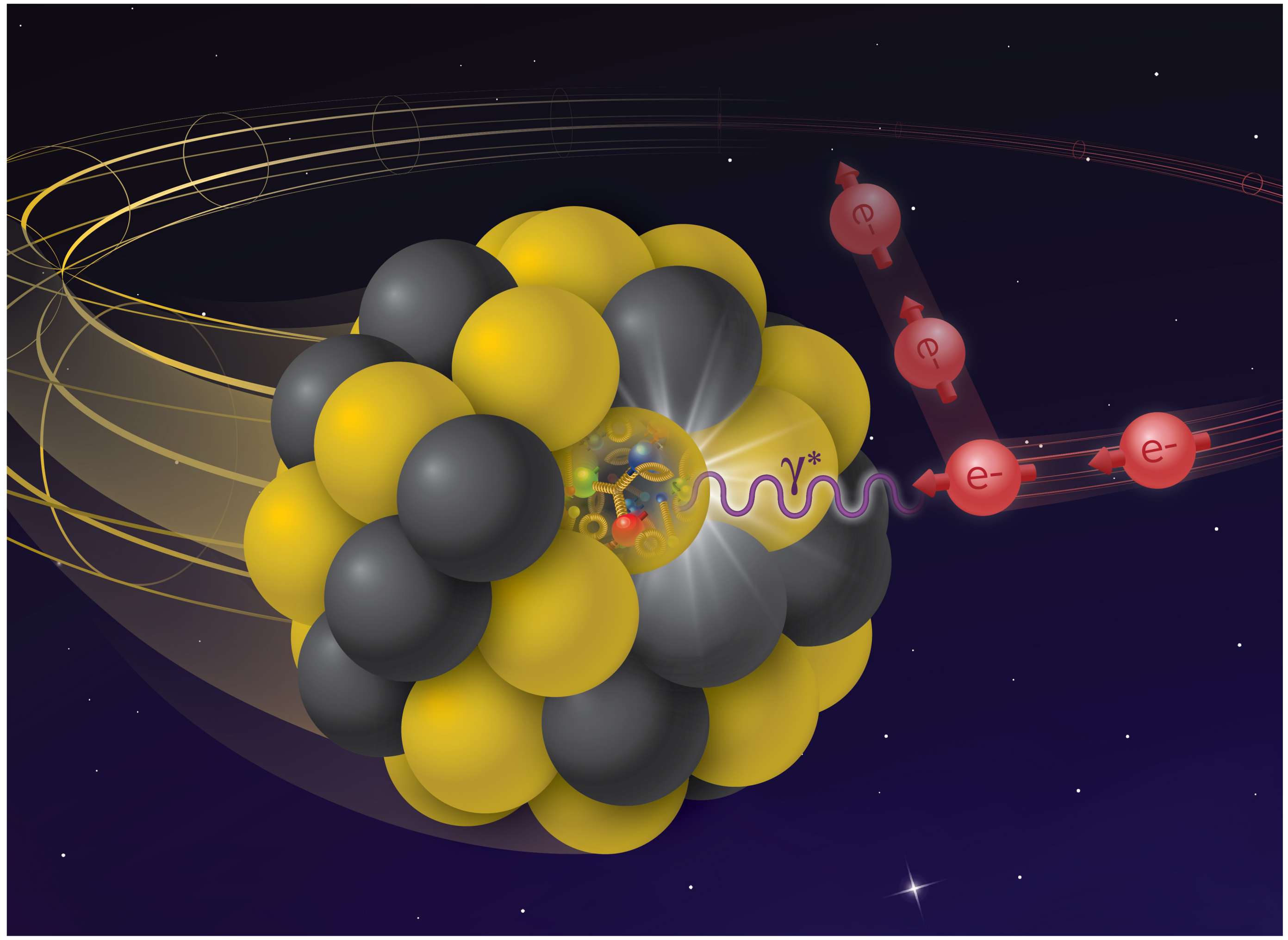


Theory perspective on the EIC physics program

with focus on questions related to structure functions, parton evolution and inclusive diffraction

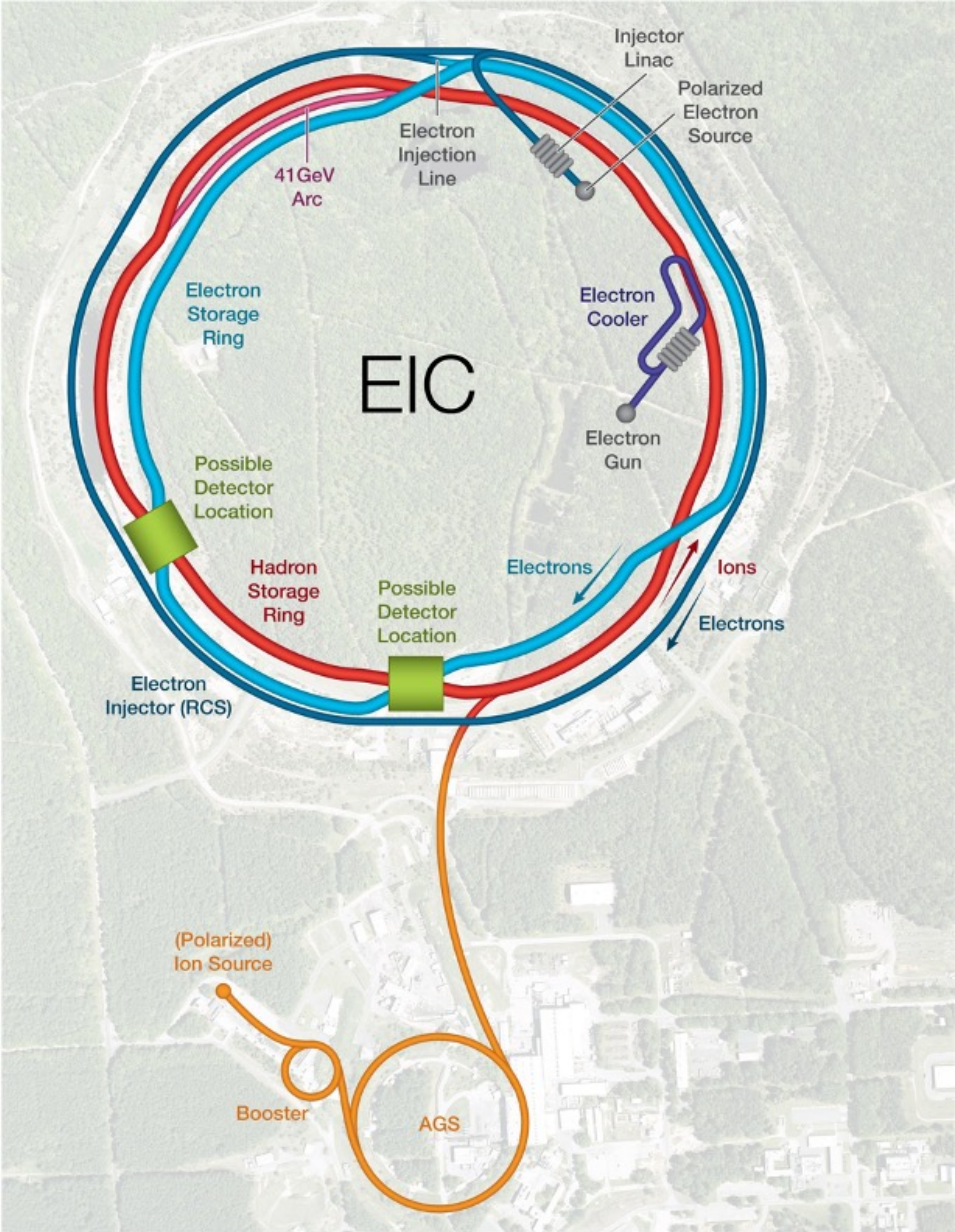
Anna Staśto

Penn State University

What is EIC ?

EIC: **E**lectron-**I**on **C**ollider facility that will be built at Brookhaven National Laboratory using and upgrading existing RHIC complex.

Partnership between BNL and Jefferson Lab.



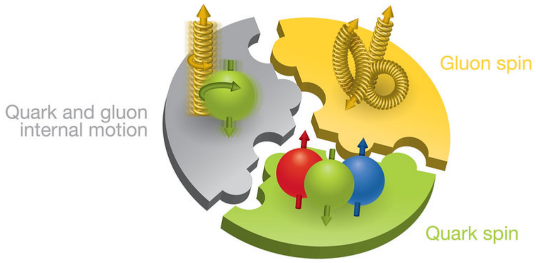
Capabilities of EIC

- **High luminosity** $10^{33} - 10^{34} cm^{-2} s^{-1}$ (100-1000 times more than HERA)
- **Variable** center of mass energies 20 -140 GeV
- Beams with different A: from **light nuclei (proton)** to the **heaviest nuclei (uranium)**
- **Polarized** electron and proton beams. Possibility of polarized light ions.
- Up to **two interaction** regions

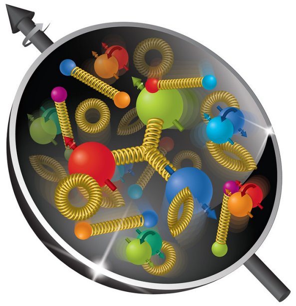
see talk by Rolf Ent

Physics questions to be explored at EIC

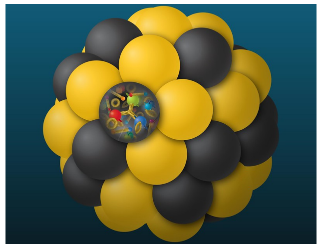
How does visible **mass** emerge from partons and their underlying interactions ?



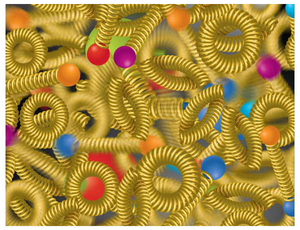
How **quark and gluon spins** and their orbital angular momentum combine in the proton **spin** ?



How are partons inside the nucleon **distributed** ?

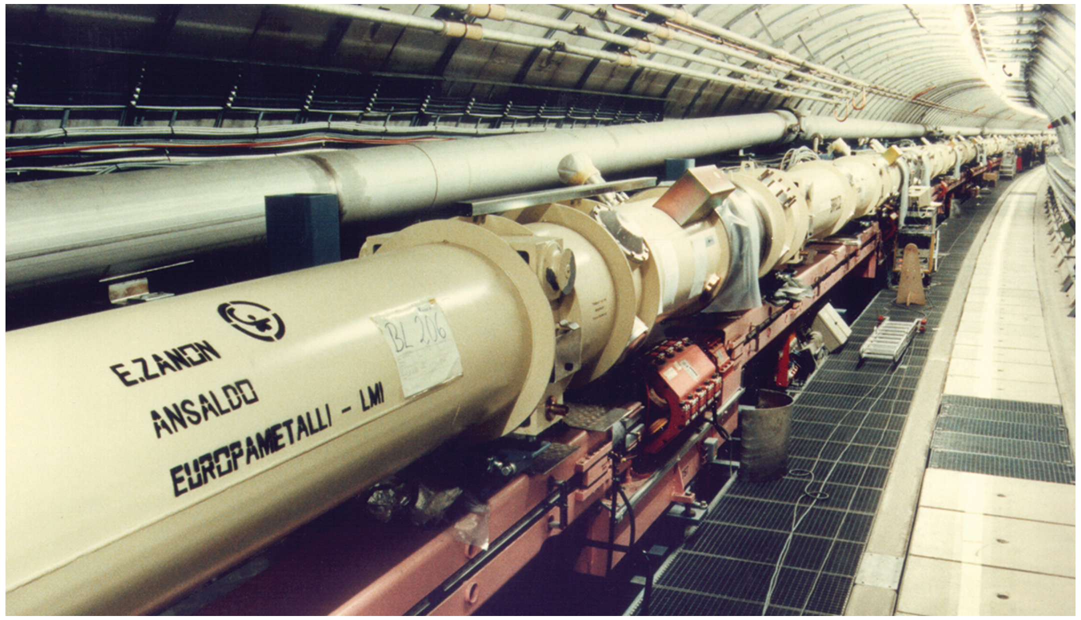


How do the quark-gluon interactions create **nuclear binding**? How do color-charged quarks and gluons, and colorless jets, **interact with a nuclear medium** ?

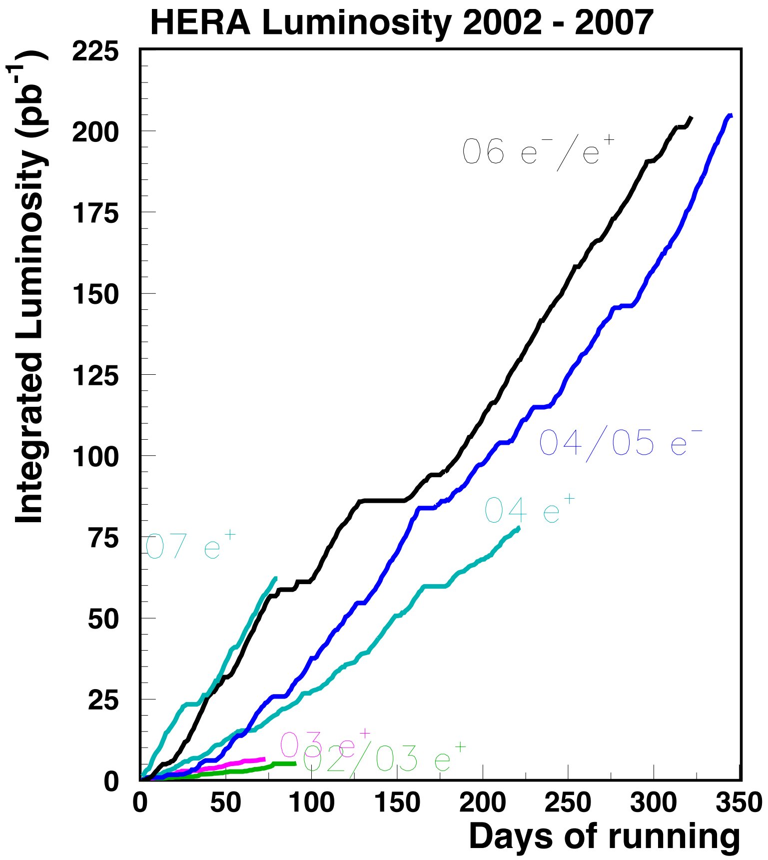


How does a **dense nuclear environment affect** the quark and gluon distributions? What happens to the **gluon density in nuclei** ? Does gluon density in a nucleus **saturate** at **high energies** ?

First electron-proton collider: HERA



HERA Hamburg 1992-2007



Theory predictions before HERA…

PHYSICAL REVIEW D VOLUME 42, NUMBER 11 1 DECEMBER 1990

Parton distributions at small *x*

J. Kwiecinski,* A. D. Martin, and W. J. Stirling
Department of Physics, University of Durham, DH1 3LE, England

R. G. Roberts
Rutherford Appleton Laboratory, Chilton, Didcot, OX11 0QX, England
(Received 24 July 1990)

We perform a next-to-leading-order QCD analysis of the recent data for deep-inelastic lepton-nucleon scattering and related processes, in which we pay particular attention to the forms of the parton distributions at very small x. We discuss in detail, and we incorporate in the analysis, the theoretical QCD results leading to the singular $x^{-1/2}$-type behavior of the gluon and sea-quark distributions, as well as the modifications due to shadowing effects. We find the QCD shadowing corrections are significant for $x \lesssim 10^{-3}$ even though the parton distributions are below their saturation limit. We give predictions for the structure functions F_2 and F_L accessible at the DESY *ep* collider HERA, and for W and Z production up to the energies of the CERN Large Hadron Collider and the Superconducting Super Collider. We discuss the possibility of experiments at these colliders probing the parton distributions in the very-small-x region.

Physics Letters B 306 (1993) 145–150
North-Holland PHYSICS LETTERS B

Parton distributions updated

A.D. Martin , W.J. Stirling
Department of Physics, University of Durham, Durham DH1 3LE, UK

and

R.G. Roberts
Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, UK

Received 12 March 1993; revised manuscript received 29 March 1993
Editor: P.V. Landshoff

We refine our recent determination of parton distributions with the inclusion of the new published sets of precise muon and neutrino deep inelastic data. Deuteron screening effects are incorporated. The $t\bar{t}$ cross section at the FNAL $p\bar{p}$ collider is calculated.

PHYSICAL REVIEW D VOLUME 47, NUMBER 3 1 FEBRUARY 1993

New information on parton distributions

A. D. Martin and W. J. Stirling
Department of Physics, University of Durham, Durham DH1 3LE, England

R. G. Roberts
Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, England
(Received 5 May 1992; revised manuscript received 28 August 1992)

PHYSICAL REVIEW D VOLUME 47, NUMBER 9 1 MAY 1993

QCD predictions for deep-inelastic structure functions at the DESY *ep* collider HERA

A. J. Askew, J. Kwiecinski,* A. D. Martin, and P. J. Sutton
Department of Physics, University of Durham, DH1 3LE, England
(Received 10 December 1992)

Perturbative QCD is used to predict the deep-inelastic electron-proton structure functions $F_{T,L}(x,Q^2)$ in the small x region ($x \sim 10^{-3}$) from an experimental knowledge of the behavior at larger x. Shadowing corrections are quantified.

Predictions based on:

- **DGLAP** evolution
- **BFKL** small x evolution
- **shadowing** corrections

Before HERA: DGLAP fits

PHYSICAL REVIEW D VOLUME 47, NUMBER 3 1 FEBRUARY 1993

New information on parton distributions

A. D. Martin and W. J. Stirling
Department of Physics, University of Durham, Durham DH1 3LE, England

R. G. Roberts
Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, England
(Received 5 May 1992; revised manuscript received 28 August 1992)

DGLAP evolution

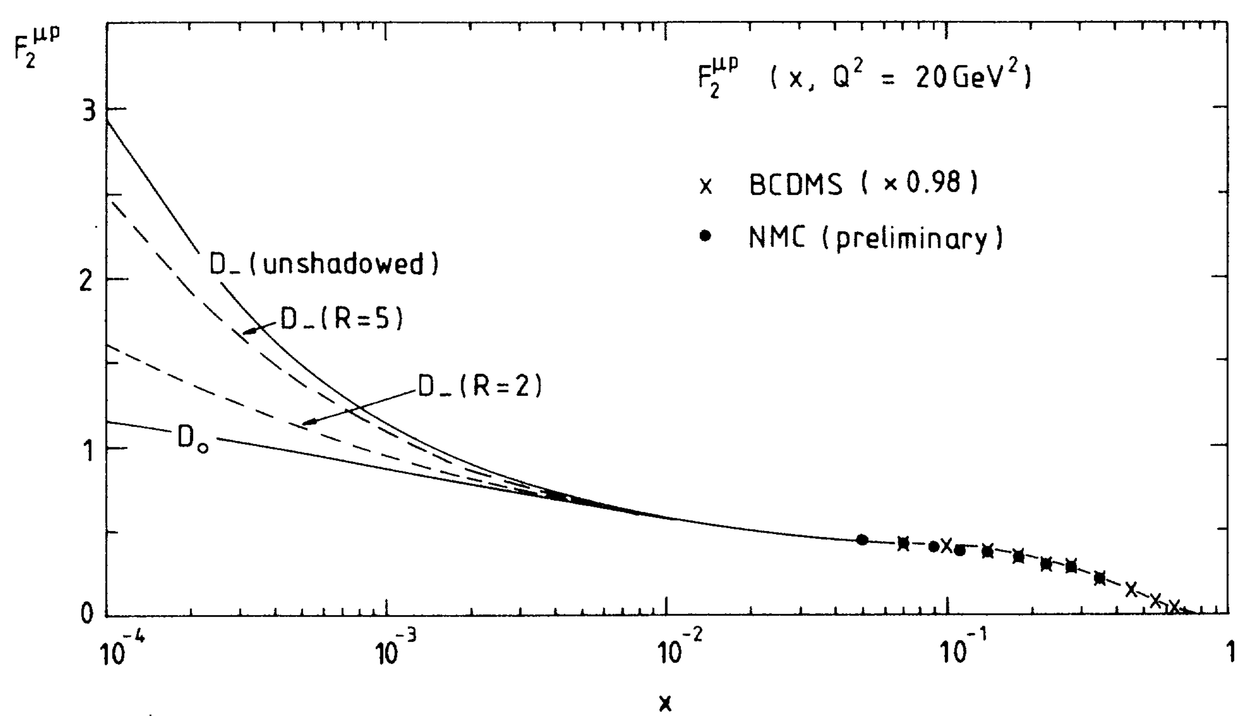
$$\mu^2 \frac{\partial}{\partial \mu^2} \begin{pmatrix} q_i(x,\mu^2) \\ g(x,\mu^2) \end{pmatrix} = \sum_j \int_x^1 \frac{dz}{z} \begin{pmatrix} P_{q_i q_j} & P_{q_i g} \\ P_{g q_j} & P_{gg} \end{pmatrix} \begin{pmatrix} q_j(\frac{x}{z},\mu^2) \\ g(\frac{x}{z},\mu^2) \end{pmatrix}$$

Initial conditions

$$xg(x,Q_0^2) = A_g x^{\delta_g} (1+\gamma_g x)(1-x)^{\eta_g}$$

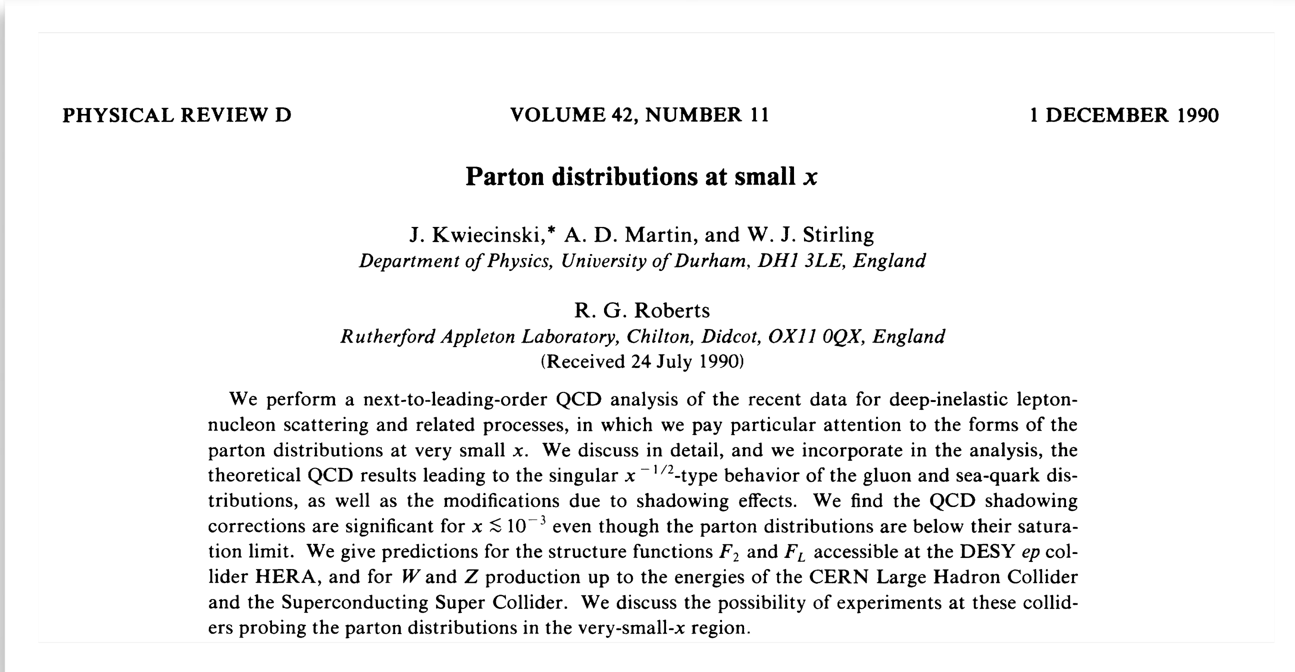
$\delta_g = 0$ $\quad D_0$ *fit*

$\delta_g = -\frac{1}{2}$ $\quad D_-$ *fit*



Of course we can already make predictions for the very small-x region based on extrapolations of our fits, but the major uncertainty arises from the assumed behavior of the gluon and sea-quark distributions. As a measure of this uncertainty we provide two possible sets of partons, one (D_0) based on "finite" gluons and sea quarks as $x \to 0$ and the other (D_-) based on singular forms $\sim x^{-\lambda}$ which have theoretical justification based on resumming soft gluon emissions. However this "Lipatov" gluon is almost certainly softened by some shadowing correction the size of which, in turn, is a matter of debate. We have therefore provided another two parton sets which choose either a conventional shadowing correction (with radius

Beyond DGLAP evolution: nonlinear corrections



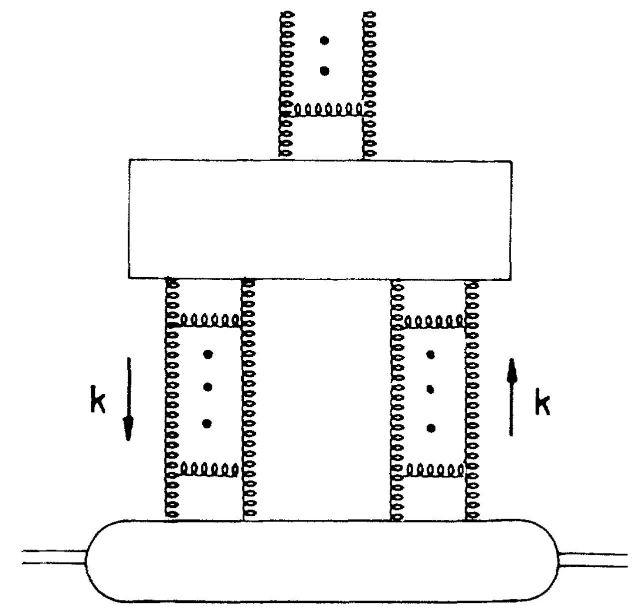
PHYSICAL REVIEW D VOLUME 42, NUMBER 11 1 DECEMBER 1990

Parton distributions at small x

J. Kwiecinski,* A. D. Martin, and W. J. Stirling
Department of Physics, University of Durham, DH1 3LE, England

R. G. Roberts
Rutherford Appleton Laboratory, Chilton, Didcot, OX11 0QX, England
(Received 24 July 1990)

We perform a next-to-leading-order QCD analysis of the recent data for deep-inelastic lepton-nucleon scattering and related processes, in which we pay particular attention to the forms of the parton distributions at very small x. We discuss in detail, and we incorporate in the analysis, the theoretical QCD results leading to the singular $x^{-1/2}$-type behavior of the gluon and sea-quark distributions, as well as the modifications due to shadowing effects. We find the QCD shadowing corrections are significant for $x \lesssim 10^{-3}$ even though the parton distributions are below their saturation limit. We give predictions for the structure functions F_2 and F_L accessible at the DESY ep collider HERA, and for W and Z production up to the energies of the CERN Large Hadron Collider and the Superconducting Super Collider. We discuss the possibility of experiments at these colliders probing the parton distributions in the very-small-x region.



