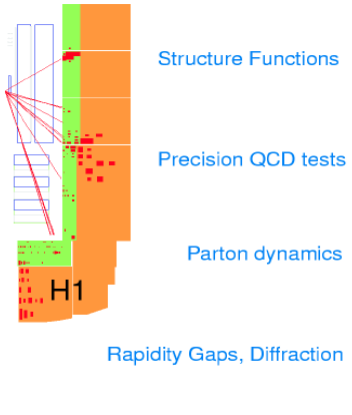






The Hadronic Final State / Semi-Inclusive

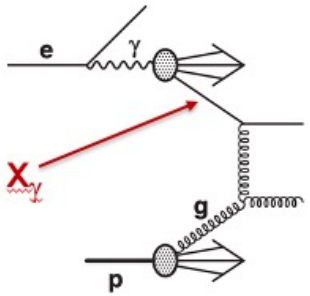


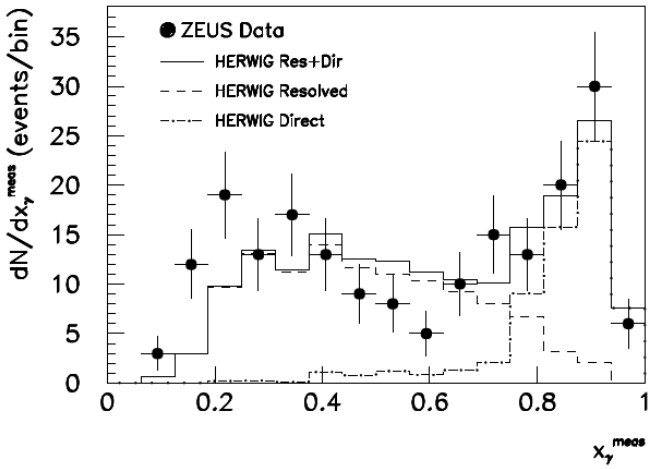


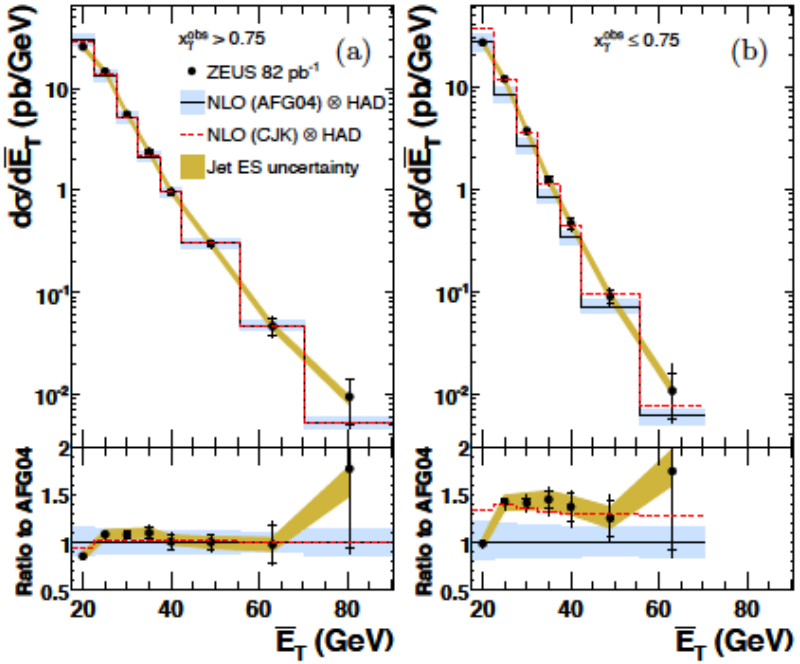
- HERA collider experiments emphasised precision jet and charm measurements as tests of pQCD and low x dynamics

- Somewhat different from our focus on TMDs → 3D structure, flavour decomp.