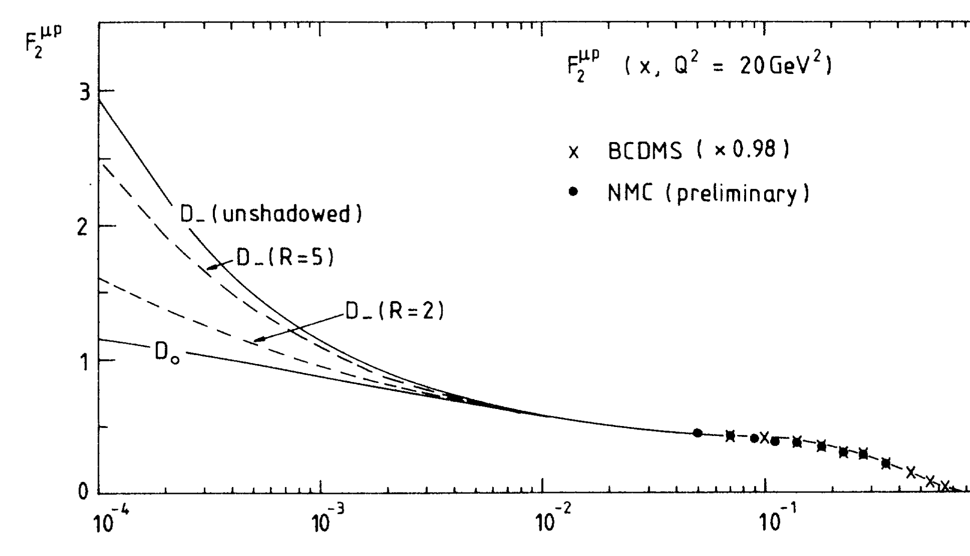
shadowing contribution to the evolution

linear terms: DGLAP evolution

$$Q^2\frac{\partial(xg(x,Q^2))}{\partial Q^2} = P_{gg}\otimes g + P_{gq}\otimes q$$

$$-\frac{81\alpha_s^2(Q^2)}{16R^2Q^2}\theta(x_0-x)\times\int_x^{x_0}\frac{dx'}{x'}[x'g(x',Q^2)]^2\,,$$

R: characteristic size arising from the integral over 4-momentum flowing along the ladders



Martin, Roberts,Stirling

First HERA data

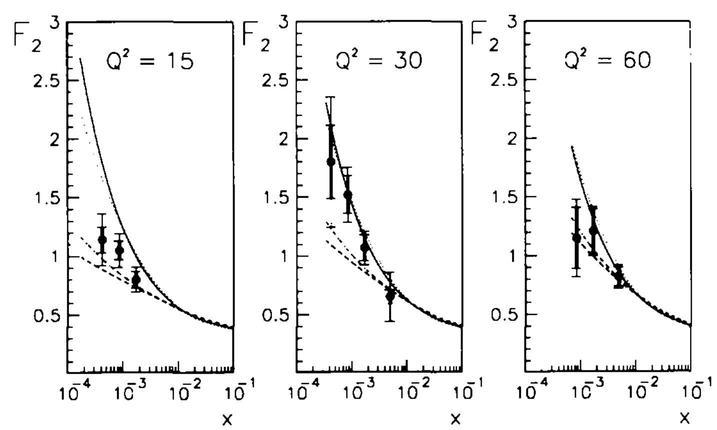
Physics Letters B 316 (1993) 412–426
North-Holland

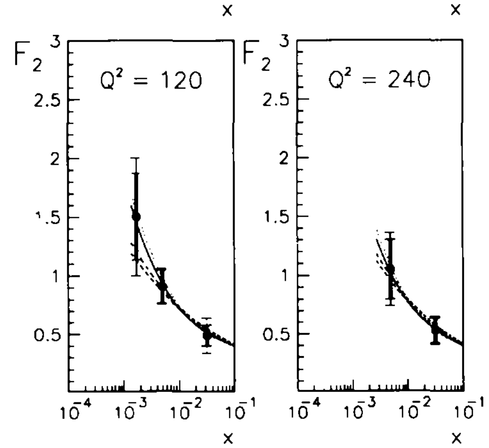
PHYSICS LETTERS B

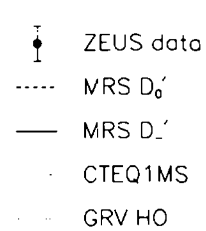
Measurement of the proton structure function F_2 in ep scattering at HERA

ZEUS Collaboration

This paper presents our first measurement of the F_2 structure function in neutral-current, deep inelastic scattering using the ZEUS detector at HERA, the ep colliding beam facility at DESY. The data correspond to an integrated luminosity of 24.7 nb^{-1}. Results are presented for data in a range of Q^2 from 10 GeV^2 to 4700 GeV^2 and Bjorken x down to 3.0×10^{-4}. The F_2 structure function increases rapidly as x decreases.







tion expectations. At the lowest Q^2 value the data points lie below the MRS D'_- [6] extrapolations and the predictions of GRV(HO) [4], but above the extrapolations of MRS D'_0 [6] and CTEQ1MS [5]. Fig. 4 shows the F_2 structure function as a function of Q^2 for fixed x. The data are in accord with the expected logarithmic violation of scaling.

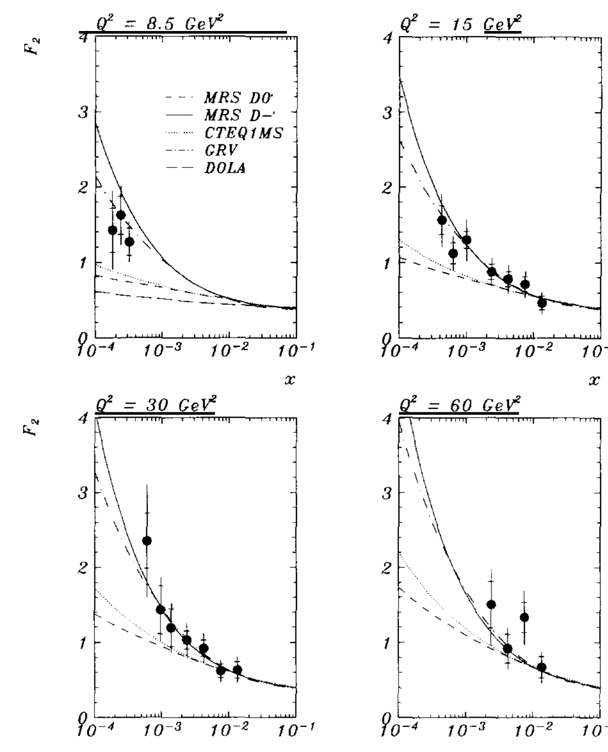
Nuclear Physics B407 (1993) 515–535
North-Holland

NUCLEAR PHYSICS B

Measurement of the proton structure function $F_2(x, Q^2)$ in the low-x region at HERA

H1 Collaboration

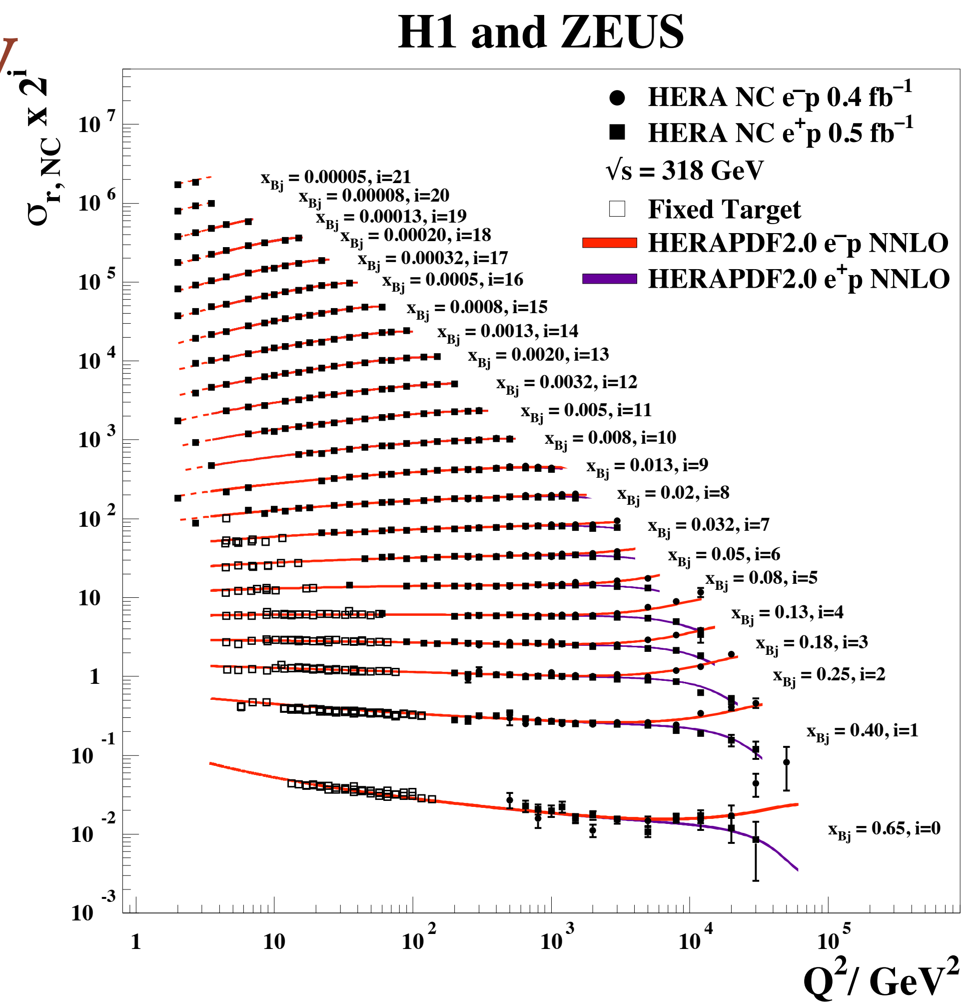
A measurement of the proton structure function $F_2(x, Q^2)$ is presented with about 1000 neutral current deep inelastic scattering events for Bjorken x in the range $x \simeq 10^{-2} - 10^{-4}$ and $Q^2 > 5\,GeV^2$. The measurement is based on an integrated luminosity of 22.5 nb^{-1} recorded by the H1 detector in the first year of HERA operation. The structure function $F_2(x, Q^2)$ shows a significant rise with decreasing x.



These parametrizations, which all describe the existing low-energy fixed-target data give F_2 values at $x \simeq 10^{-4}$ which differ by more than a factor 4. Our data are consistent with the GRV and also the MRSD−′ parametrizations. The present measurement narrows the possible range of parton densities at low x substantially, giving a much better basis to predict hard scattering processes at high-energy pp and heavy-ion colliders. Moreover, it gives guidelines for the development of a better theoretical description of the low-x region.

Implications of HERA data

HERA legacy



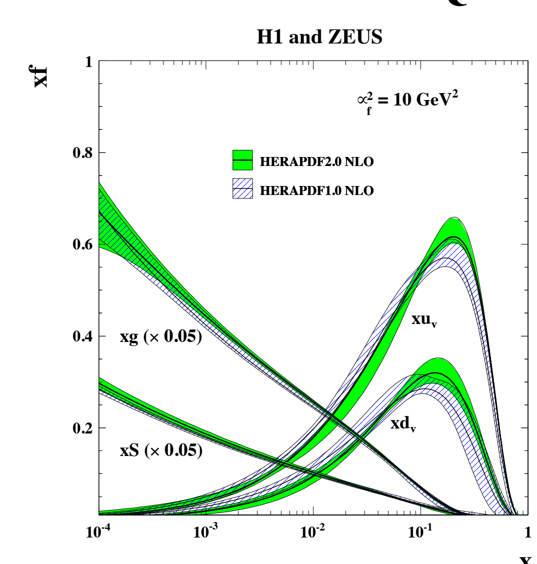
- HERA discovered steep rise of the structure function with decreasing x
- Scaling violations present
- Predictions varied by factor 4 at small x
- Extreme scenarios (flat gluon and very singular gluon) were excluded
- DGLAP works very well
- uncertainties in PDFs reduced substantially

  <u>**but**</u>
- **initial conditions in linear evolution can in principle mimic the other effects, like that of the non-linear evolution**

What does it imply for EIC ?

EIC will measure **nuclear** structure functions with great precision

Can one pin down effects due to possible nonlinear evolution in nuclear parton densities ?

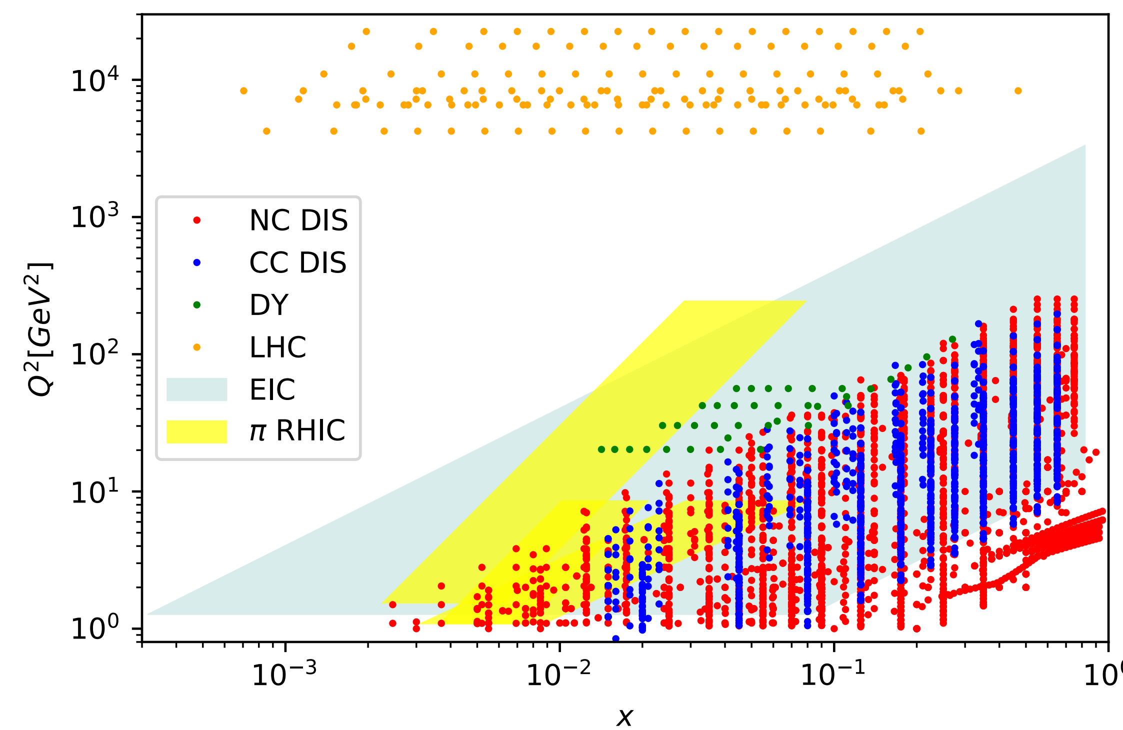


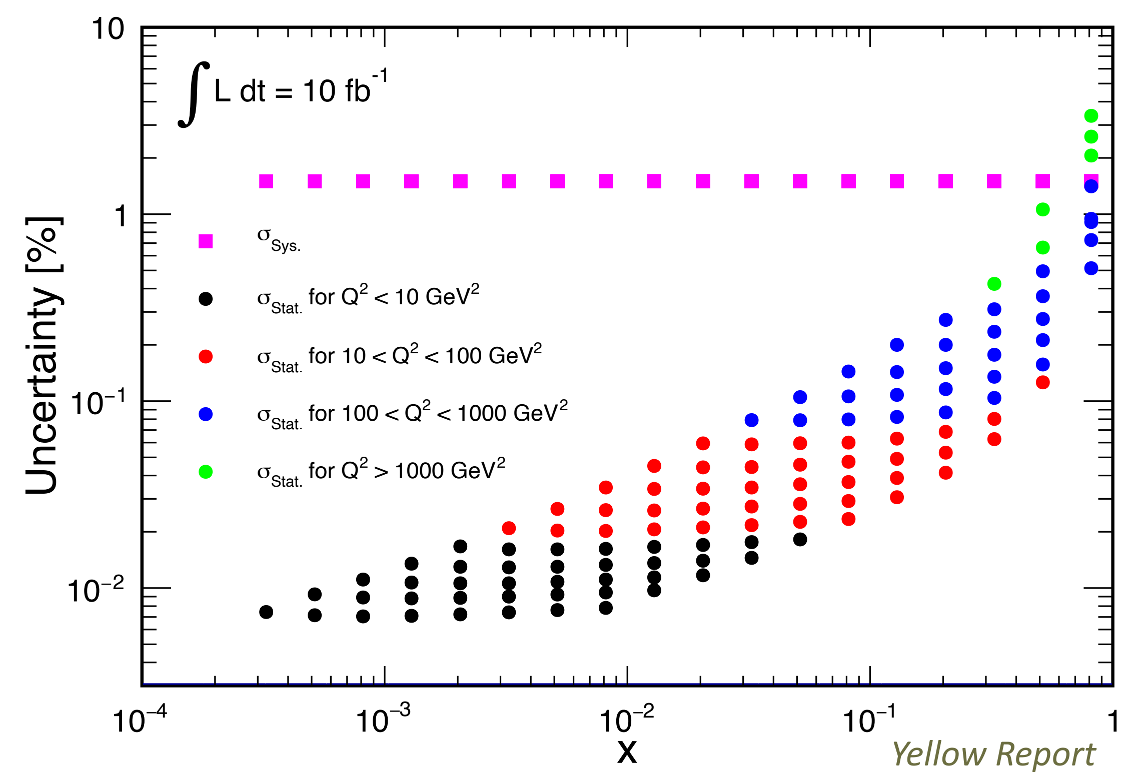
Prospects at EIC : global structure of nuclei

$$Y_+ = 1 + (1-y)^2$$

$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha_{\rm em}^2}{xQ^4}\, Y_+\, \sigma_{\rm r}(x,Q^2)$$

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

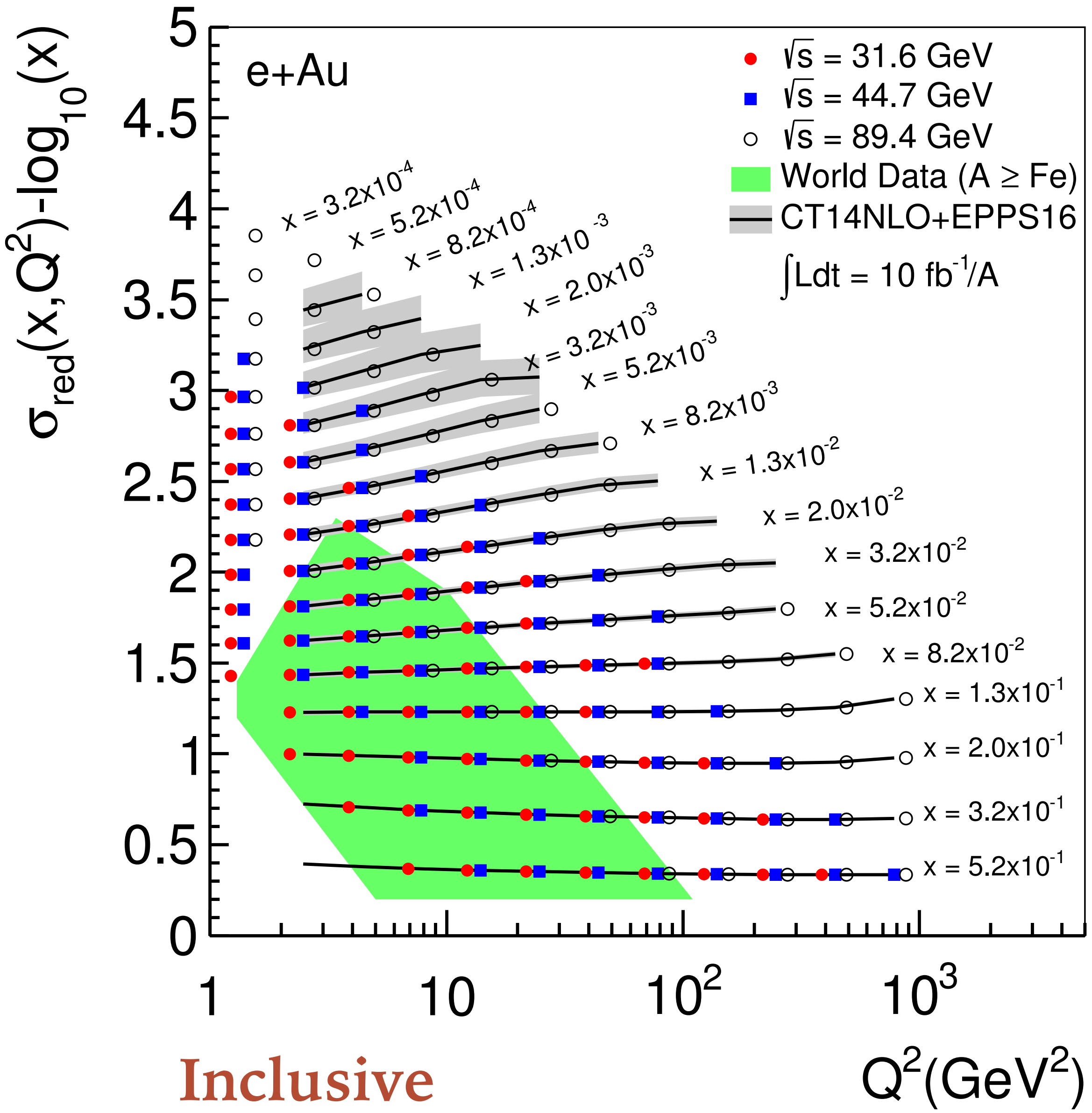




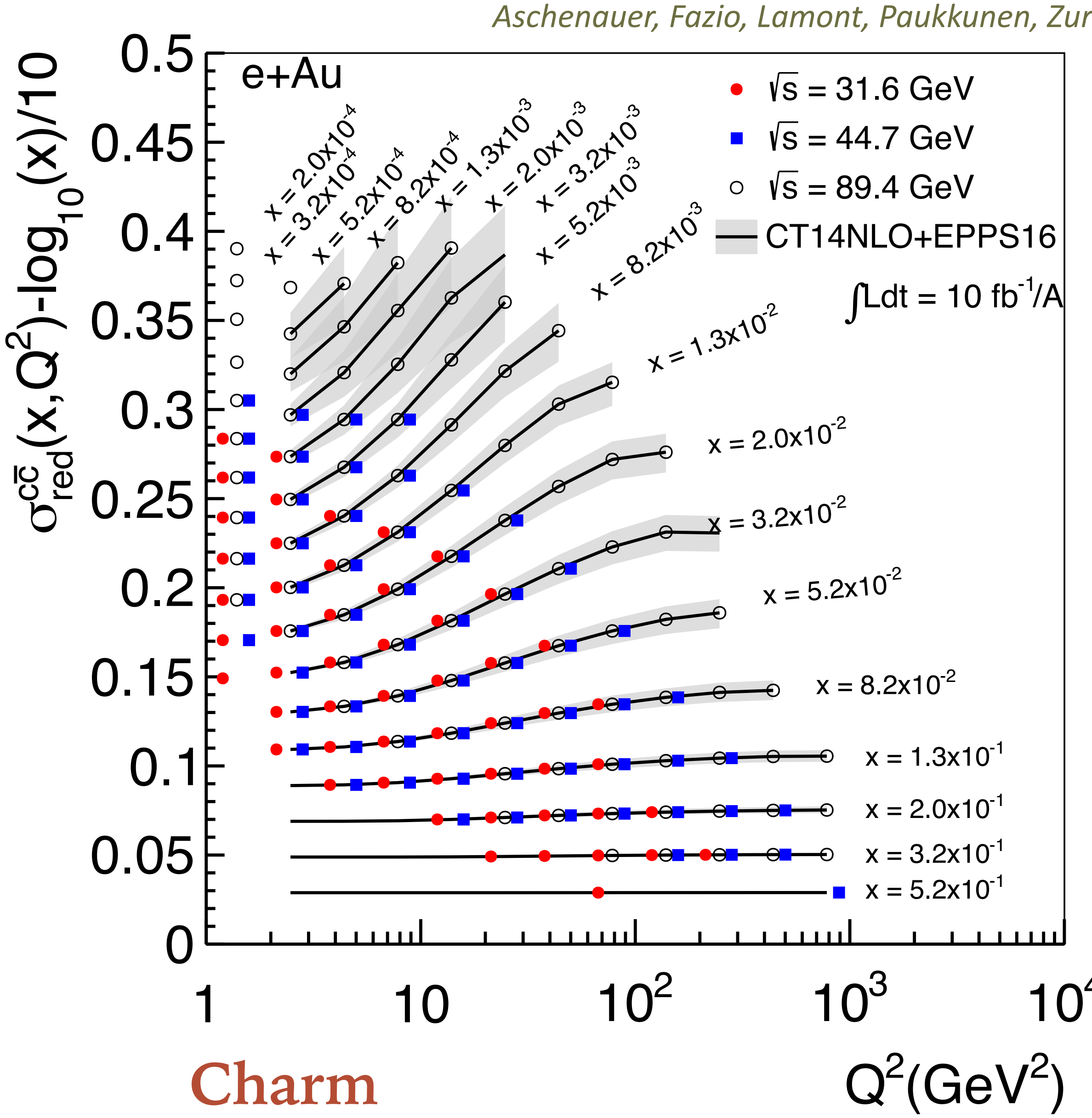
- Precise measurement of **nuclear structure functions** for wide range of nuclei and **wide kinematic range**
- Extraction of **nuclear PDFs** which are essential for understanding **nuclear structure**
- **Initial conditions for Quark-Gluon Plasma**
- Sys. uncertainties at most few %, stat. negligible
- Proton, deuteron and wide range nuclei structure function within **one facility:** reduction of uncertainties

Global nuclear structure: structure functions

Aschenauer, Fazio, Lamont, Paukkunen, Zurita



Inclusive



Charm

- Precision measurements of the reduced cross section
- Charm component in nuclei
- Errors much smaller than the uncertainties of QCD predictions

Impact of EIC on nuclear PDFs

Collinear factorization

$$F_{2,L}(x,Q^2) = \sum_j \int_x^1 dz\, C_{2,L}(Q/\mu, x/z; \alpha_s)\, f_j(z,\mu) + \boxed{\ldots}$$

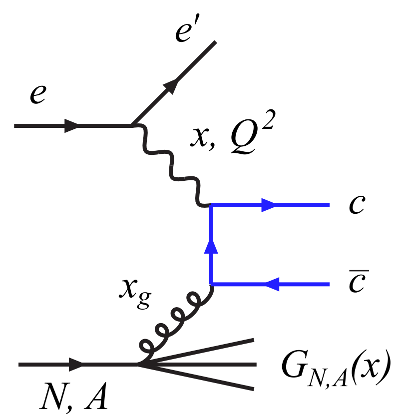
DGLAP : linear evolution

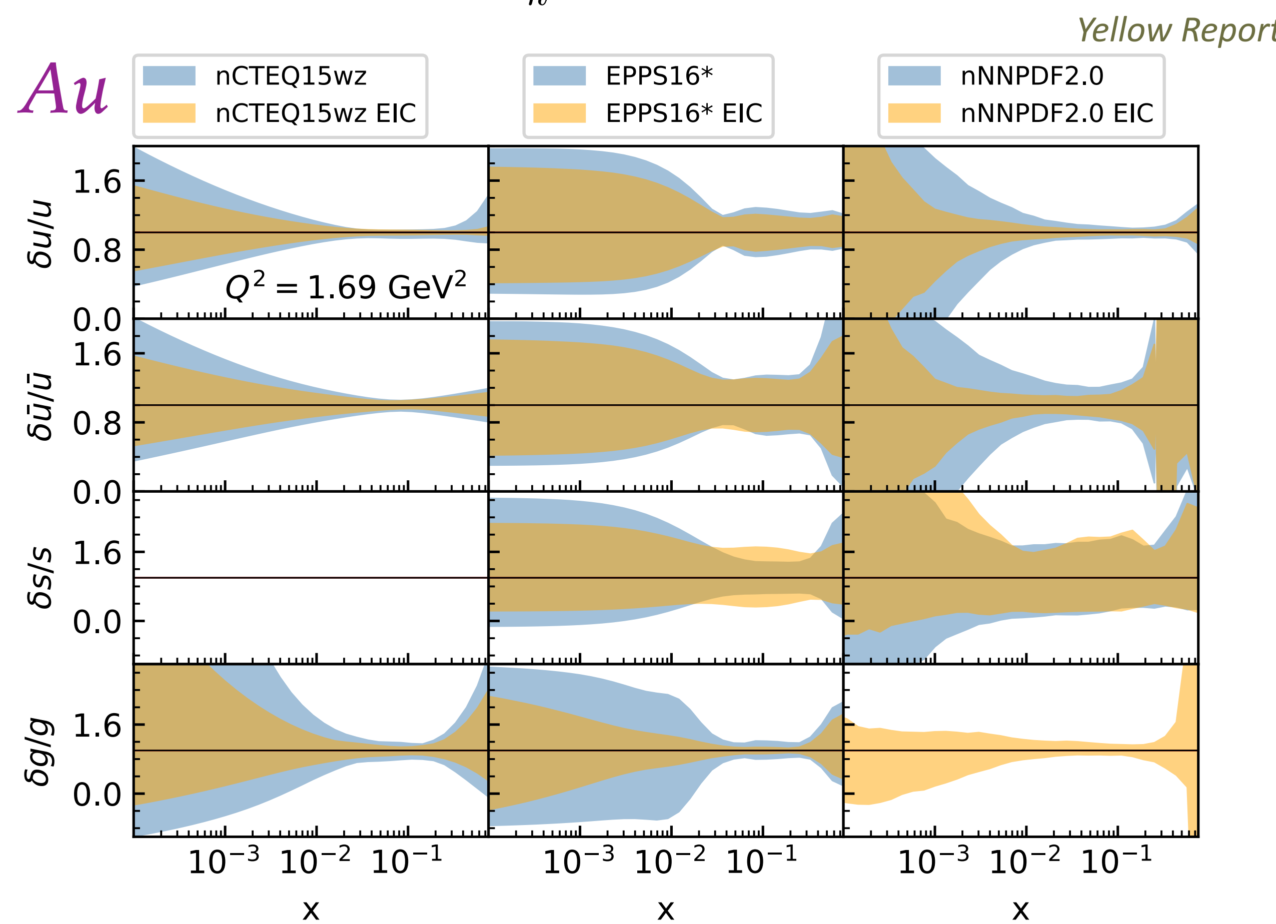
$$\frac{d}{d\ln\mu^2} f_j(z,\mu) = \sum_k \int \frac{d\xi}{\xi} P_{jk}(\xi,\alpha_s) f_k(z/\xi,\mu)$$

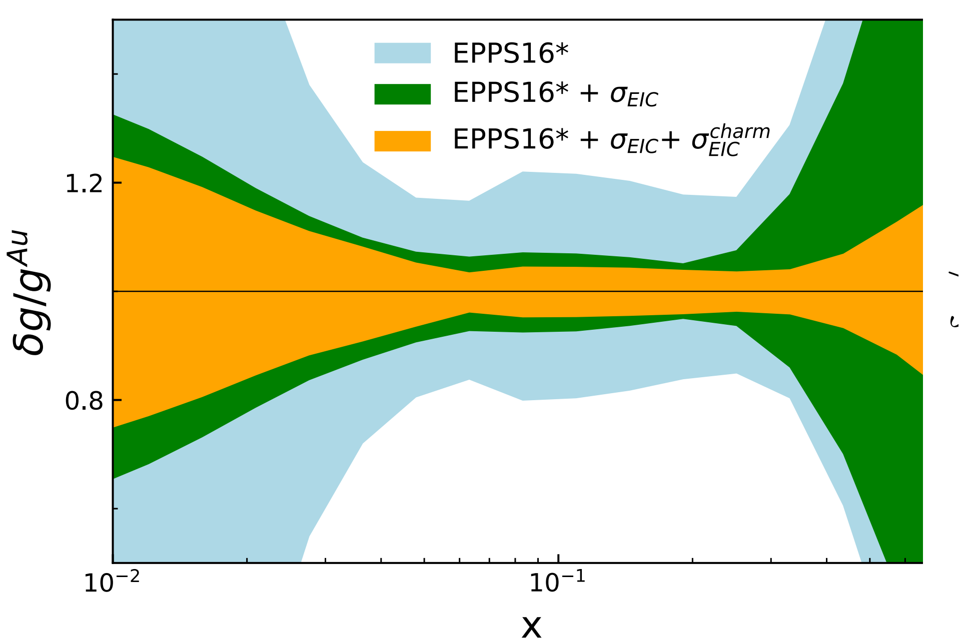
Nuclear modification in this framework:

initial condition at low scales, **linear evolution with scale**

- Impact of **charm cross section** on the gluon PDF at high x
- Charm is produced mainly in the photon-gluon fusion process
- Further constraints: $\mathbf{F_L}$







Significant impact of EIC measurements on nuclear PDFs

Testing saturation through inclusive structure functions at EIC

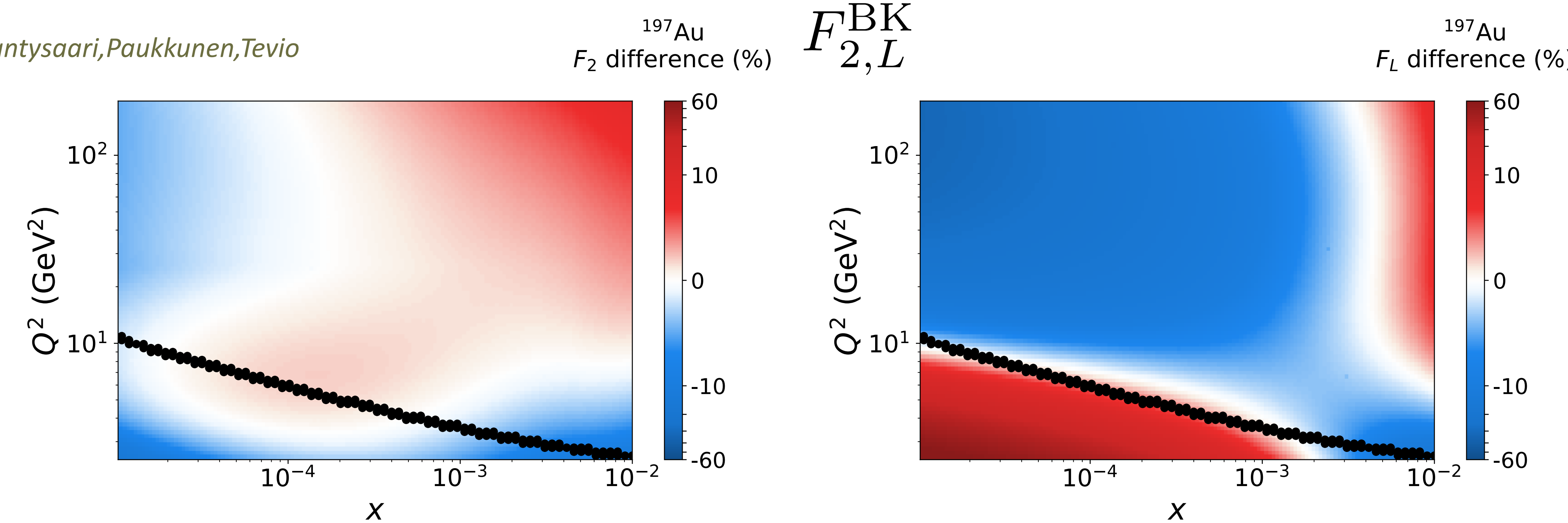
Study differences in evolution between **linear DGLAP** evolution and **nonlinear** evolution with **saturation**

Matching of both approaches in the region where saturation effects expected to be small

Quantify differences away from the matching region: **differences in evolution dynamics**

$$\frac{F_{2,L}^{\mathrm{BK}} - F_{2,L}^{\mathrm{Rew}}}{F_{2,L}^{\mathrm{BK}}}$$

Armesto, Lappi,Mantysaari,Paukkunen,Tevio



$$F_2 = C_2^q \otimes q + C_2^g \otimes g$$

$$F_L = C_L^q \otimes q + C_L^g \otimes g$$

Different weighting of quark and gluon in F_L, F_2. Independent constraint

Heavy nucleus: difference between DGLAP and nonlinear are few % for F_2^A and up to 20% for F_L^A

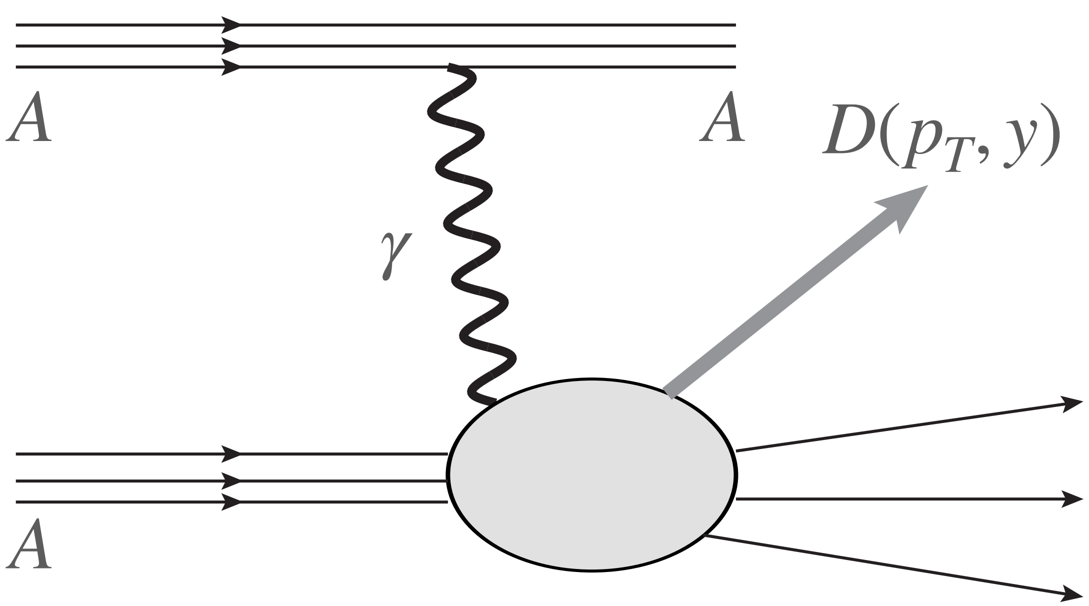
Longitudinal structure function can provide good sensitivity at EIC

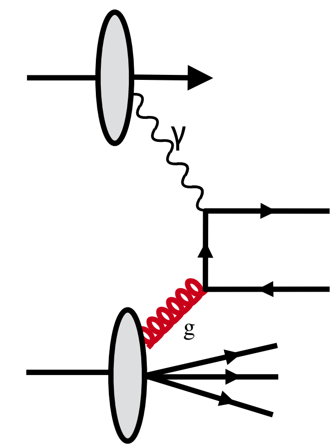
Nuclear PDF information from LHC

Complementary information about nuclear PDFs from LHC

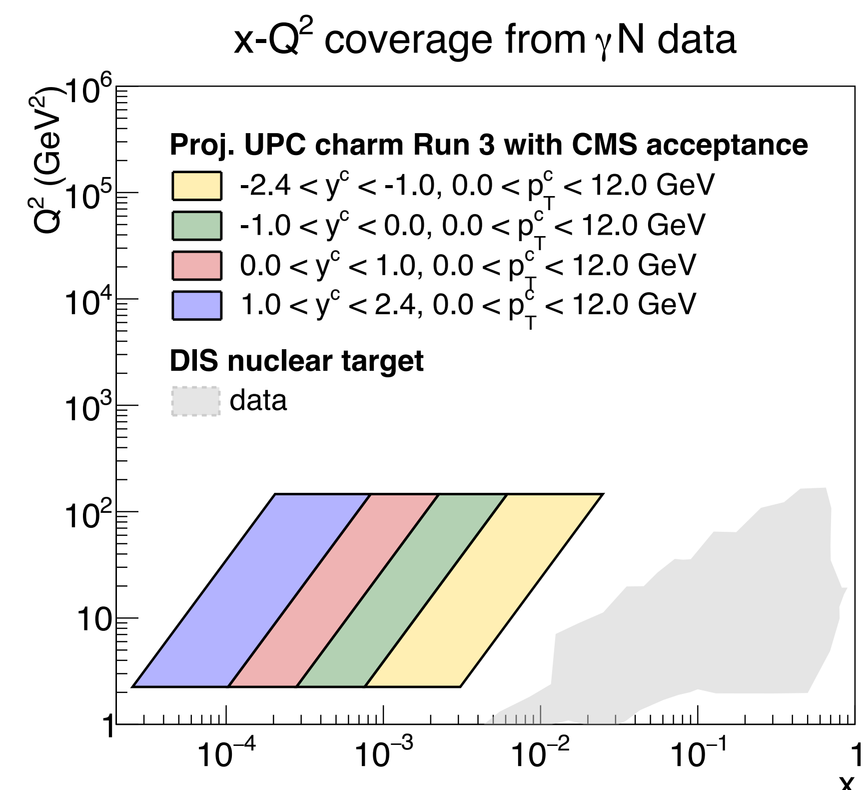
Example: photoproduction of open charm in UPC

$$A\,A \to A\,D\,X$$



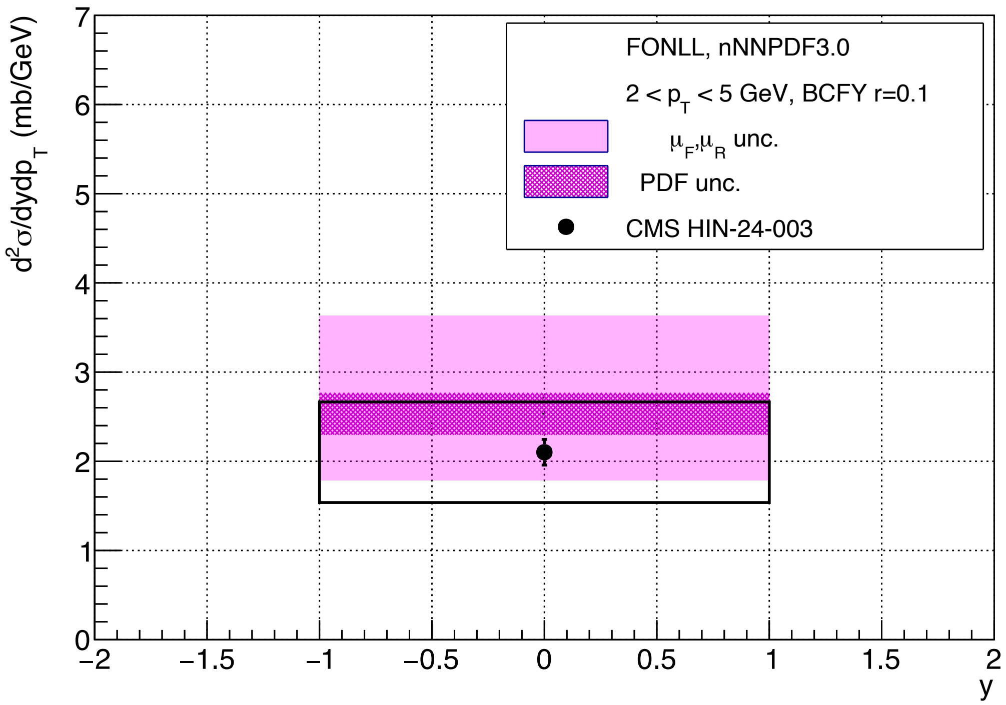


- Advantage: access to **wide range of scales** : $m_T = \sqrt{p_T^2 + m_c^2}$
- Inclusive$^{(*)}$ process: test of **factorization** and **universality** of PDFs
- **Charm** produced mainly in γg **fusion**
- Sensitive to the **nuclear gluon density: nuclear modification**
- Tests of parton evolution: **DGLAP** vs **BFKL** vs **CGC …**



Comparison of FONLL with CMS data on D^0

Cacciari, Innocenti, AS



Cross section: FONLL (collinear fixed order NLO+logarithmic resummation)

nPDF: nNNPDF

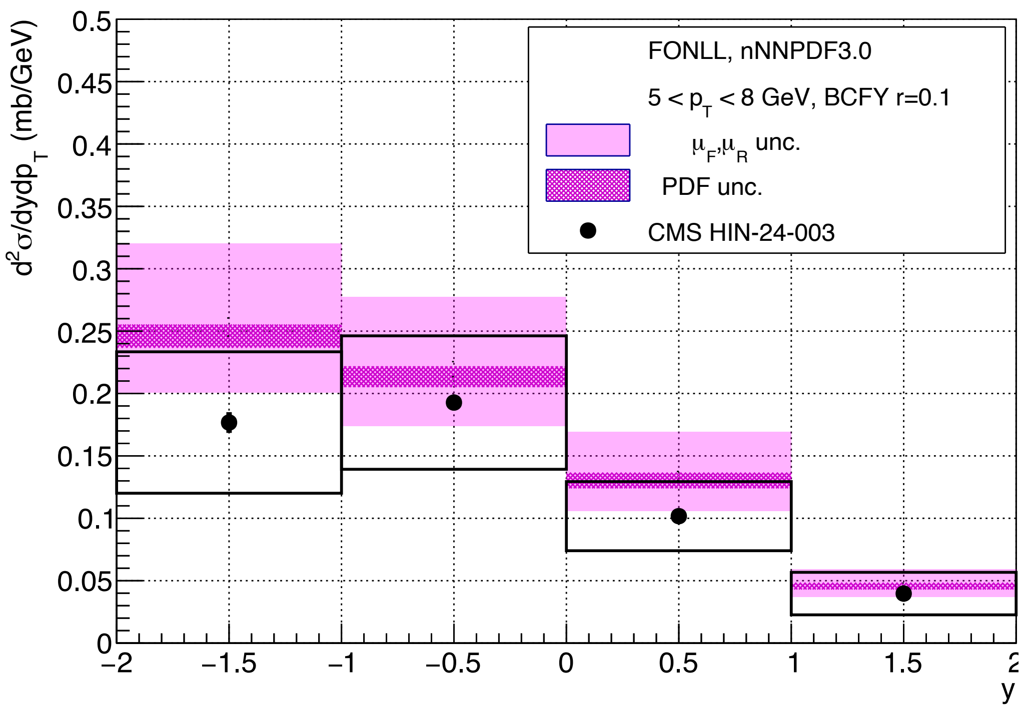
Fragmentation: BCFY, r=0.1

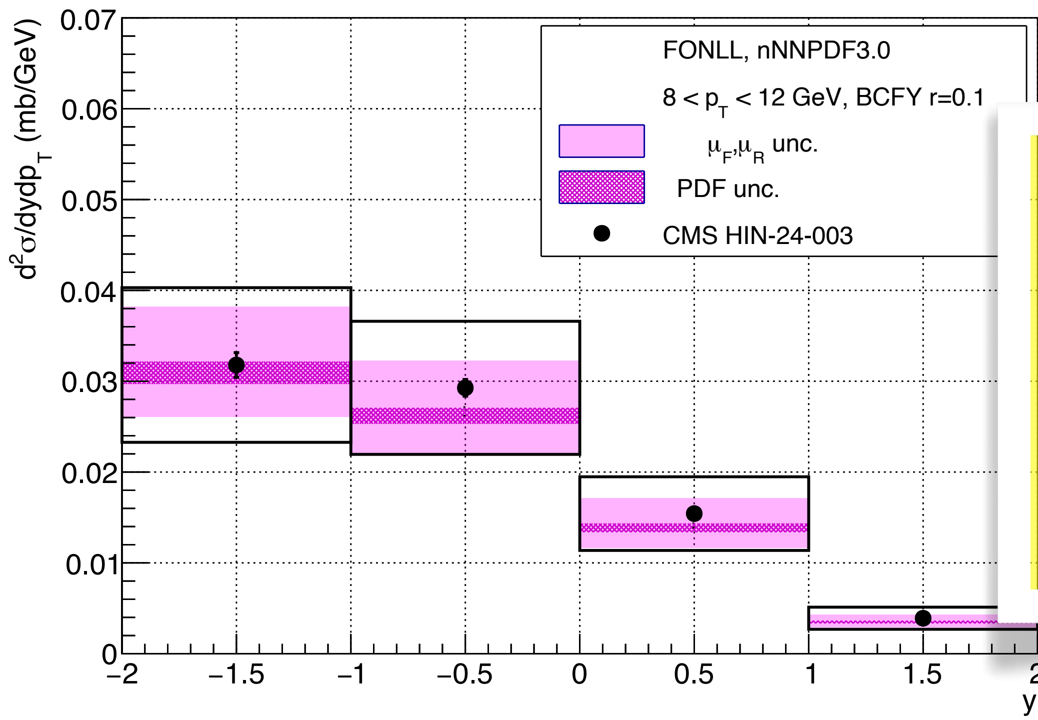
Lighter bands/lines

Scale variation: μ_f/m_T, $\mu_r/m_T(0.5,1,2)$, $\frac{1}{2} \leq \mu_f/\mu_r \leq 2$