- Is photon structure under-represented In EIC physics - both in its own right and for understanding our EIC hard probe data? [Frank Krauss et al]



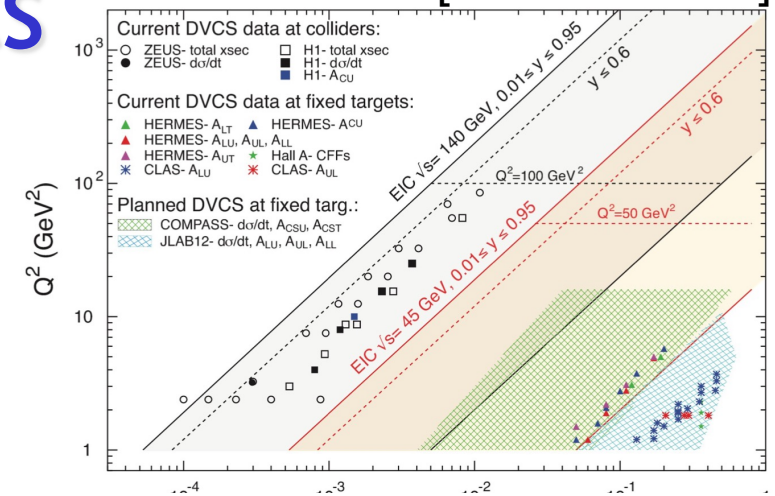




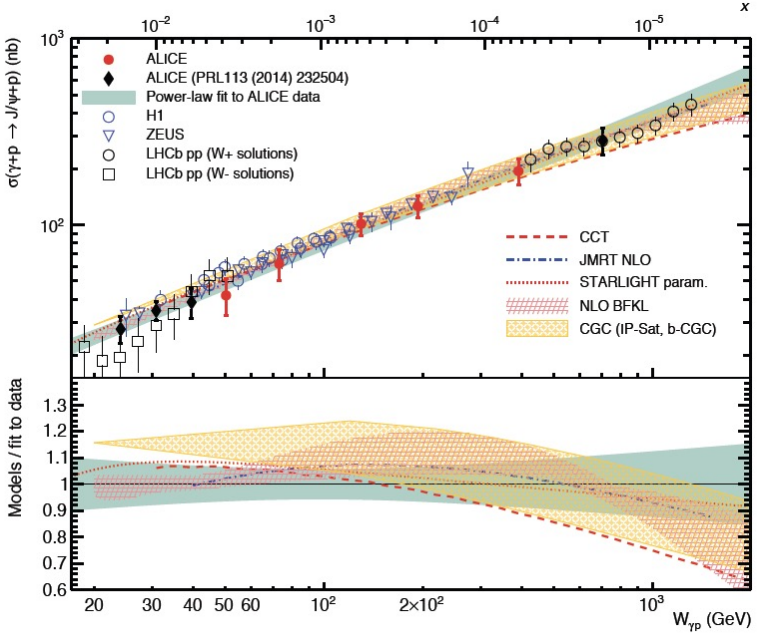
Exclusive Diffraction & DVCS

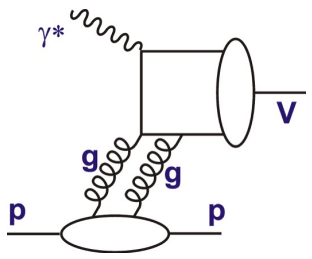
[arXiv:1304.0077]

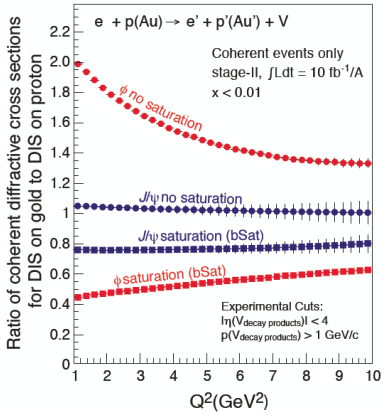
- H1/ZEUS were lumi-limited in e.g. DVCS, but they did establish pQCD treatments of vector Mesons
  - → proton size (t dependence / B slopes)
  - → scaling between different VM species
  - → dipole models
  - → gluon constraints (→ UPCs at LHC)