Darker/smaller bands: PDF uncertainty

$m_c = 1.5$ GeV

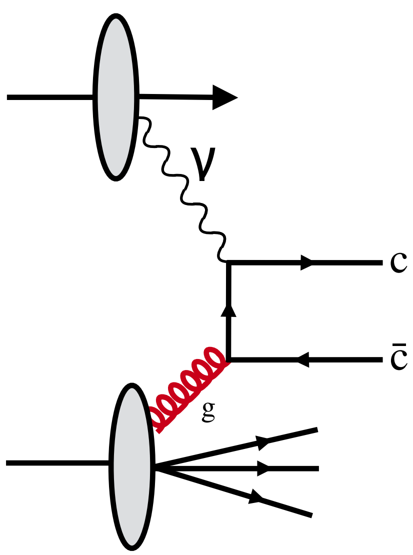




Comparison of FONLL with CMS data

Reasonable agreement within the theoretical/ experimental uncertainties

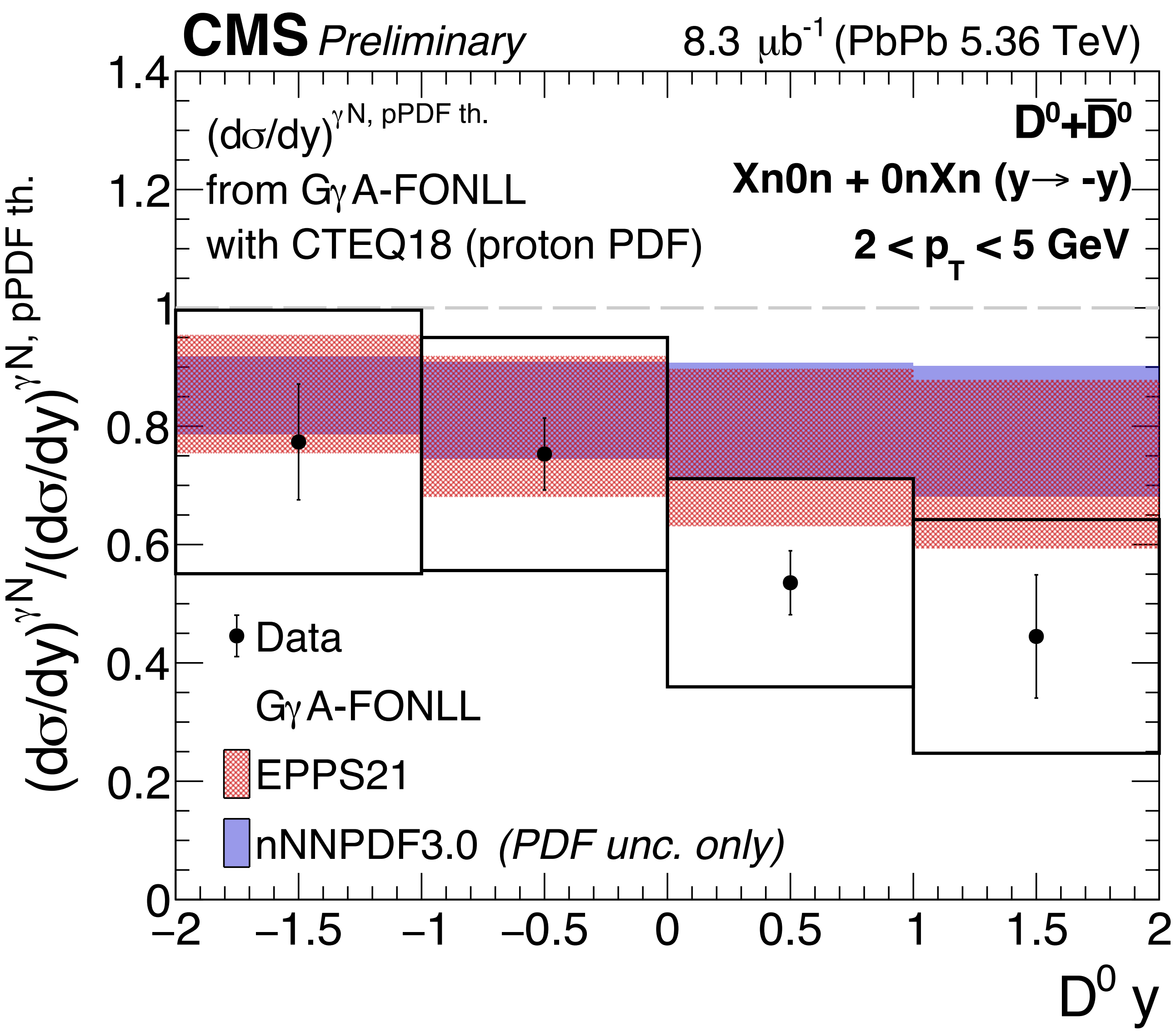
y-differential measurement of D^0 UPC production



p_T (2-12 GeV)

y (-2 to 2)

Ratio to GγA-FONLL with proton PDFs

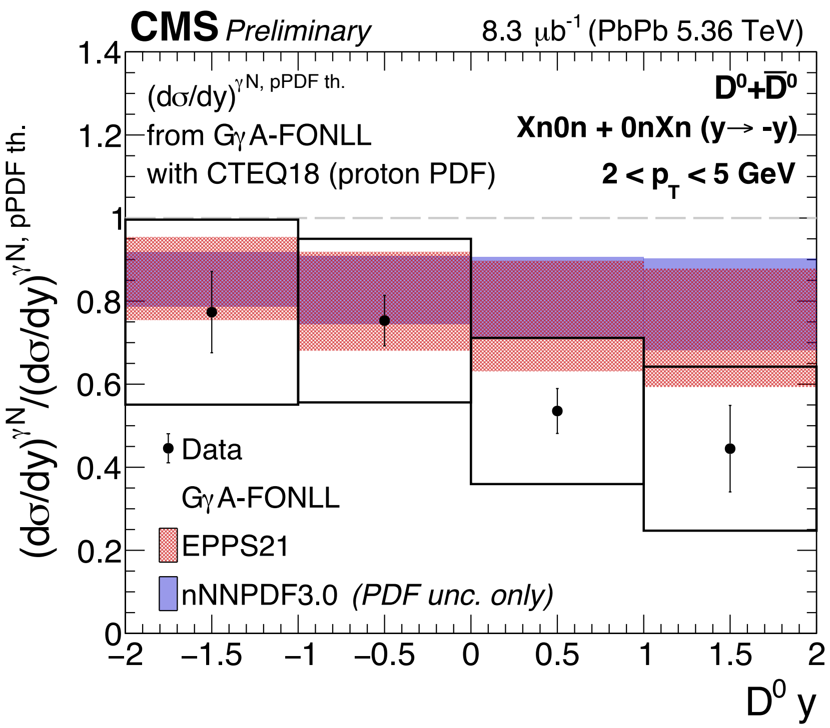


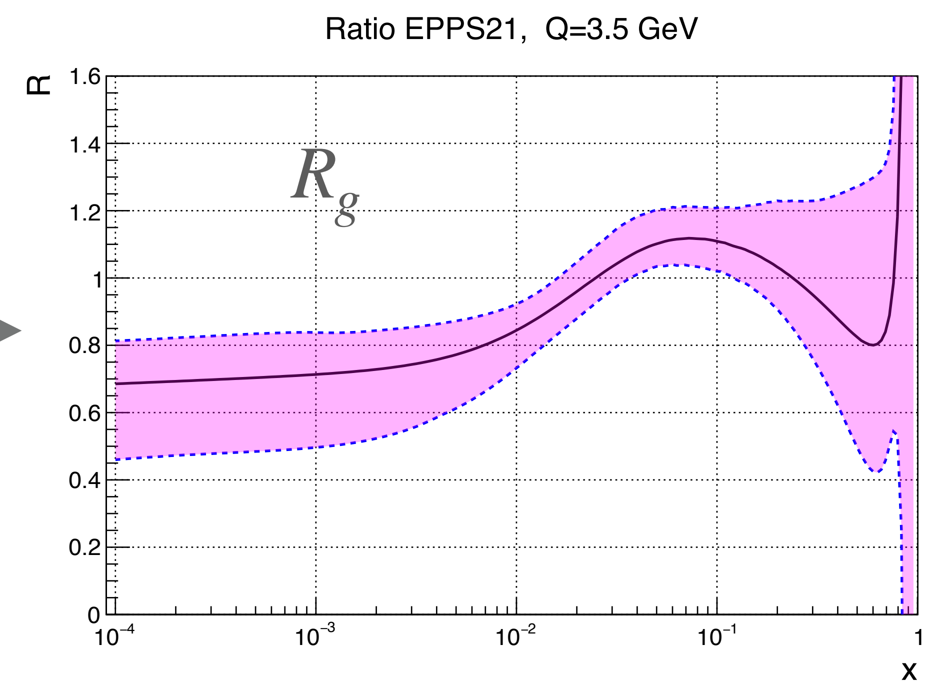
higher-x ← → *lower-x*

Sensitivity to nPDF down to ~ 10^{-4} at low Q^2

Indication of more suppression at low x ?

Implications of LHC data on nuclear gluon density





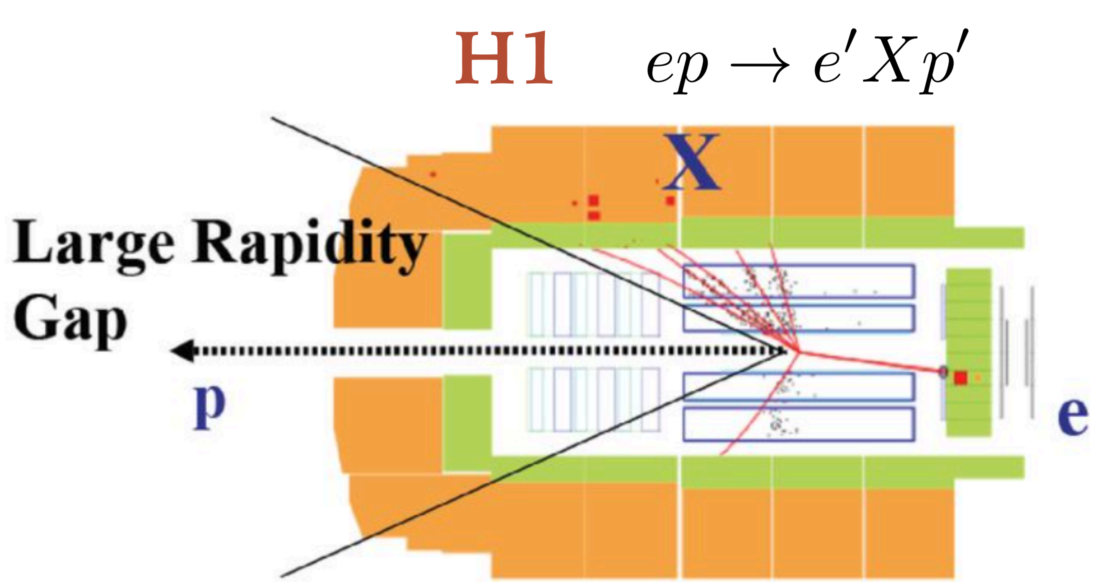
- Do CMS data imply the need for more **suppression** of the nuclear gluon density at low x ?
- Which modelling: **DGLAP initial conditions, leading twist shadowing**, or **non-linear evolution** ?
- Additional complications:
  - LHC UPC measurement not entirely inclusive: **0nXn** selection
  - Need to include **electromagnetic dissociation factor** (0.8-0.4 for CMS kinematics)
  - Part of **coherent diffraction** is rejected
  - Sensitivity to modeling of the **photon flux** from nucleus

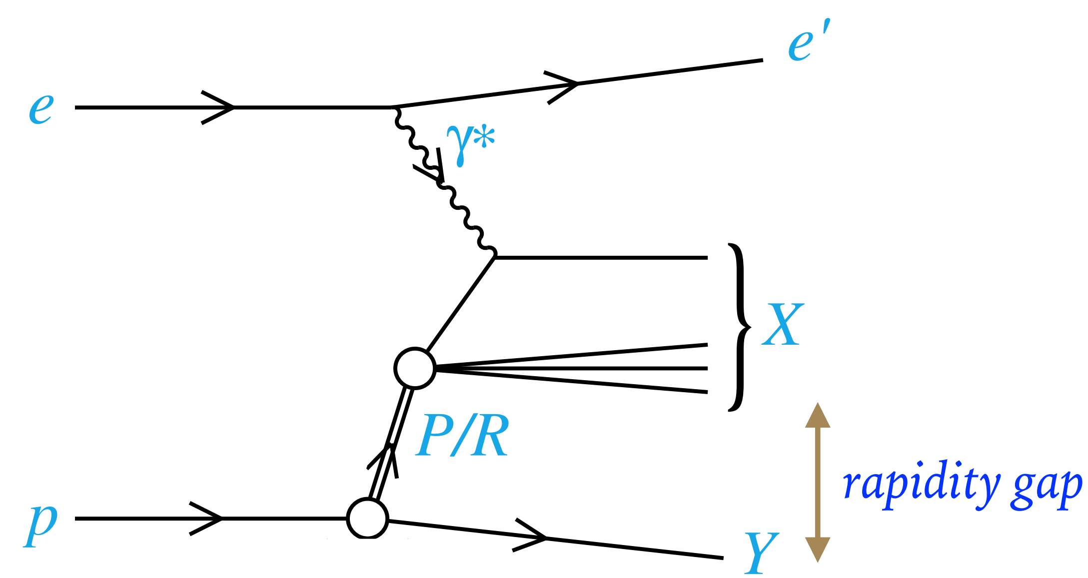
Measurements at EIC from eA collisions are necessary to pin down gluon density in nuclei

Importance of measurements of F_L to provide additional constraint

Diffraction in DIS

- Diffractive characterized by the **rapidity gap**: no activity in part of the detector
- At HERA in electron-proton collisions: about **10% events** diffractive
- Interpretation of diffraction : need **colorless** exchange

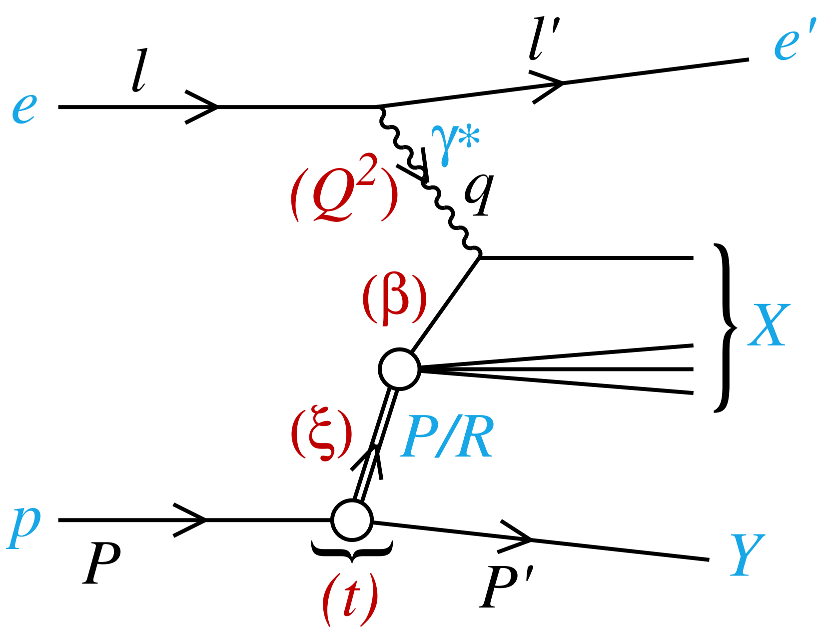




Questions:

- What is the nature of this exchange ? Partonic composition ?
- One, two, or more exchanges ? Pomeron $I\!P$, Reggeon $I\!R$?
- Evolution ? Relation to saturation, higher twists ?
- Energy, momentum transfer dependence ?
- What is the fraction of coherent/incoherent diffraction on nuclei ?

Diffractive kinematics in DIS



$$x = \xi\beta$$

Standard DIS variables:

electron-proton
cms energy squared:

$$s = (l + P)^2$$

photon-proton
cms energy squared:

$$W^2 = (q + P)^2$$

inelasticity

$$y = \frac{P \cdot q}{P \cdot l}$$

Bjorken x

$$x = \frac{Q^2}{2P \cdot q} = \frac{Q^2}{ys} = \frac{Q^2}{Q^2 + W^2}$$

(minus) photon virtuality

$$Q^2 = -q^2$$

Diffractive DIS variables:

$$\xi = x_{IP} = \frac{x}{\beta} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2}$$

momentum fraction of the Pomeron w.r.t hadron

$$\beta = \frac{Q^2}{2(P - P') \cdot q} = \frac{Q^2}{Q^2 + M_X^2 - t}$$

momentum fraction of parton w.r.t Pomeron

$$t = (P' - P)^2$$

4-momentum transfer squared

Diffractive cross section, structure functions

Diffractive cross section depends on 4 variables (ξ, β, Q^2, t):

$$\frac{d^4\sigma^D}{d\xi d\beta dQ^2 dt} = \frac{2\pi\alpha_{\rm em}^2}{\beta Q^4} Y_+ \, \sigma_{\rm r}^{\rm D(4)}(\xi,\beta,Q^2,t)$$

where $Y_+ = 1 + (1-y)^2$

Reduced cross section depends on two **structure functions:**

$$\sigma_{\rm r}^{\rm D(4)}(\xi,\beta,Q^2,t) = F_2^{\rm D(4)}(\xi,\beta,Q^2,t) - \frac{y^2}{Y_+} F_L^{\rm D(4)}(\xi,\beta,Q^2,t)$$

Upon integration over t:

$$F_{2,L}^{\rm D(3)}(\xi,\beta,Q^2) = \int_{-\infty}^{0} dt \, F_{2,L}^{\rm D(4)}(\xi,\beta,Q^2,t)$$

$$\sigma_{\rm r}^{\rm D(3)}(\xi,\beta,Q^2) = F_2^{\rm D(3)}(\xi,\beta,Q^2) - \frac{y^2}{Y_+} F_L^{\rm D(3)}(\xi,\beta,Q^2)$$

When $y \ll 1$

$$\sigma_{\rm r}^{\rm D(4,3)} \simeq F_2^{\rm D(4,3)}$$

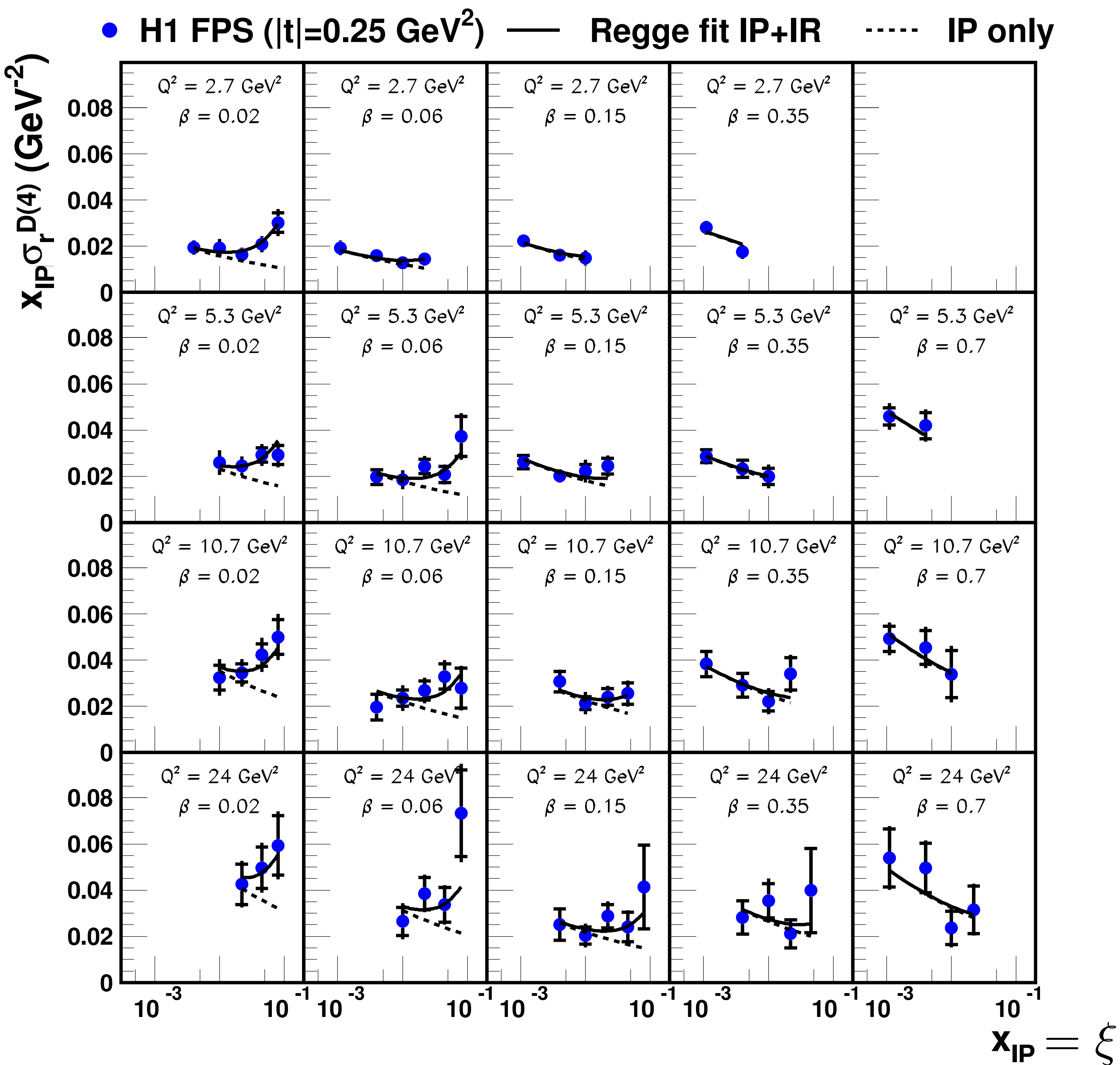
Dimensions:

$[\sigma_{\rm r}^{\rm D(4)}] = {\rm GeV}^{-2}$

$\sigma_{\rm r}^{\rm D(3)}$ Dimensionless

Diffraction at HERA: importance of 'Reggeon'

$\xi\sigma_r^{D(4)} \simeq \xi F_2^{D(4)}$ vs ξ for fixed $|t| = 0.25\,\mathrm{GeV}^2$ in bins of β, Q^2



Described by two contributions:

Leading 'Pomeron' at low ξ

$\xi f_{I\!P} \sim \xi^{-0.22}$

Subleading 'Reggeon' at high ξ

$\xi f_{I\!R} \sim \xi^{1.0}$

Subleading terms poorly constrained

Diffraction at EIC

EIC complementarity to HERA

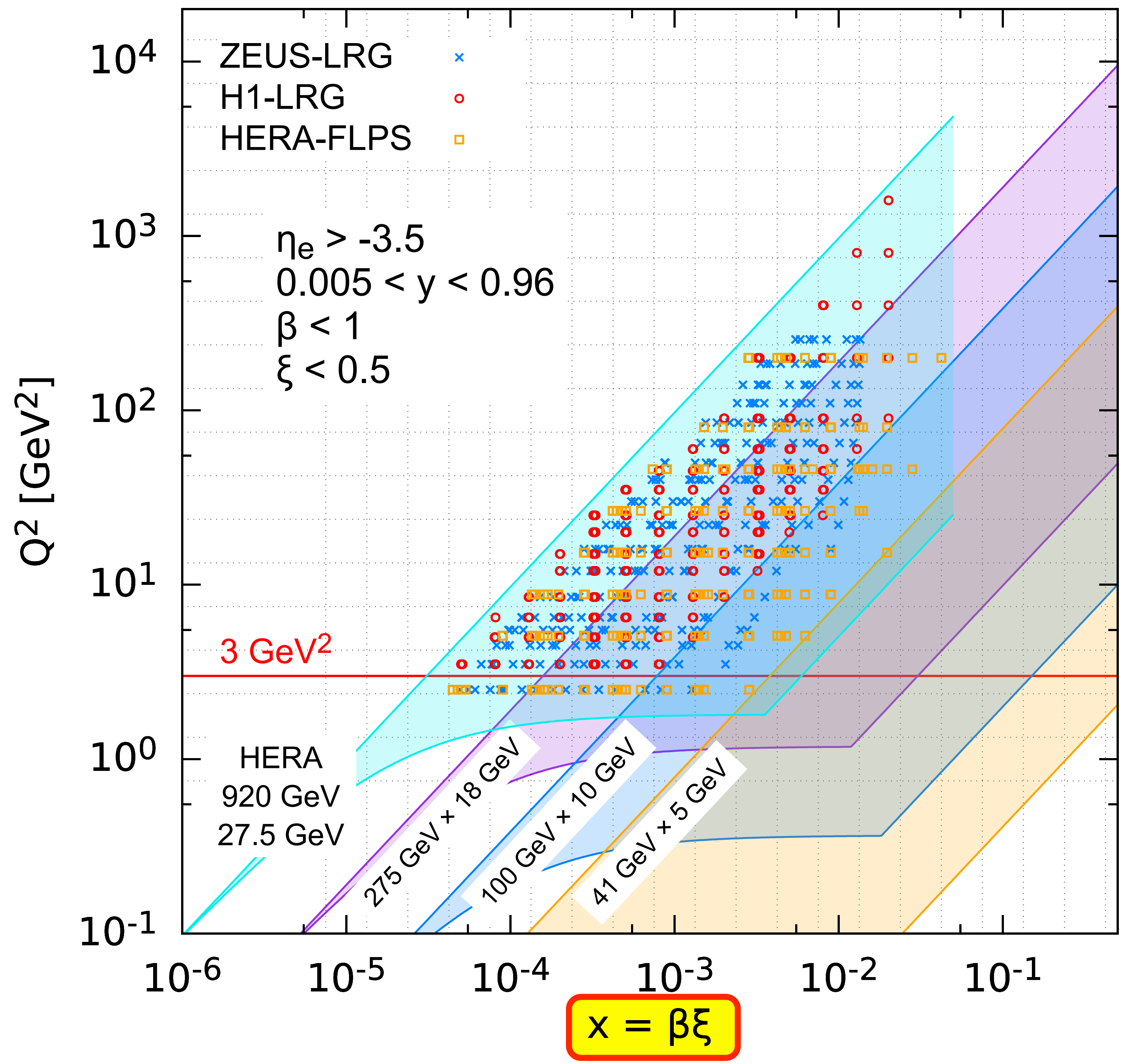
Large $x \rightarrow$ Large ξ : constraints on subleading (Reggeon) exchange

Large $x \rightarrow$ Large β : constraints on large z region of DPDFs

At EIC use **forward tagging** instrumentation to detect forward protons and study diffraction

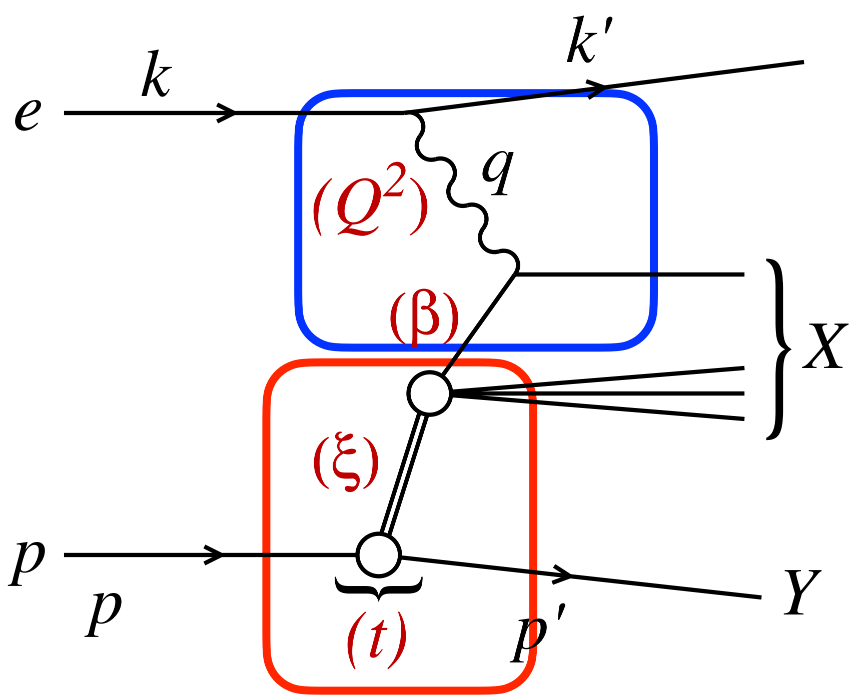
Only selected energy scenarios at EIC shown

EIC 3 scenarios - HERA



Collinear factorization for diffraction

Use the collinear factorization for the description of HERA and pseudodata simulation



Collins

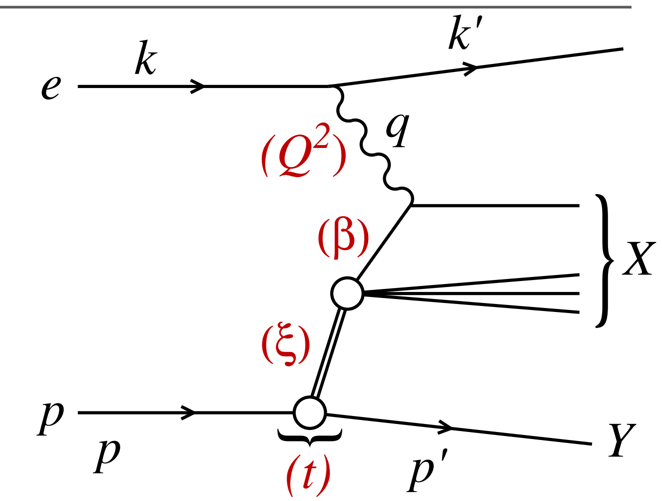
Collinear factorization in diffractive DIS

$$F_{2/L}^{D(4)}(\beta,\xi,Q^2,t) = \sum_i \int_\beta^1 \frac{dz}{z}\, C_{2/L,i}\left(\frac{\beta}{z},Q^2\right) f_i^{\mathrm{D}}(z,\xi,Q^2,t)$$

- Diffractive cross section can be factorized into the convolution of the perturbatively calculable **partonic cross sections** and **diffractive parton distributions (DPDFs)**
- Partonic cross sections are the **same as in the inclusive DIS**
- The DPDFs are non-perturbative objects, but evolved perturbatively with **DGLAP**

Model for diffractive structure functions

- Parametrization of the DPDFs as in H1 and ZEUS analysis
- **Regge factorization** assumed
- (β(or z), Q^2) dependence in parton distribution of diffractive exchange factorized from flux factors with (t, ξ) dependence
- Dominant term **'Pomeron'**, at low ξ
- At higher ξ additional exchanges **'Reggeons'** need to be included



$$f_i^{D(4)}(z,\xi,Q^2,t) = \underbrace{f_{I\!P}^p(\xi,t)\, f_i^{I\!P}(z,Q^2)}_{\text{Pomeron}} + \underbrace{f_{I\!R}^p(\xi,t)\, f_i^{I\!R}(z,Q^2)}_{\text{Reggeon}}$$

Regge type flux:

$$f^p_{I\!P,I\!R}(\xi,t) = A_{I\!P,I\!R}\frac{e^{B_{I\!P,I\!R}t}}{\xi^{2\alpha_{I\!P,I\!R}(t)-1}}$$

Trajectory:

$$\alpha_{I\!P,I\!R}(t) = \alpha_{I\!P,I\!R}(0) + \alpha'_{I\!P,I\!R}\, t$$

For t-integrated case

$$f_i^{D(3)}(z,\xi,Q^2) = \phi^p_{I\!P}(\xi)\, f_i^{I\!P}(z,Q^2) + \phi^p_{I\!R}(\xi)\, f_i^{I\!R}(z,Q^2)$$

Integrated flux:

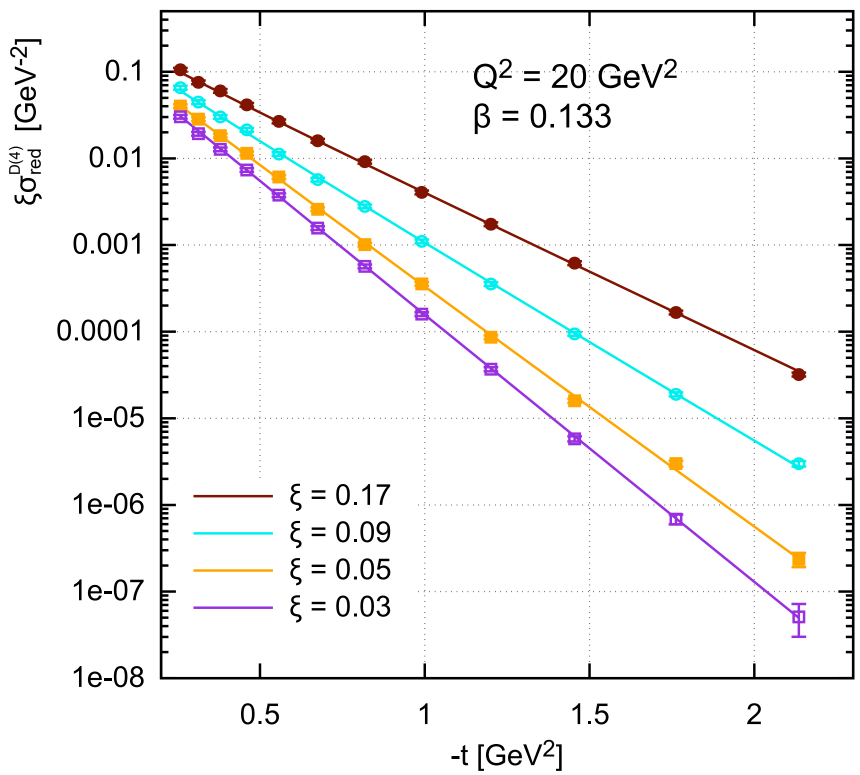
$$\phi^p_{I\!P,I\!R}(\xi) = \int dt\, f^p_{I\!P,I\!R}(\xi,t)$$

Pomeron PDFs obtained via NLO DGLAP evolution starting at initial scale $\mu_0^2 = 1.8$ GeV^2

$$z f_i(z,\mu_0^2) = A_i z^{B_i}(1-z)^{C_i} \qquad i=q,g$$

Reggeon PDFs taken from the GRV fits to the pion structure function (***could also be determined at EIC!***)

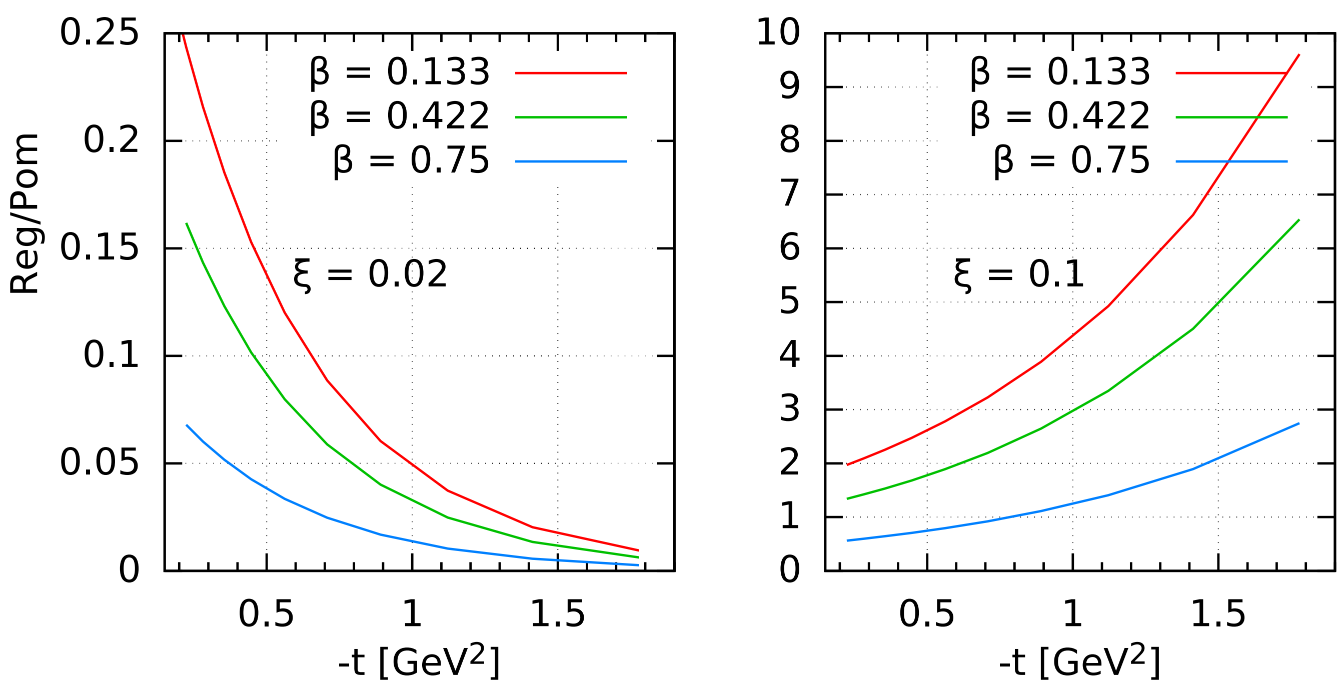
Reggeon and Pomeron component in cross section at EIC



$ep \to epX$

4D cross section pseudodata

- Changing t slope as transitioning from Pomeron to Reggeon dominated region
- σ_r^D slowly varying with Q^2



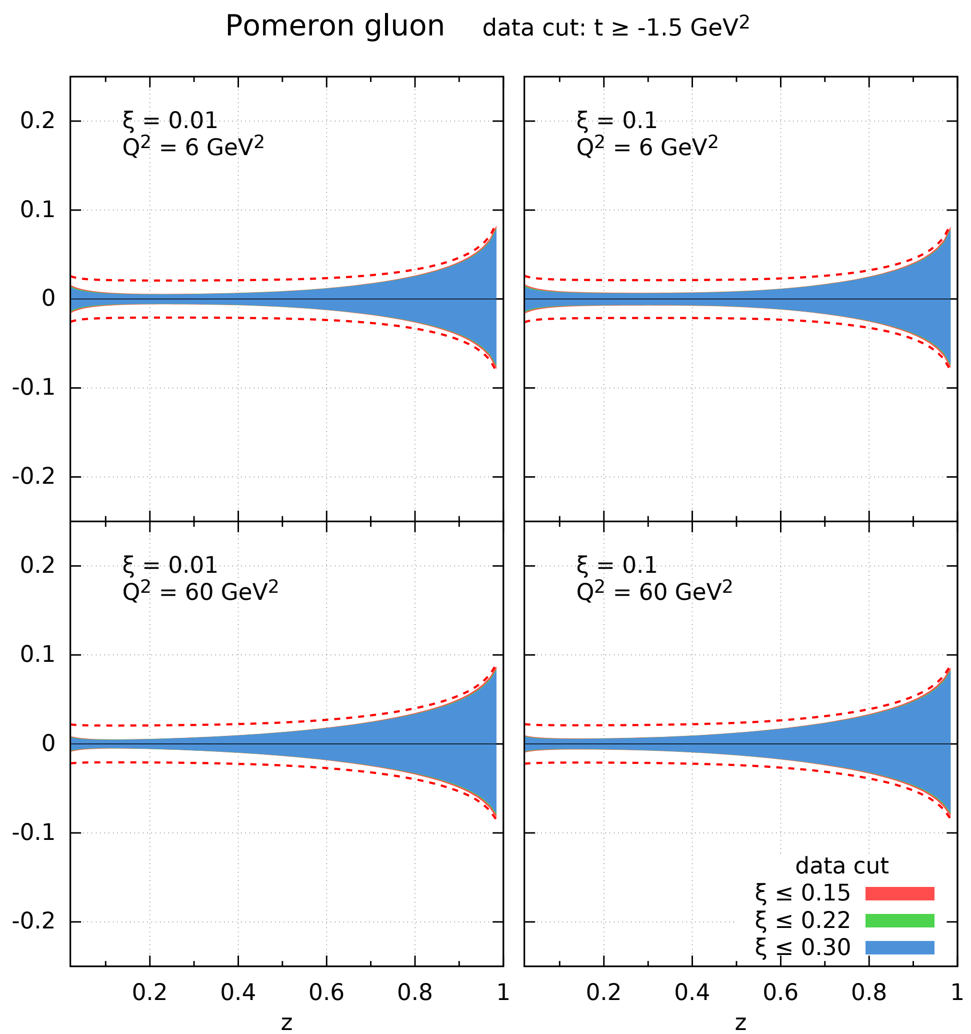
Armesto, Newman, Slominski, AS

$\mathbb{R}/\mathbb{P}$ ratio vs $-t$ for $\xi = 0.01, 0.1$

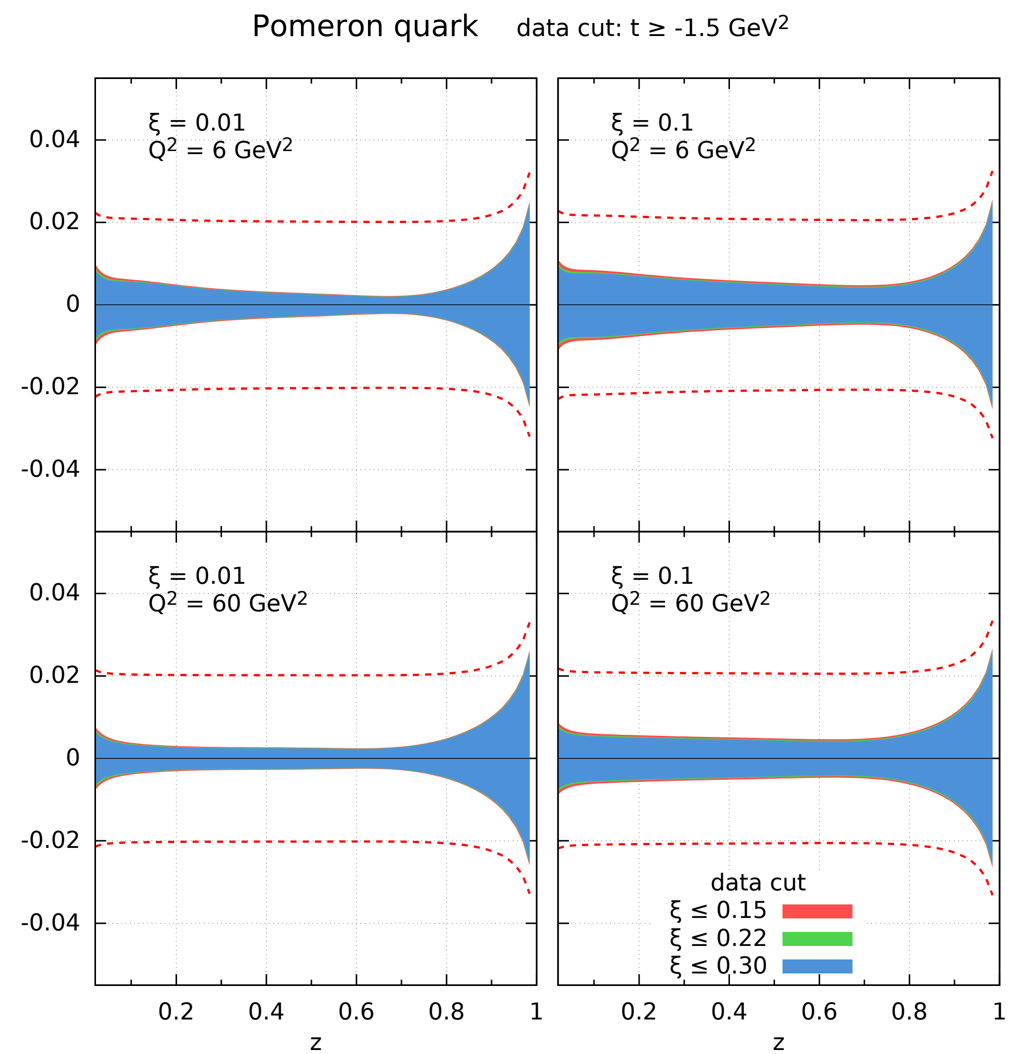
- Change of ratio for small vs large ξ as a function of $-t$: different slope
- $\mathbb{R}/\mathbb{P} < 1$ for small $\xi \sim 0.02$
- $\mathbb{R}/\mathbb{P} > 1$ for larger $\xi \geq 0.1$: not accessible at HERA

Uncertainties of diffractive PDFs: Pomeron

Pomeron gluon



Pomeron quark

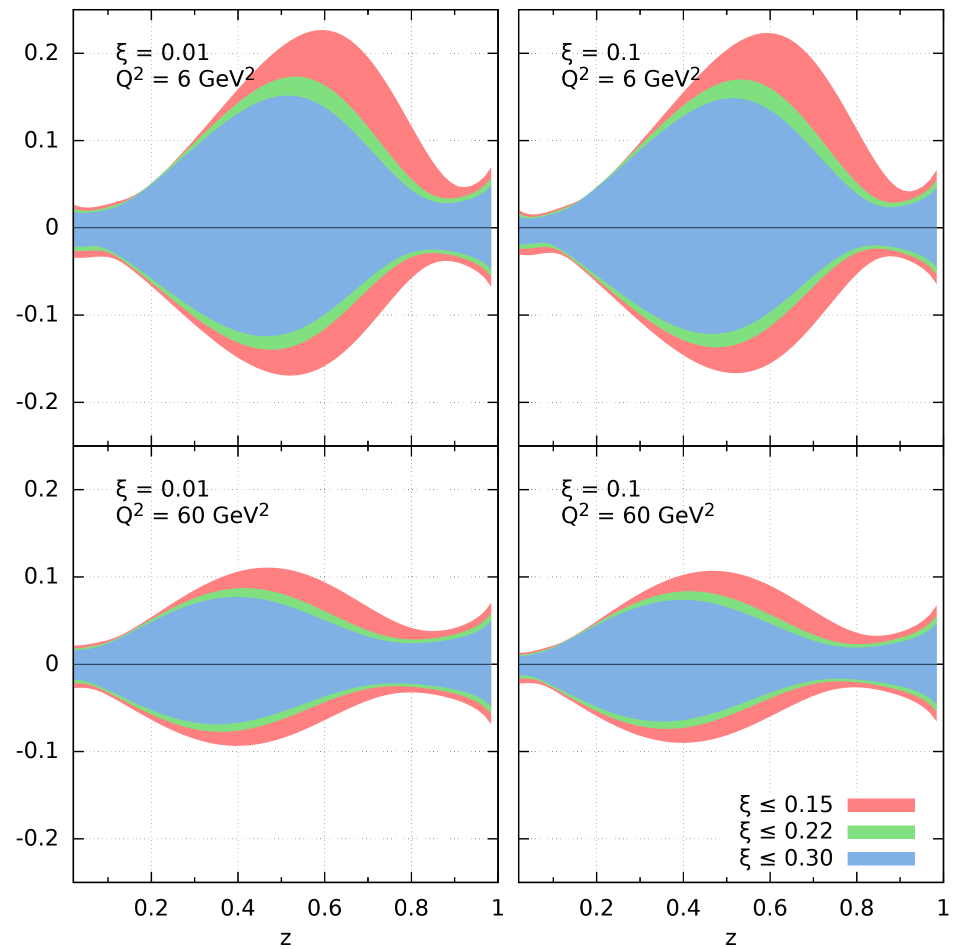


- relative uncertainty
- $<$few % or better in most regions
- larger uncertainty for gluon at large z (and also small z)
- normalization error at 2% is dominant at most regions (dashed red)