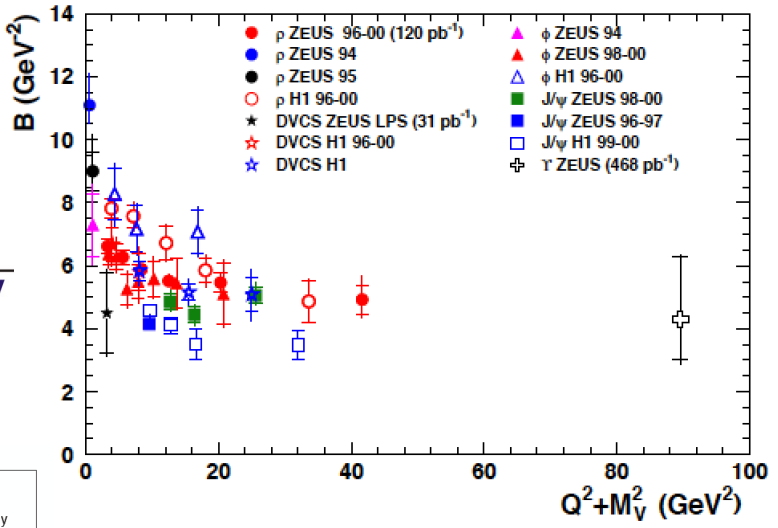


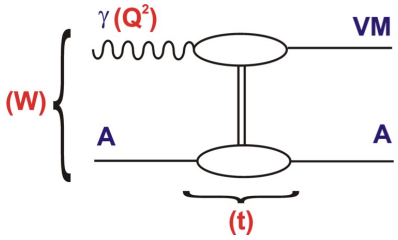
- Potentially big sensitivity to saturation from exclusive VMs in eA …



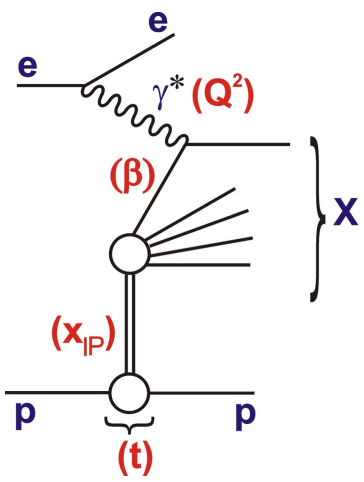








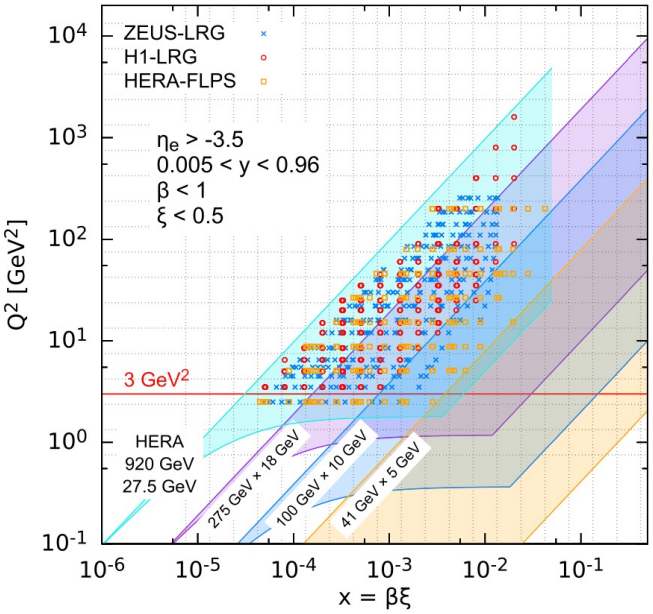
The Structure of Colourless Exchange (DPDFs)



- Inclusive diffraction was a HERA success story → diffactive PDFs

- 'Diffraction' is an asymptotically high energy process

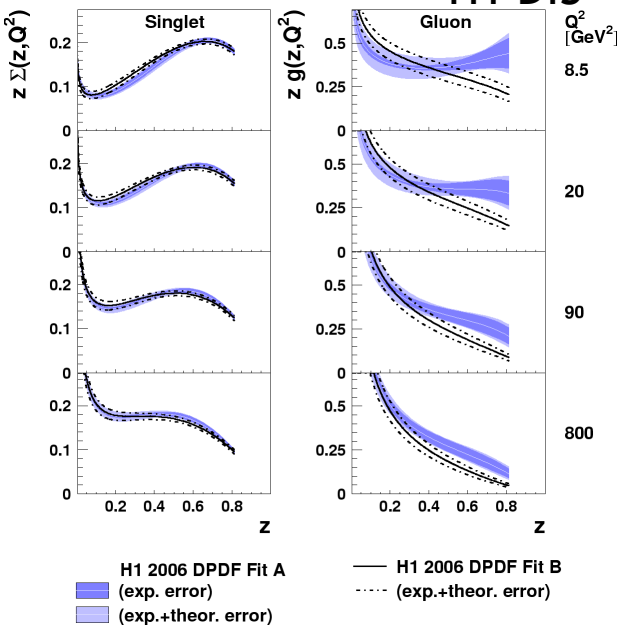
- EIC opens up completely new kinematic region (higher ξ)



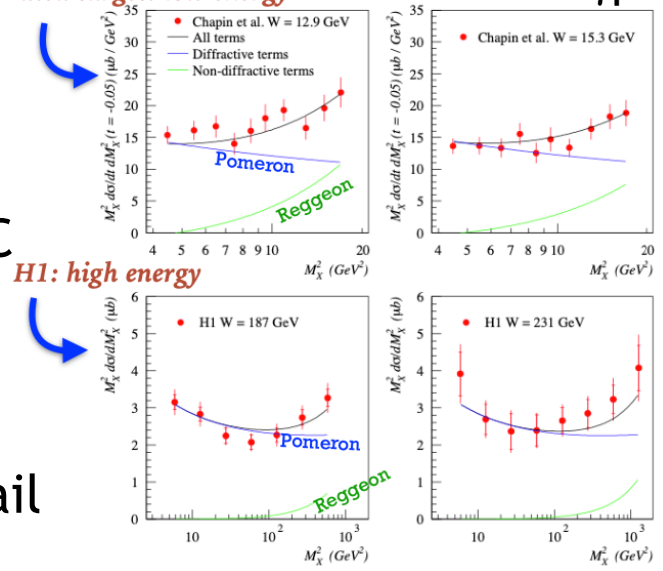
- Expect rich mixture of (possibly interfering) IP, IR, π exchange at EIC