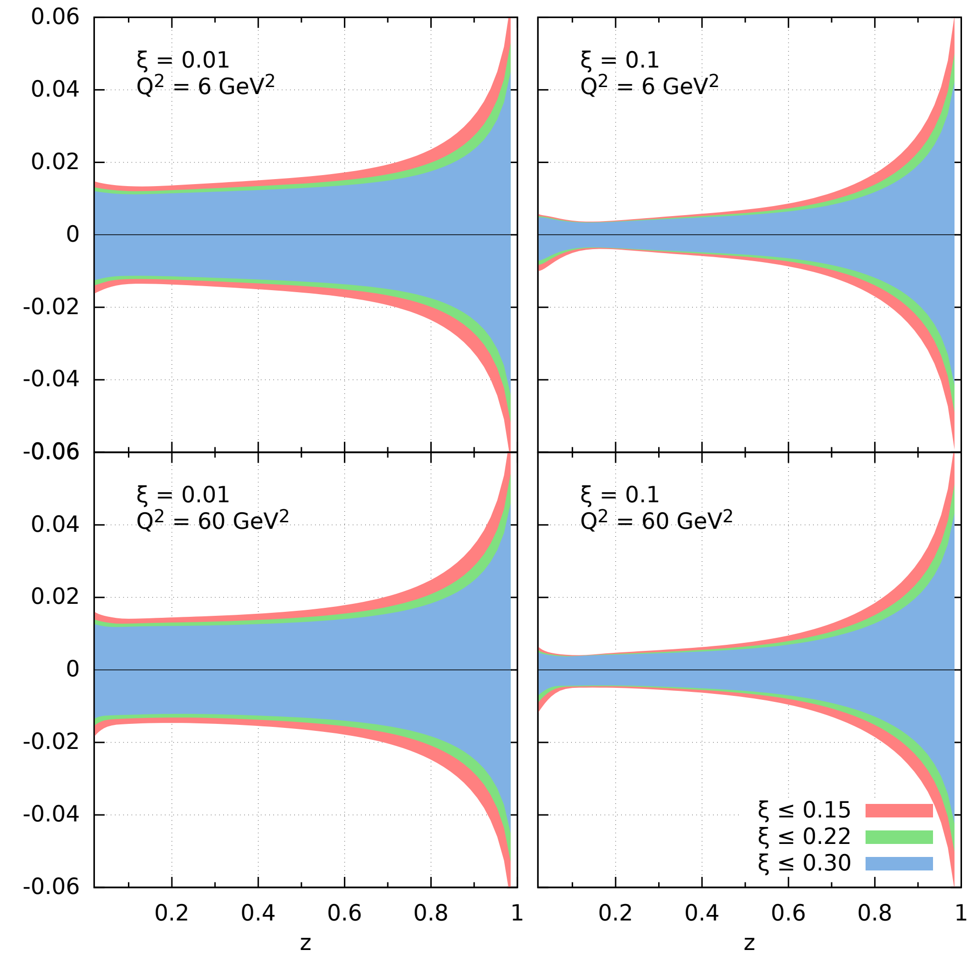
linear horizontal scale
note different vertical scale for gluons and quarks

Uncertainties of diffractive PDFs: Reggeon

Reggeon gluon



Reggeon quark



- <2 % or better in most regions for quark except at large z
- Larger uncertainty for Reggeon gluon which is much smaller than Pomeron gluon
- Mild sensitivity to the cut on ξ for gluon, quark less sensitive
- Minimal sensitivity to the cut on t, dense vs sparse binning, lower luminosity $\mathscr{L} = 10\,\text{fb}^{-1}$

EIC can constrain Reggeon at similar level of precision as the Pomeron
even when restricting data to $|t| \leq 0.5\ \text{GeV}^2$ and $\xi_{\max} \simeq 0.15 \div 0.2$

Diffraction in ep/eA: longitudinal structure function

F_L^D diffractive longitudinal structure function

$$\sigma_{\rm r}^{\rm D(3)} = F_2^{\rm D(3)} - \frac{y^2}{Y_+} F_L^{\rm D(3)}$$

F_L^D vanishes in the parton model, similarly to inclusive case

Gets non-vanishing contributions in QCD

As in inclusive case, particularly sensitive to the diffractive **gluon density**

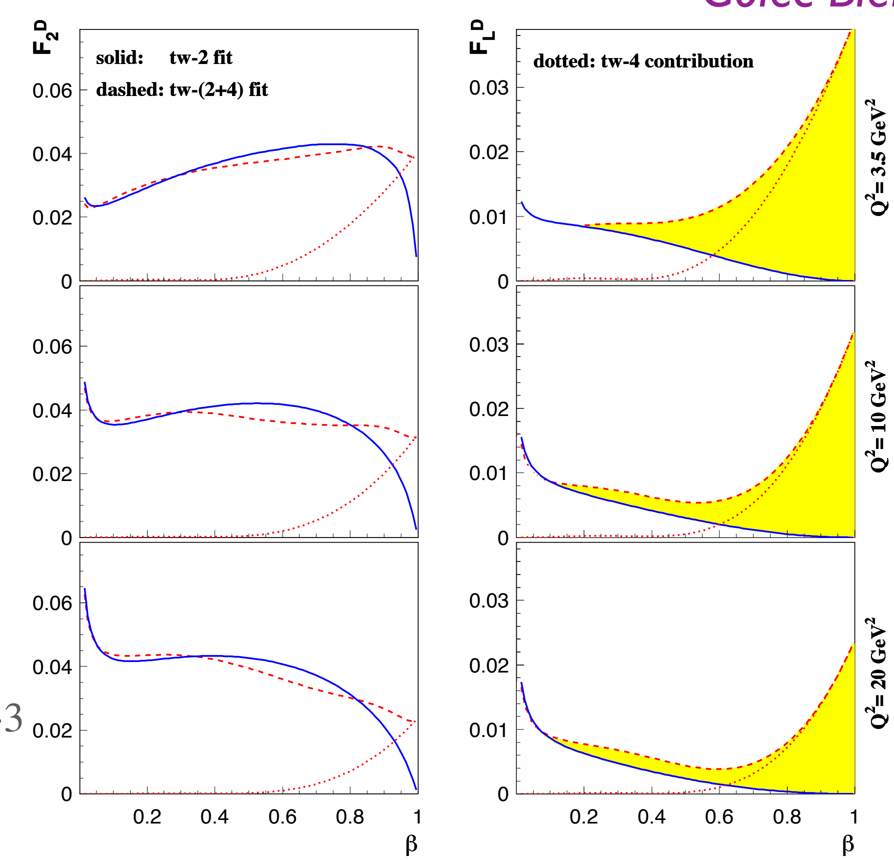
Expected large **higher twists**, provides test of the **non-linear, saturation phenomena**

Golec-Biernat, Łuszczak

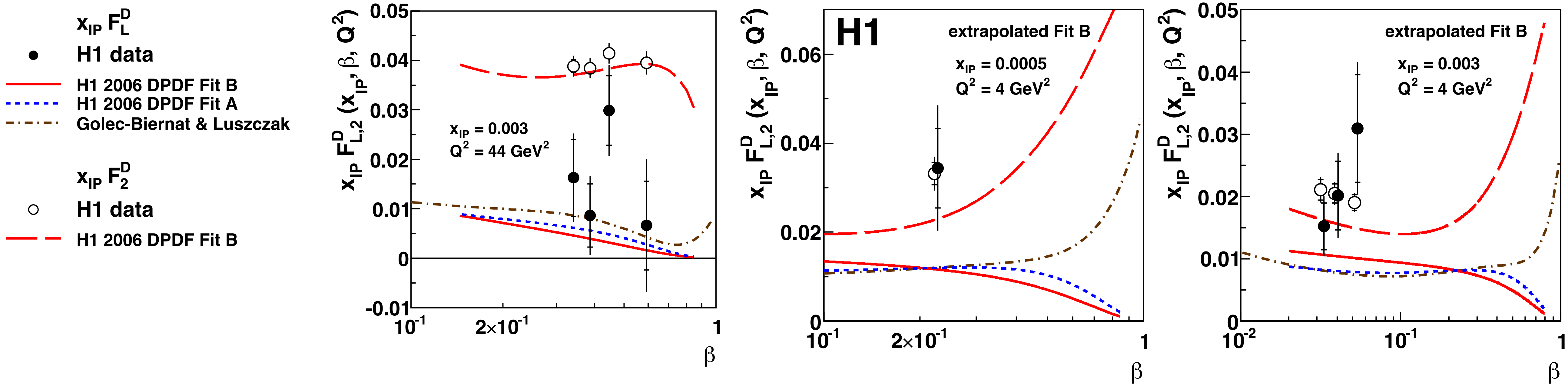
Theoretical studies indicate important role of twist 4 contributions to F_L^D

F_2^D affected less by higher twists

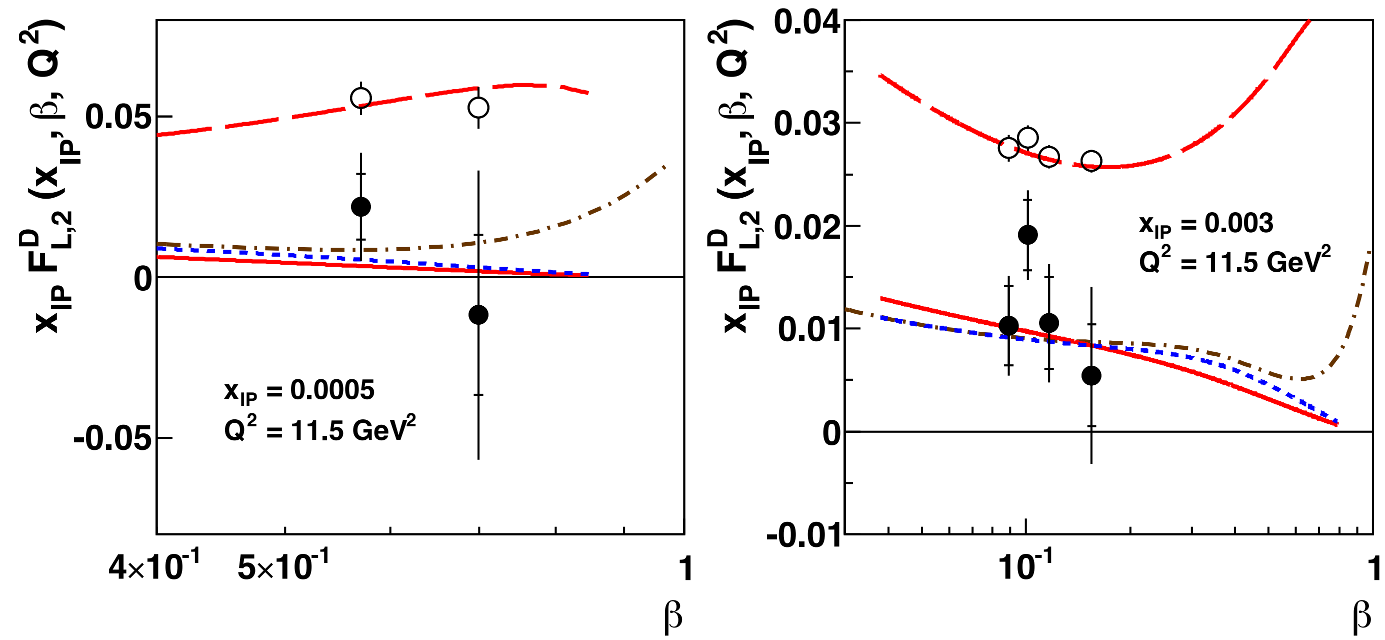
$x_{I\!P} \equiv \xi = 10^{-3}$



$F_L^{D(3)}$ at HERA



H1 conclusions:



Measurements of σ_r^D consistent with predictions from the models

Extracted F_L^D has a tendency to be higher than the predictions, though compatible with model predictions within errors

Overall: $0 < F_L^D < F_2^D$

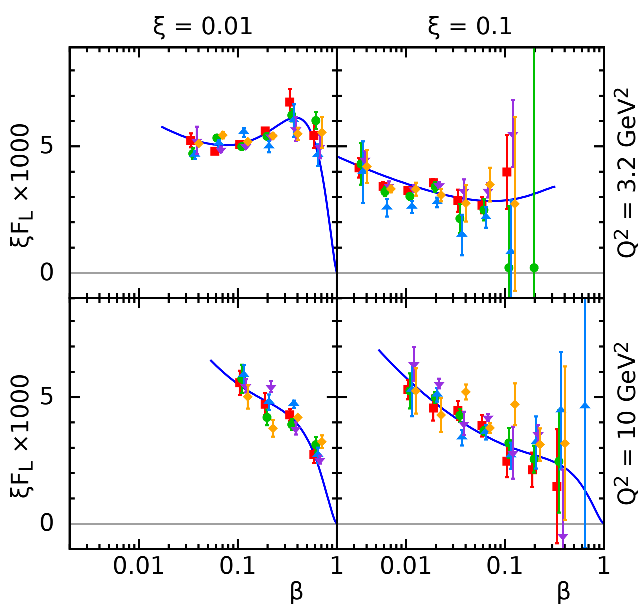
Diffraction in ep/eA: longitudinal structure function

Simulations for the EIC of F_L^D

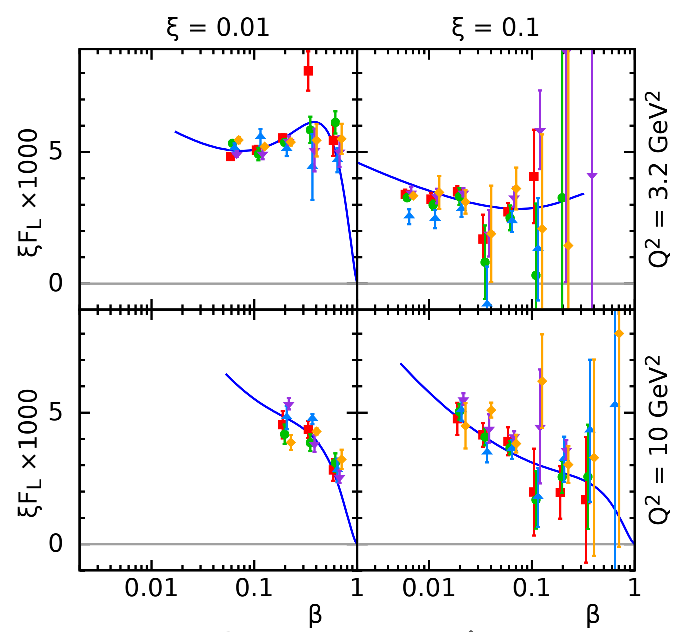
		E_p [GeV]					
		41	100	120	165	180	275
E_e [GeV]	5	**29**	**45**	49	**57**	60	74
	10	40	**63**	69	**81**	85	**105**
	18	54	**85**	93	**109**	114	**141**

Cross section generation from ZEUS-SJ diffractive PDFs evolved with DGLAP
Assumed δ_{sys}=1-2%, extrapolated from HERA 2% uncorrelated systematics; normalization/correlated systematics negligible effect on extraction of F_L^D
δ_{stat} from 10 fb^{-1} integrated luminosity; Several random samples are generated

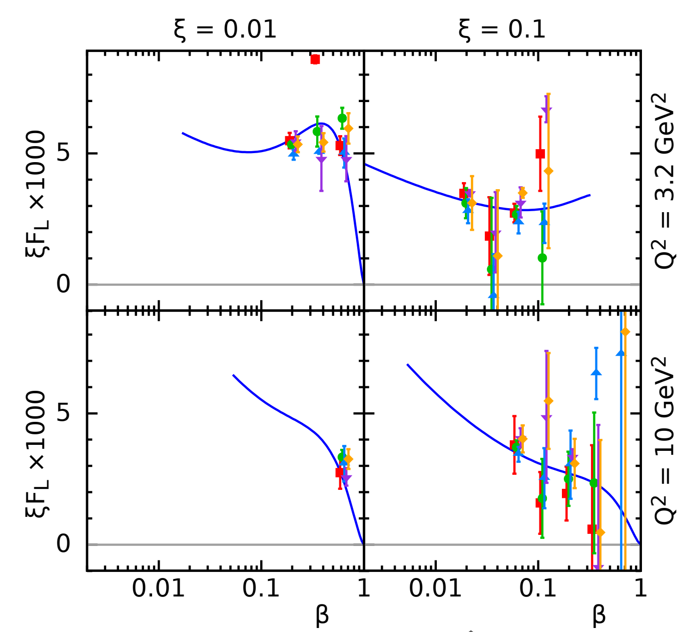
Armesto, Newman, Slominski, AS



17 energies



9 energies

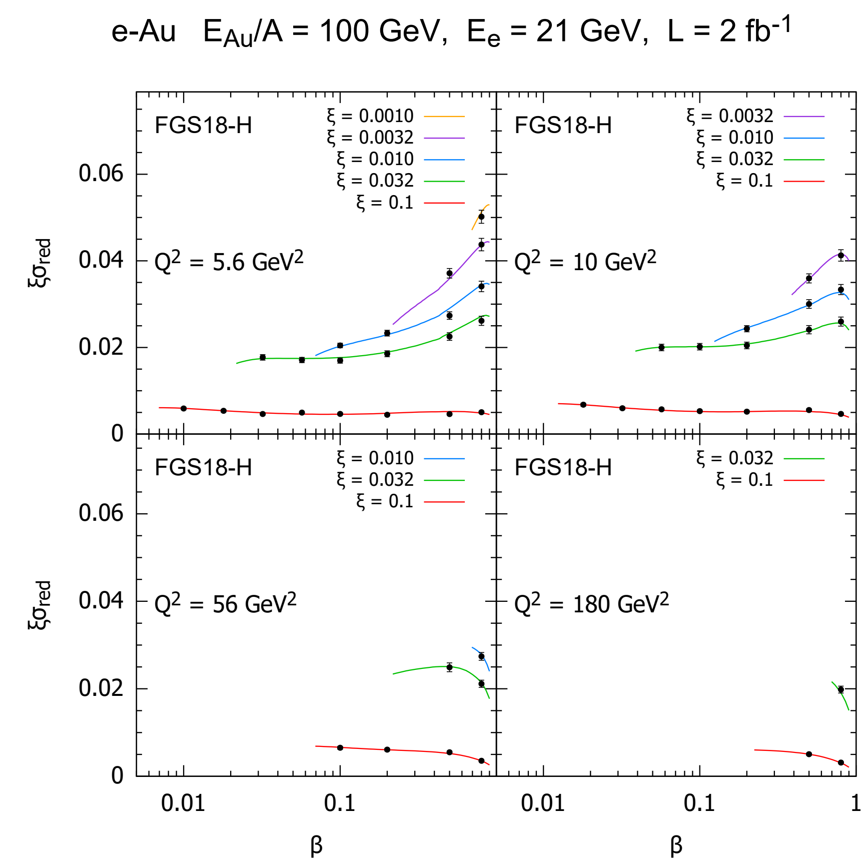


5 energies

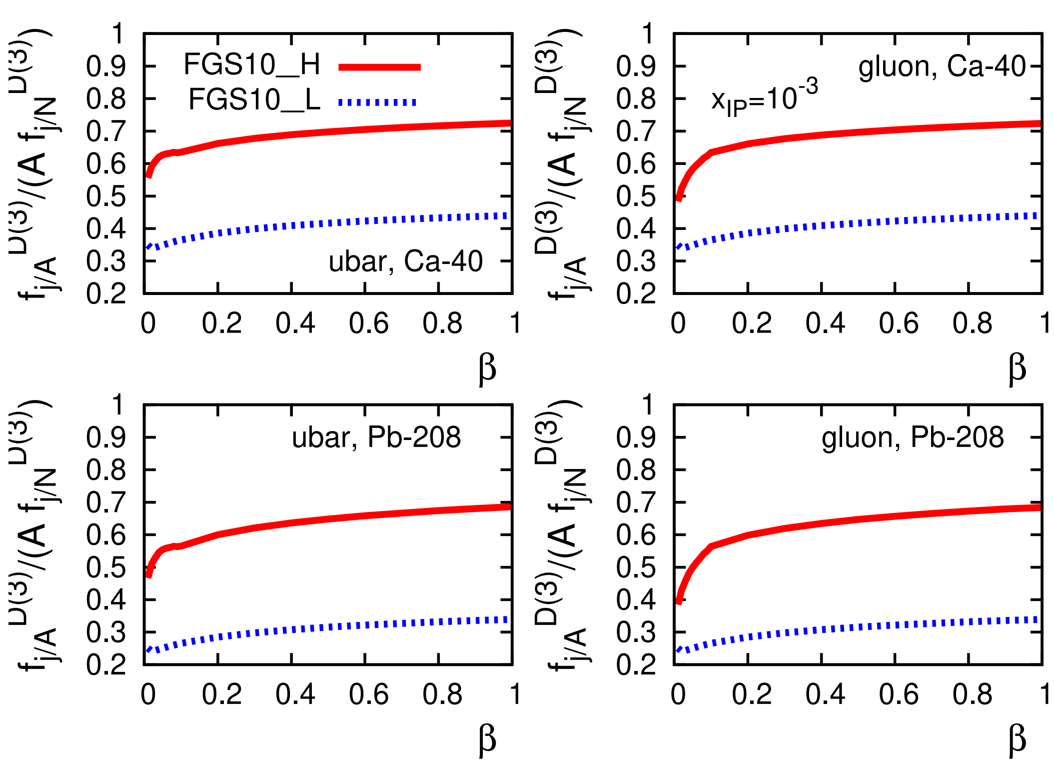
Small differences between S-17 and S-9, small reduction to range and increase in uncertainties.
More pronounced reduction in range and higher uncertainties in S-5.
An extraction of F_L^D possible with EIC-favored set of 5 energy combinations

Inclusive diffraction at EIC: nuclei

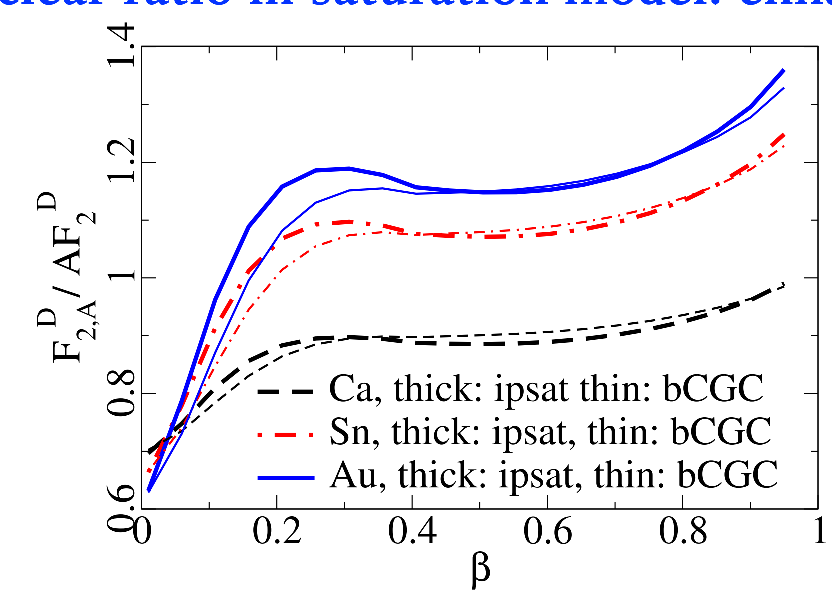
- Extraction of **nuclear diffractive parton distributions** would be possible for the first time
- Diffractive to inclusive ratio and the ratio of diffraction in nuclei to that in protons are **sensitive probes to different models**



Nuclear ratio in LT shadowing : suppression



Nuclear ratio in saturation model: enhancement



Yellow Report

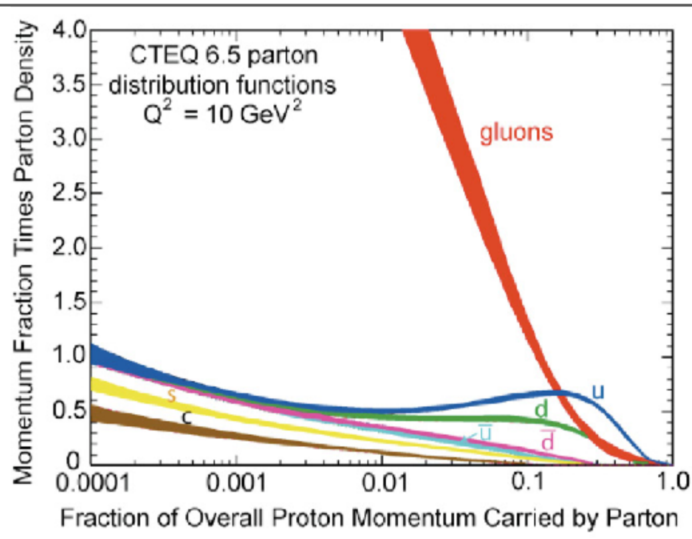
Summary

Electron Ion Collider : high energy, high luminosity, polarized, electron-proton and electron-ion collider, funded by DoE, will be built in this decade and start operating in 2030's

- **Precision tool** which will address most profound unanswered questions in QCD
- Will provide first DIS collider data for the structure functions in nuclei
- Opportunity for reducing nuclear PDF uncertainties. Challenge remains: disentangle initial conditions in linear evolution and possible nonlinear evolution effects
- Longitudinal structure function can help, if measured with high precision
- Inclusive diffraction: can provide insight into the nature of the colorless exchange(s)
- EIC is in a unique position to measure Reggeon contribution with high precision
- Opportunity to measure longitudinal structure function in diffraction: sensitivity to higher twists
- First ever measurement of the diffraction in nuclei. This may be one of the best processes to test saturation (wide variation of the models)

Backup

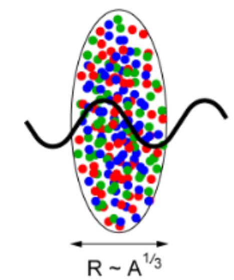
Studying saturation at EIC with nuclei



Does the rise of **gluon** $xg(x, Q^2)$ get **tamed**?