- Unfolding offers opportunity to study meson structure in detail

H1 DIS



H1 γp

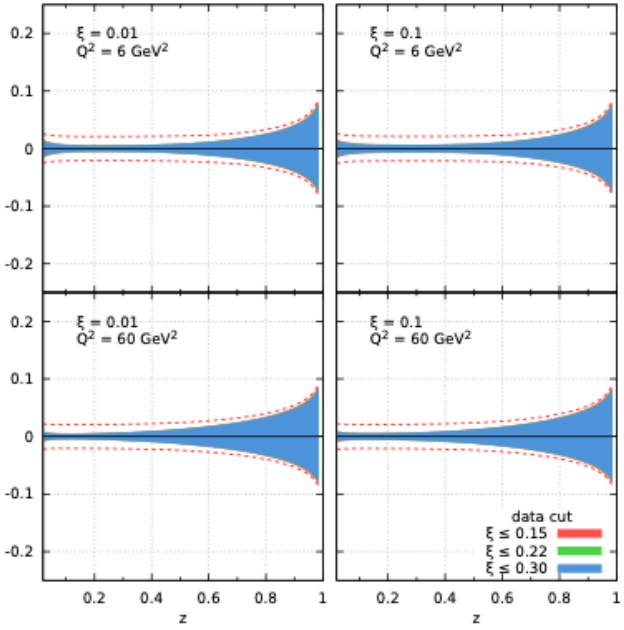


Precision on Exchanged PDFs in Sullivan Process

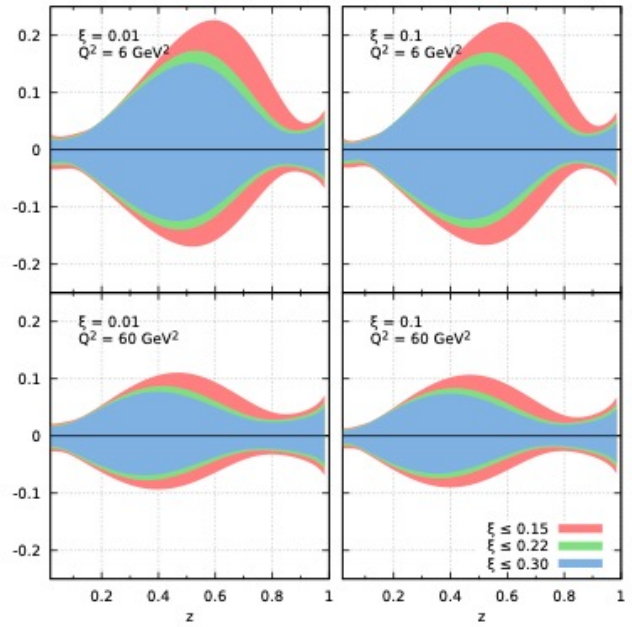
- Encouraging results in simple 2-component model (big improvement for IP and IR constrained for first time).

- Real life likely to be much more complicated (and much more interesting!)

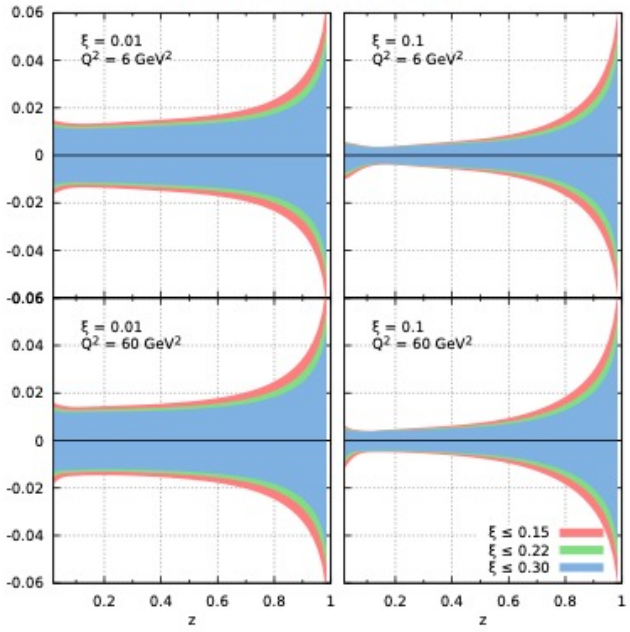
Pomeron gluon

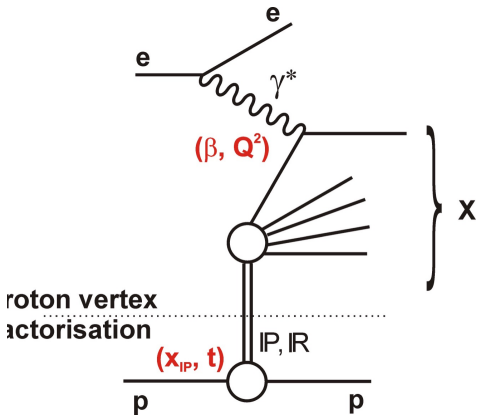


Reggeon gluon



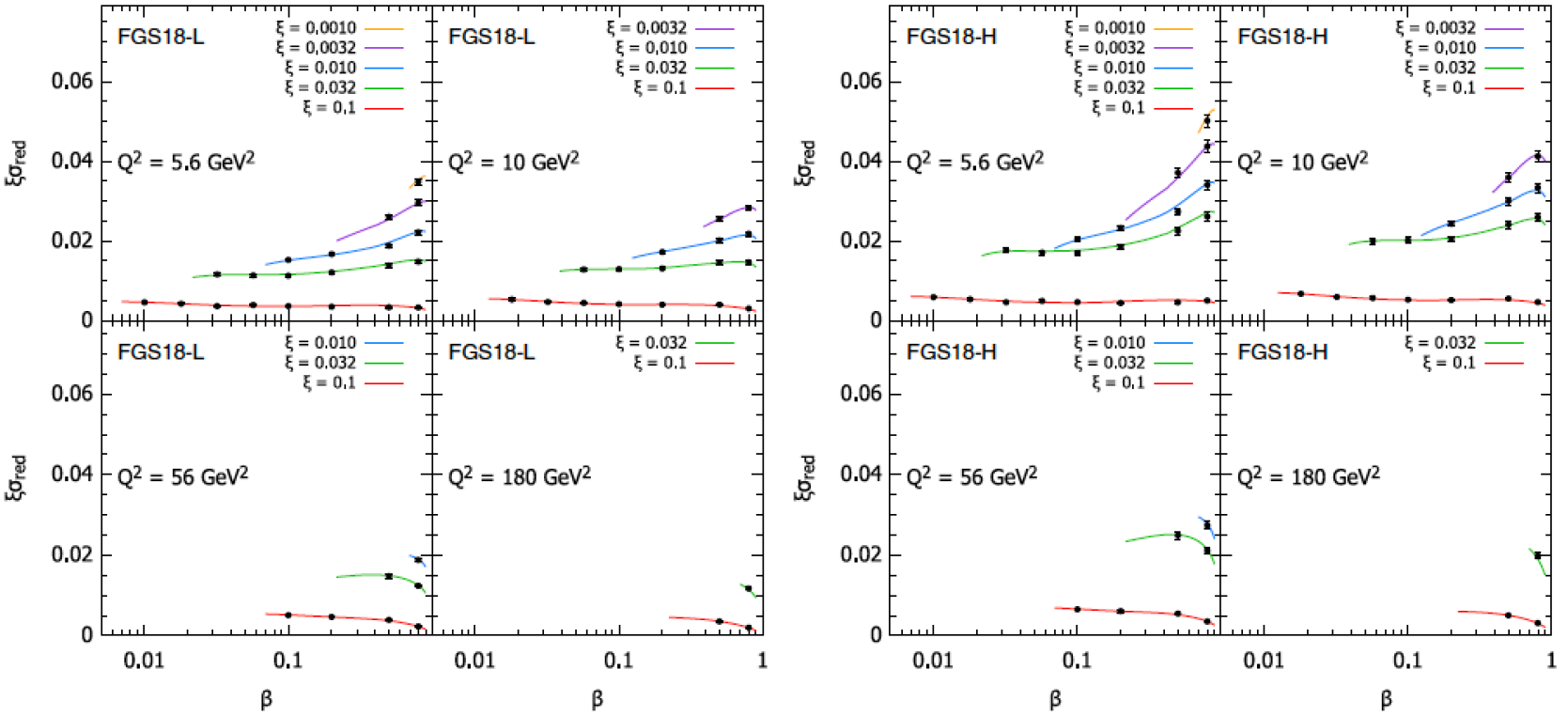
Reggeon quark





Inclusive Diffraction from Nuclei at EIC: Selected Simulated Data for e Au → e X Au

- Inclusive diffraction from nuclei never previously studied
- Comparing eA / ep may reveal non-linear (saturation) dynamics



Simulations based on 2 fb-1, 5% systematics for different versions of FGS model (H, L, with different strength colour fluctuations) → illustrates accessible kinematic range & ability to distinguish widely varying models

Thanks for the Excellent Workshop

Sources

- The Hadronic Final State at HERA [1308.3368]
- Combination of Measurements of Inclusive Deep Inelastic ep Scattering Cross Sections and QCD Analysis of HERA Data [1506.06042]
- Inclusive diffraction in future ep and eA colliders [1901.09076]
- EIC Yellow Report [2103.05419]
- Diffractive longitudinal structure function at Electron Ion Collider [2112.06839]
- Extraction of the strong coupling with HERA & EIC inclusive data [2307.01183]
- Impact of inclusive electron ion collider data on collinear parton Distributions [2309.11269]
- Extracting the partonic structure of colorless exchanges at the Electron Ion Collider [2406.02227]
- Prospects for measurements of the longitudinal proton structure function F_L at the Electron Ion Collider [2412.16123]
- The impact of inclusive electron ion collider data on the strong coupling determination in a global PDF fit [2512.06092]
- Inclusive electron-proton measurement prospects in the Electron-Ion Collider early science stage [2602.00860]