Important to understand for initial conditions in heavy ion collisions

Probe interacts **coherently** with nucleons

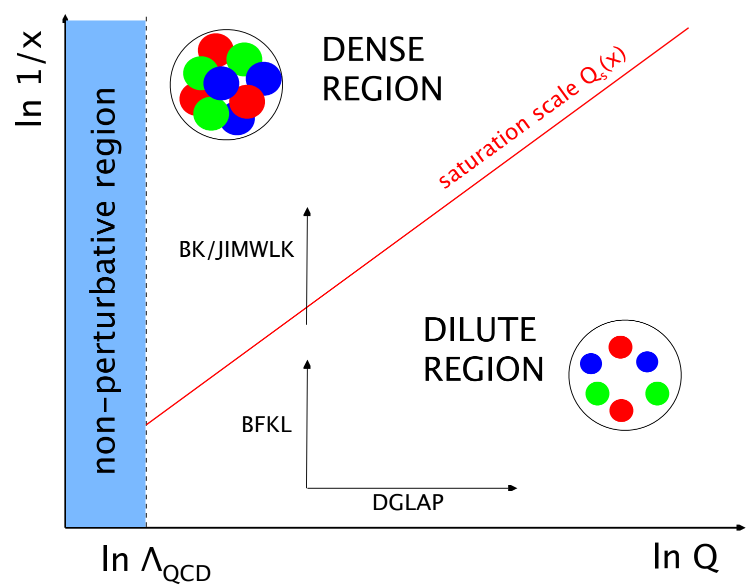


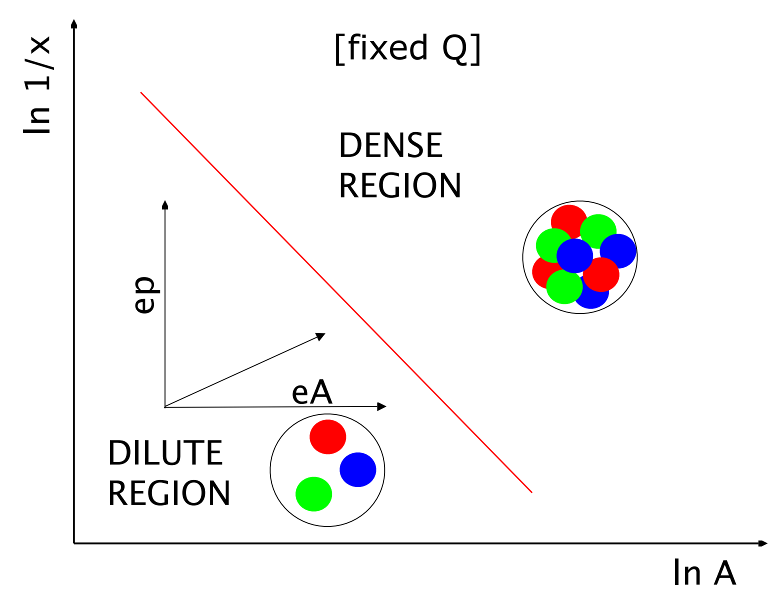
QCD at high energy (low x) and/or high density (large A) predicts **saturation** of gluons

$$Q_s^2(x, A) \sim \frac{A^{1/3}}{x^\lambda}$$

Effective theory of QCD at high energy/density:

Color Glass Condensate CGC *McLerran, Venugopalan,…*

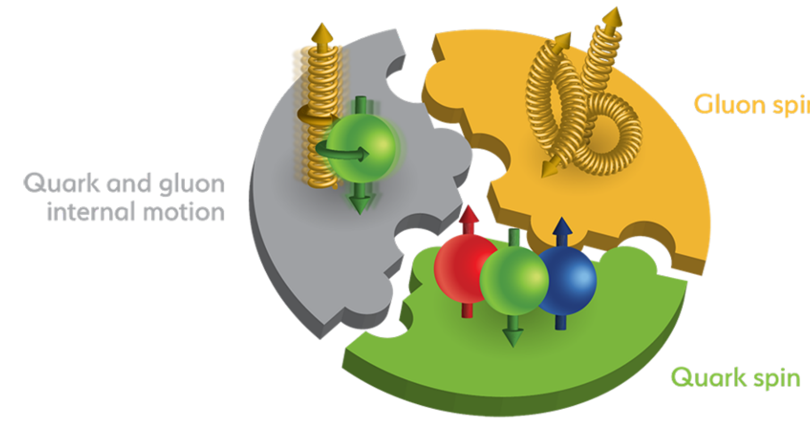




Nuclei provide enhancement of the density : opportunities to test saturation at EIC

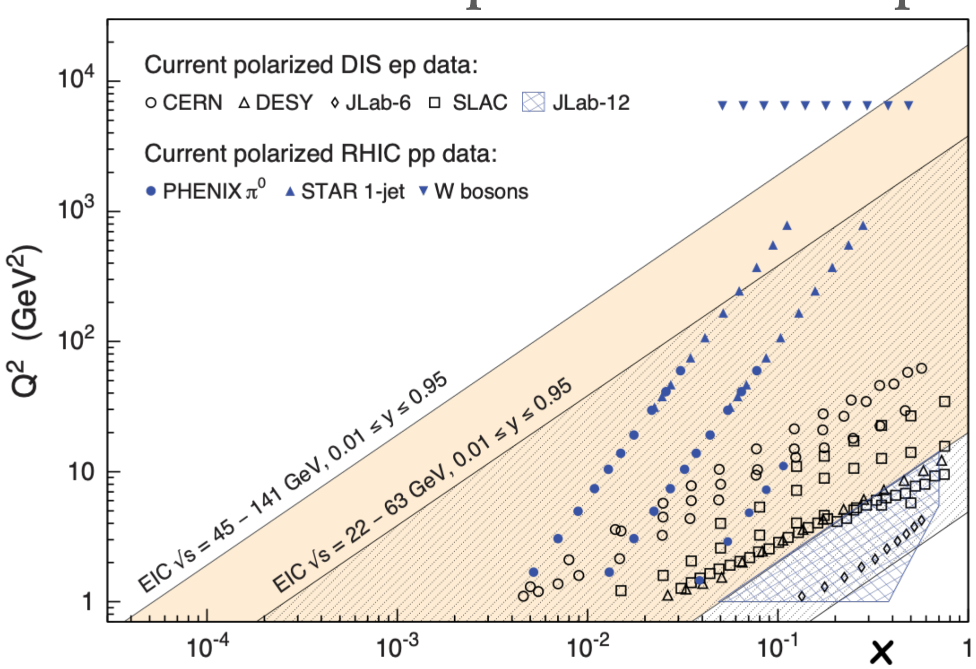
Proton spin

- **Spin** is fundamental property of particles. All elementary particles except Higgs carry non-zero spin.
- Proton spin cannot be explained within static picture.
- It depends on the intrinsic properties and interactions of quarks and gluons



$$\frac{1}{2} = \underbrace{\frac{1}{2}\int_0^1 dx\, \Delta\Sigma(x,Q^2)}_{\textit{quark spin}} + \underbrace{\int_0^1 dx\, \Delta G(x,Q^2)}_{\textit{gluon spin}} + \underbrace{\int_0^1 dx\, (\sum_q L_q + L_g)}_{\textit{orbital angular momentum}}$$

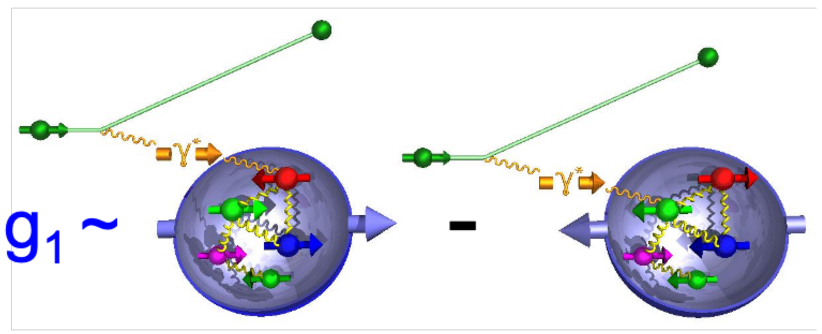
EIC kinematic plane vs current polarized data



- EIC extends range in (x,Q^2) by 1-2 orders of magnitude for polarized measurements.
- Possibilities for precision measurement of **structure function g1, gluon** contribution to proton spin, **quark** contribution, **strange** quark contribution also accessible, **polarized deuterons** allow for measurement of g_1 in a neutron

Proton spin

$$\frac{1}{2}\left[\frac{d^2\sigma^{\rightleftarrows}}{dx\,dQ^2} - \frac{d^2\sigma^{\rightrightarrows}}{dx\,dQ^2}\right] \simeq \frac{4\pi\,\alpha^2}{Q^4} y\,(2-y)\,g_1(x,Q^2)$$



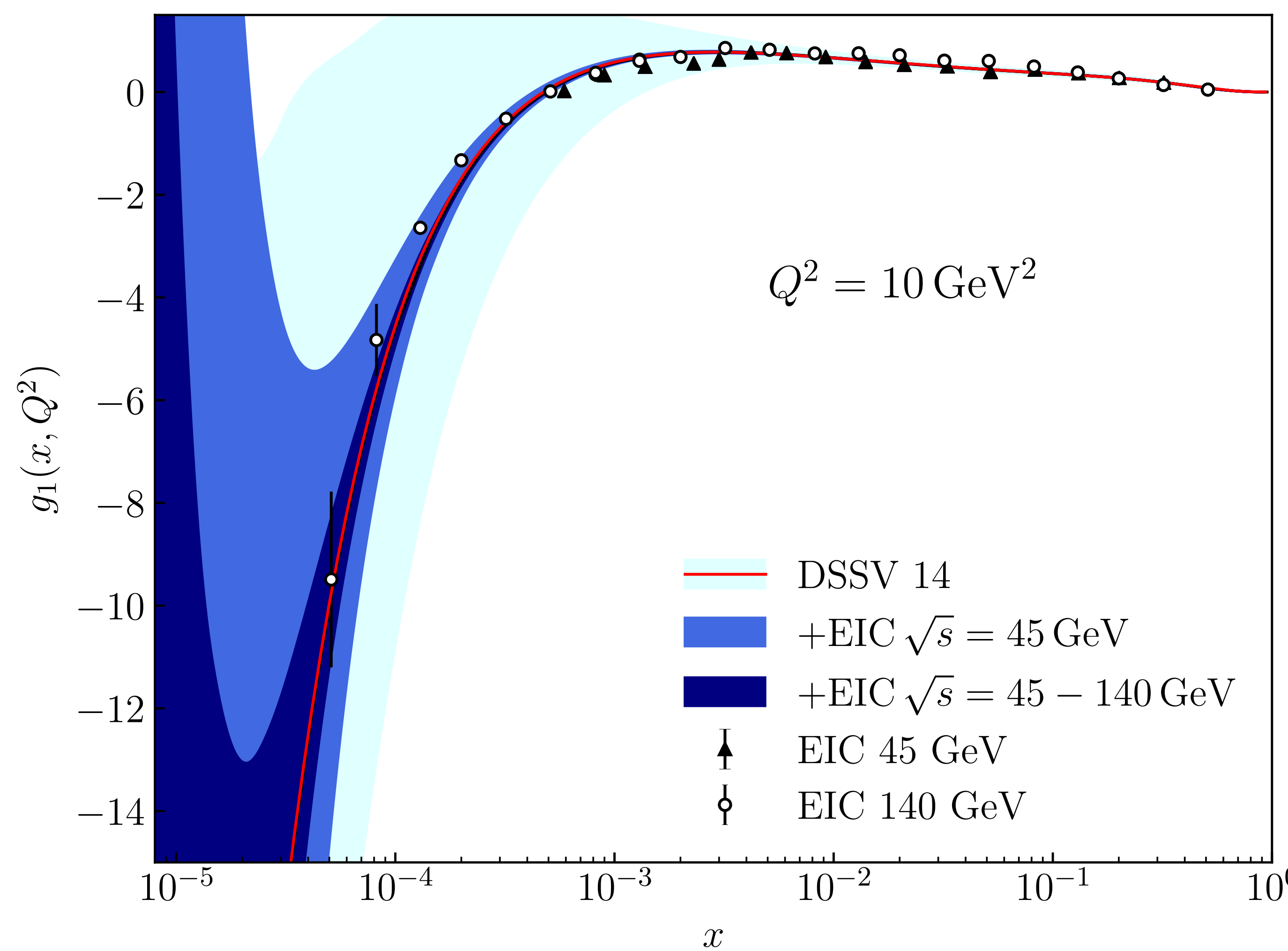
Quark contribution: integral over of g_1 over x from 0 to 1

Sensitive to **gluon** contribution Δg at higher orders: drive the scaling violations.

$$\frac{dg_1(x,Q^2)}{d\log Q^2} \sim \Delta g$$

Current uncertainties for g_1 as a function of x for fixed Q^2

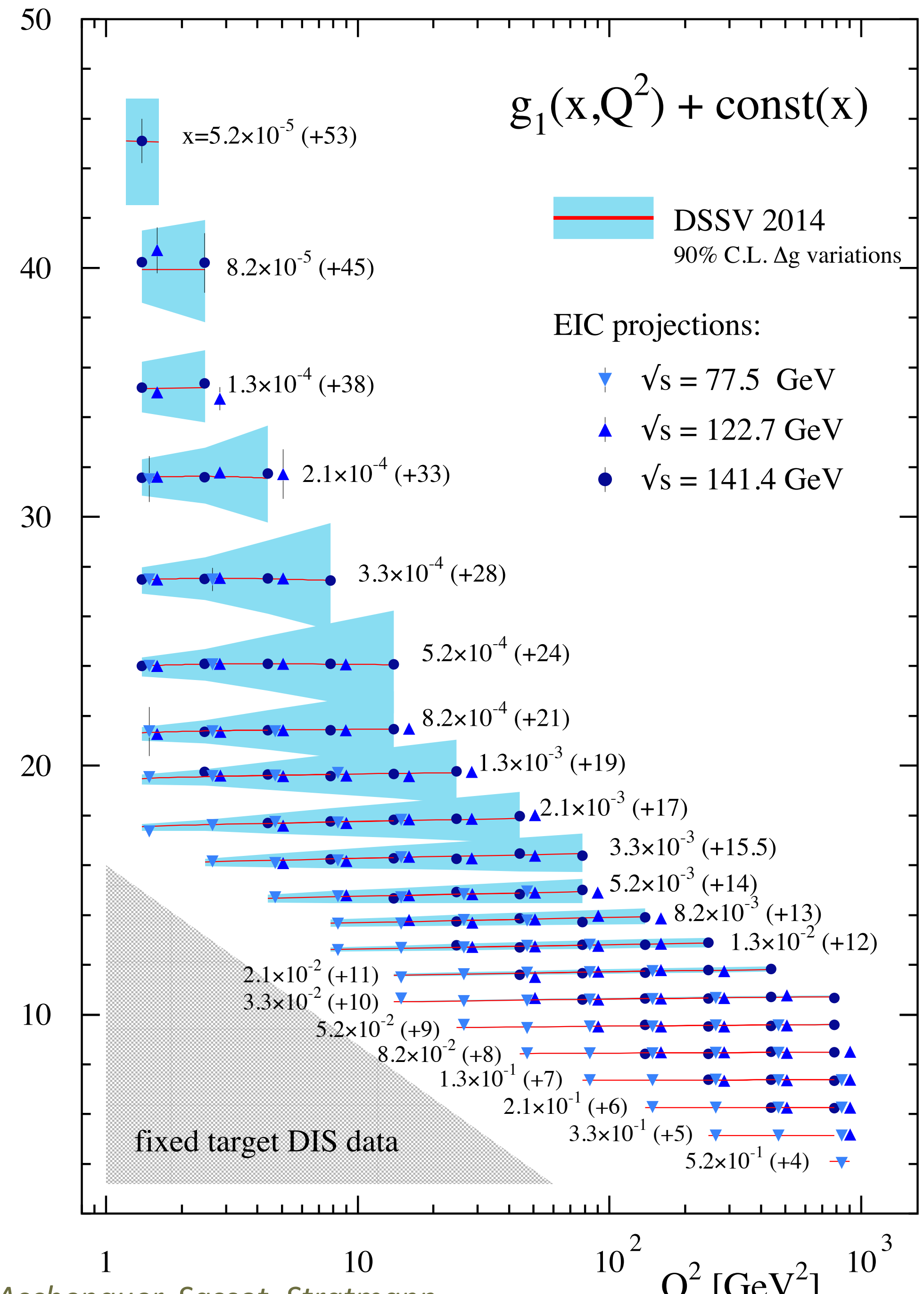
EIC projections leads to greatly reduced uncertainties



Borsa, Lucero, Sassot, Aschenauer, Nunes

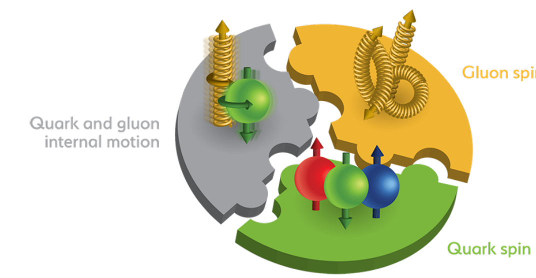
Proton spin: constraints on the OAM

EIC projections over range of x and Q²

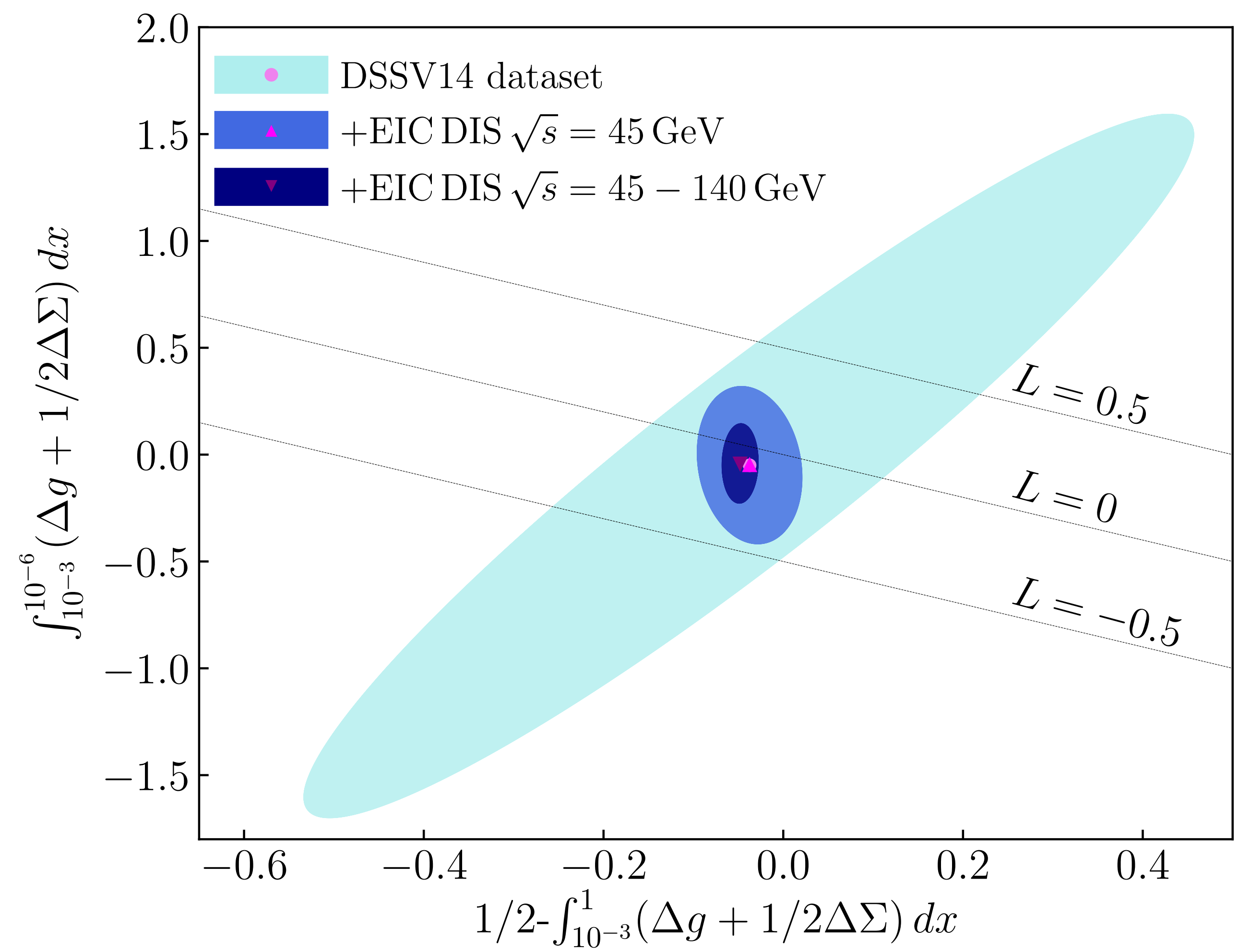


Aschenauer, Sassot, Stratmann

- Insight into quark and gluon contribution to proton spin.
- By subtracting these contributions one can constrain the parton **orbital angular momentum** contribution $L_q + L_g$.



Borsa, Lucero, Sassot, Aschenauer, Nunes

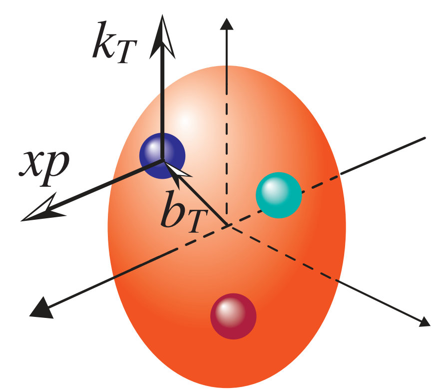


From 1D to 3D: imaging of nucleon

- Integrated PDFs provide only distribution of partons in the **longitudinal momentum fraction**
- More detailed information : **Wigner** function

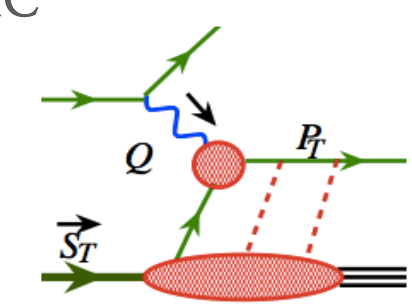
$$W(x, b_T, k_T)$$

$$\int d^2 b_T \qquad\qquad \int d^2 k_T$$



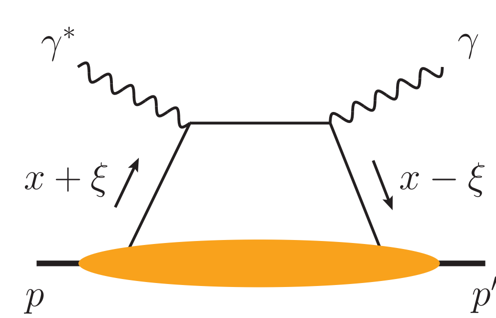
$$f(x, k_T) \qquad\qquad f(x, b_T)$$

Transverse Momentum Dependent (TMDs), measured from semi-inclusive DIS, also spin dependent at EIC

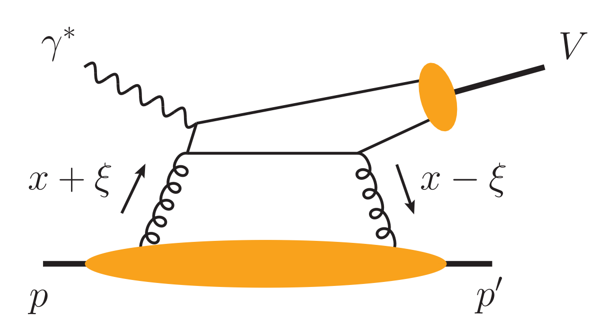


SIDIS: $Q >> P_T$

Generalized Parton Densities (GPDs) from exclusive scattering, also spin dependent at EIC



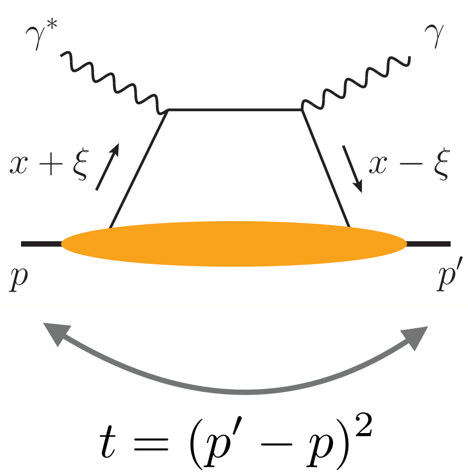
Deeply Virtual Compton Scattering

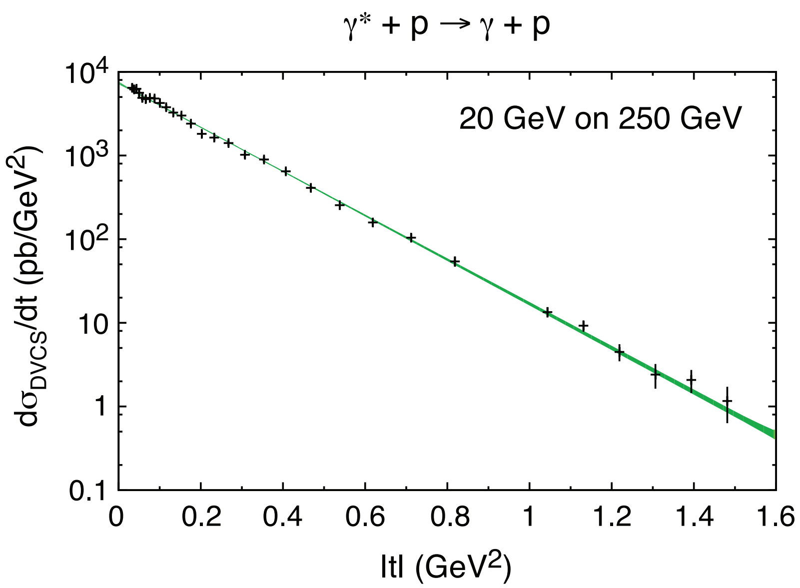


Elastic Vector Meson production

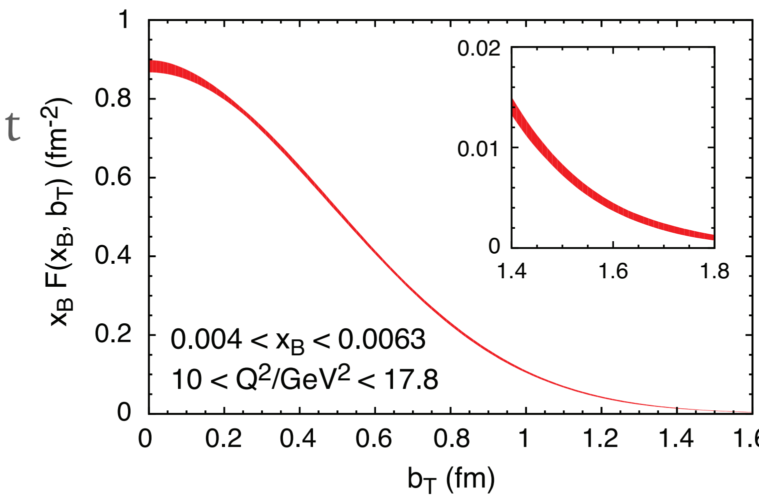
Imaging of nucleon: quarks

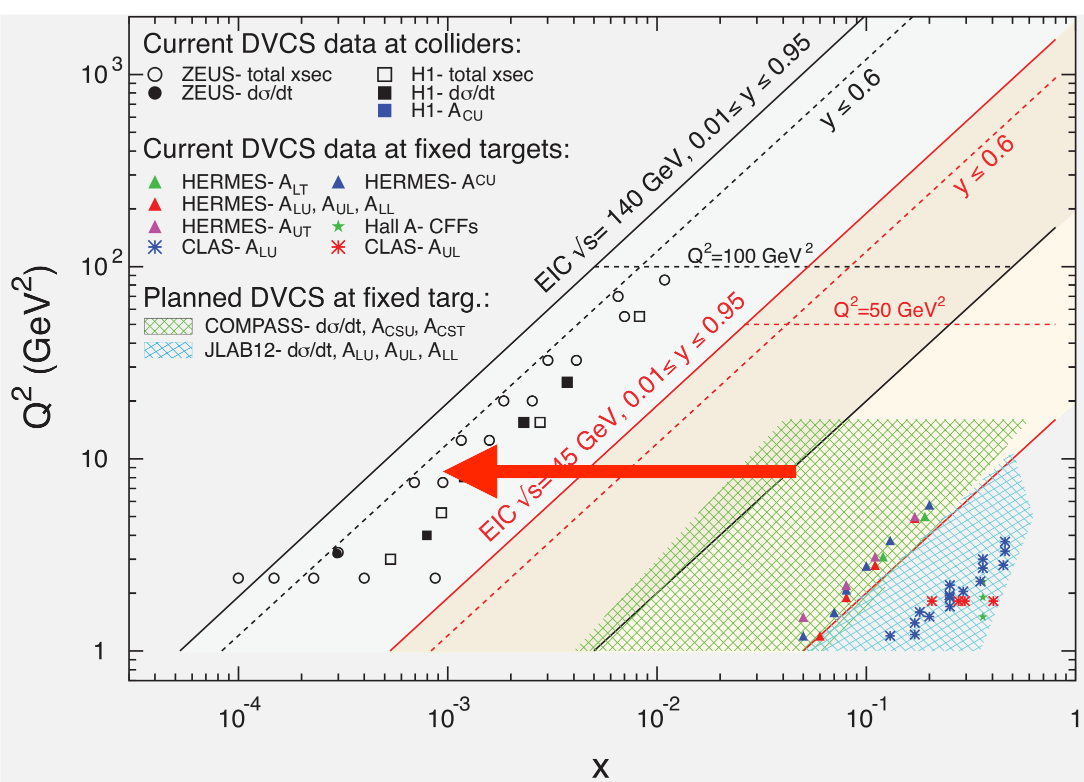
DVCS
Quark information

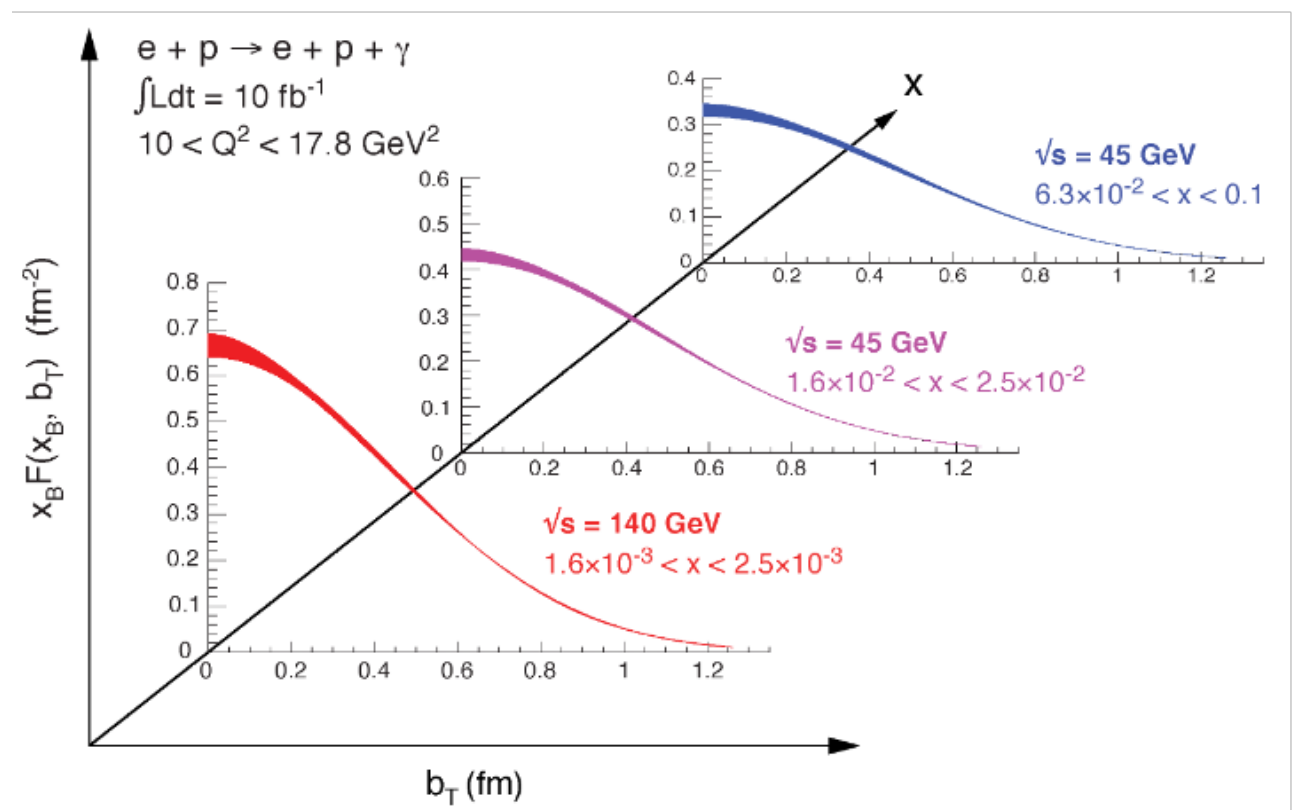




Fourier transform in t provides spatial distribution of quarks

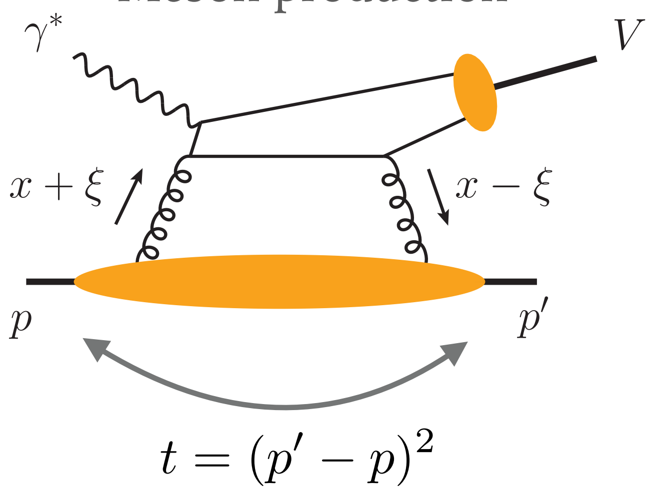


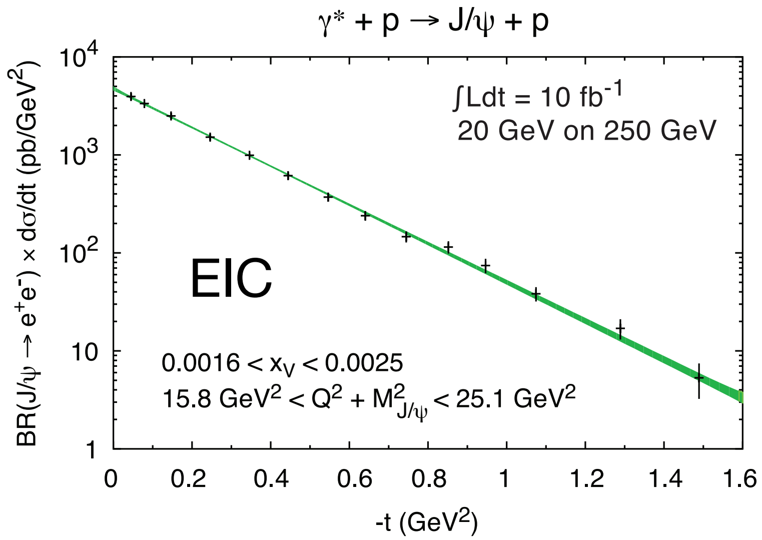




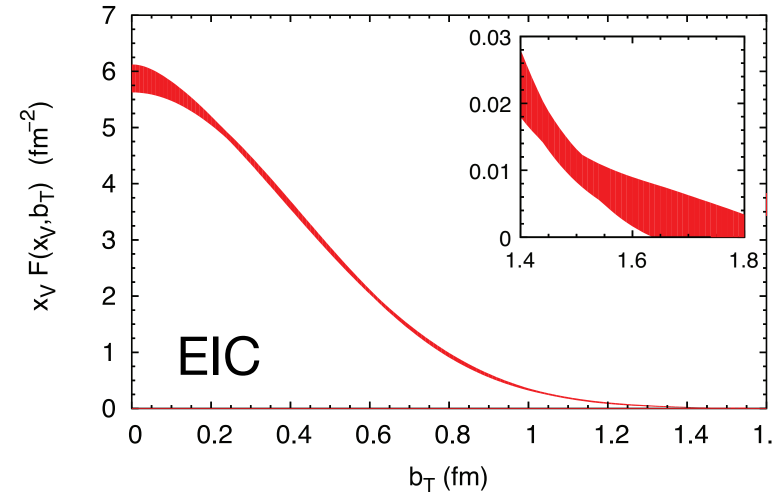
Imaging of nucleon: gluons

Elastic Diffractive Vector Meson production

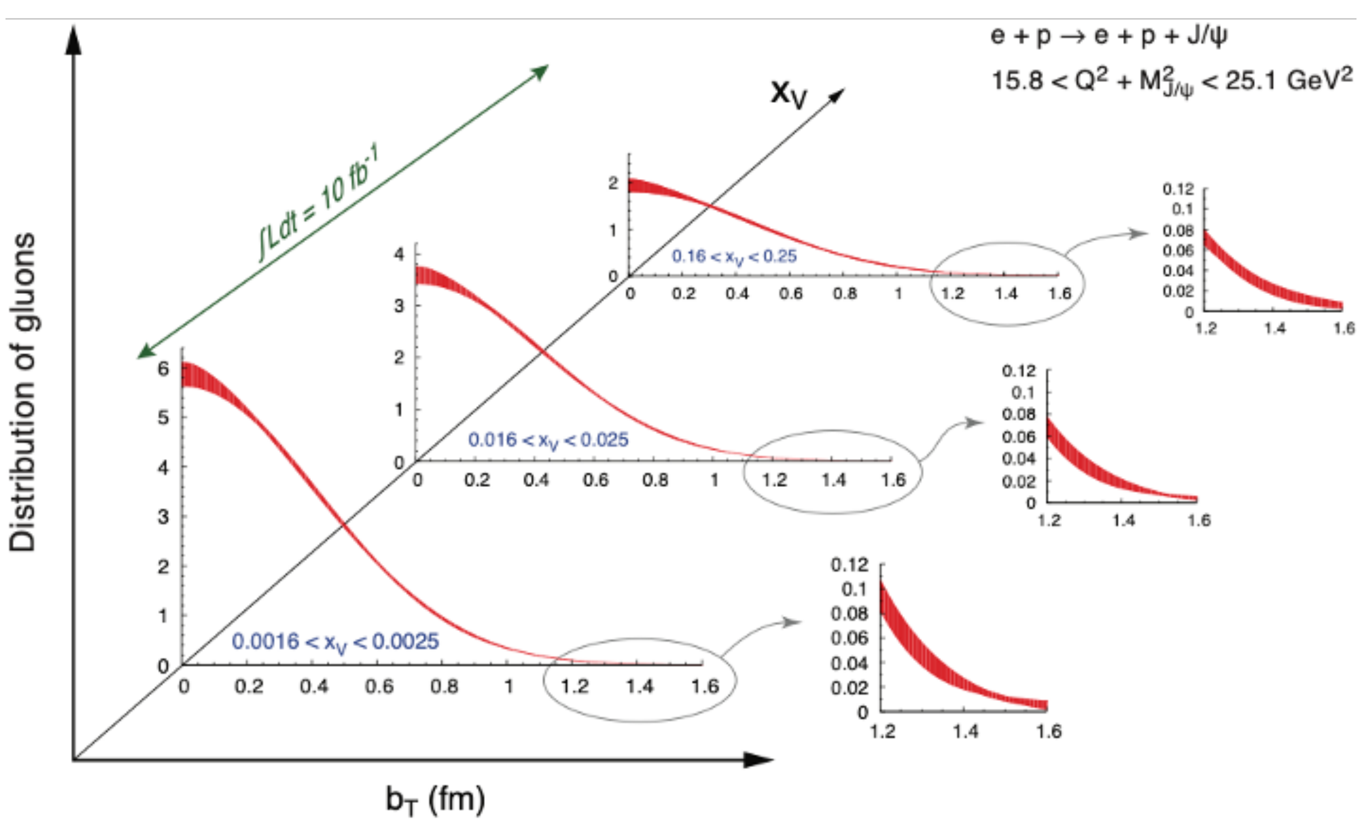




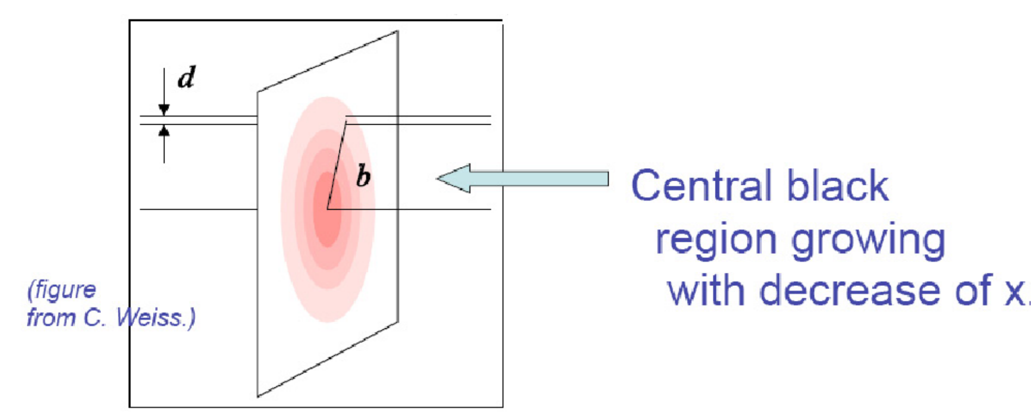
Fourier transform in t provides **spatial distribution** of gluons inside the nucleon



Extracted profiles for different x



- Large |t| probes small b : large density.
- Ideal for estimating the 'blackness' of the interaction: parton saturation



Imaging of nucleus

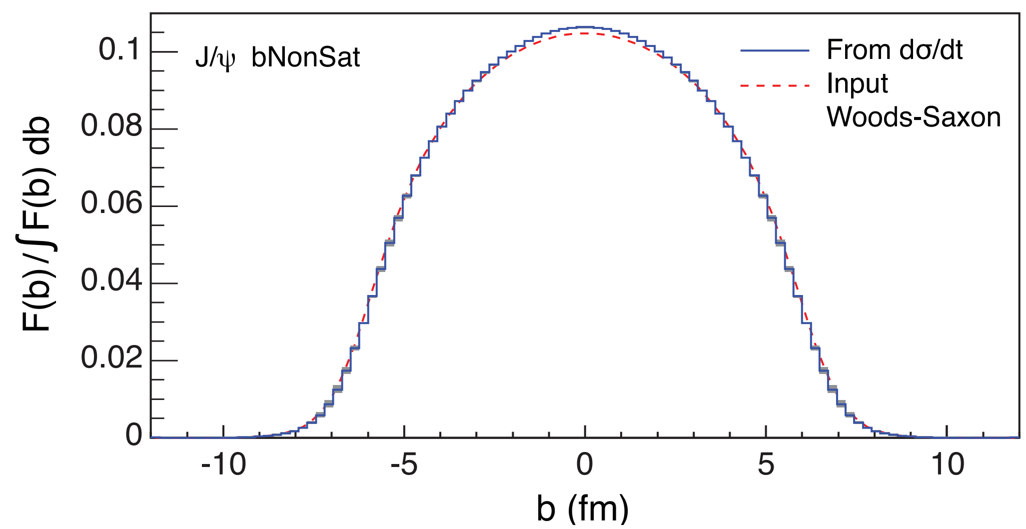
EIC, White paper

$$e + A \to e + A + J/\psi$$

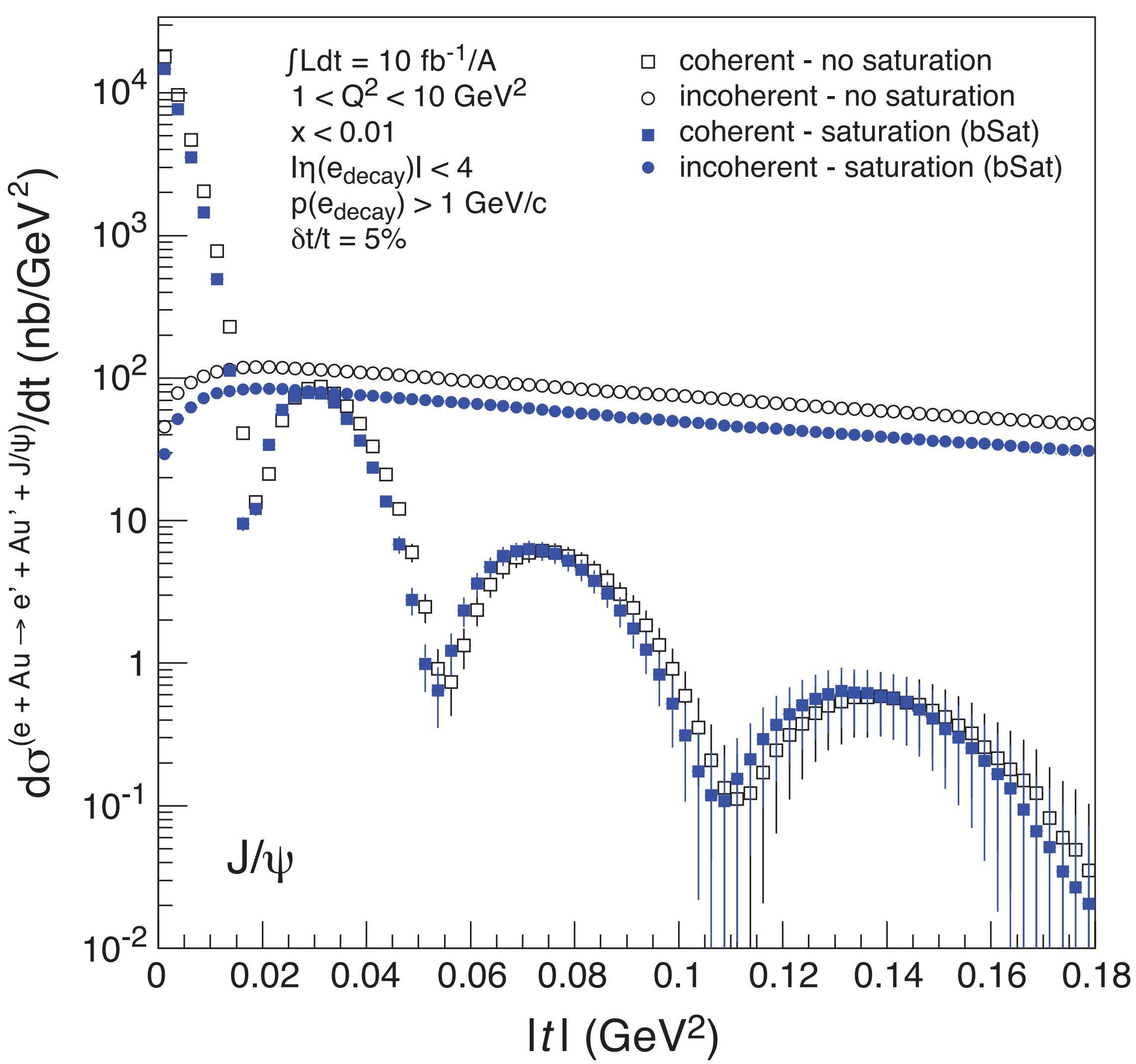
coherent: nucleus stays intact

$$e + A \to e + (A' + p + n + \ldots) + J/\psi$$

incoherent: nucleus breaks up



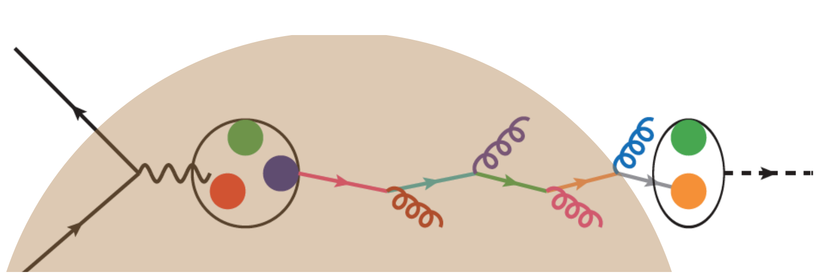
$$t = -\Delta^2 \qquad F(b) = \int_0^\infty \frac{\Delta\, d\Delta}{2\pi} J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{dt}}$$

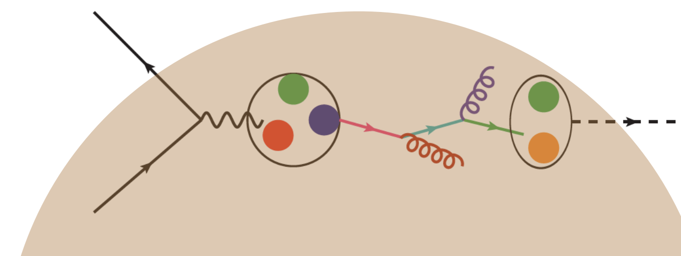


- Coherent: characteristic 'dips' in t-distribution. Sensitive to average geometry. Fourier transform: density profile
- Position of dips depends on density profile, non-linear effects, correlations
- Incoherent cross section provides information about lumpiness of the source (fluctuations)
- Experimentally very challenging (resolving dips) *see talk by Michael Pitt*
- Prospects for this process with **deuteron** and **light ions:** probing shadowing in a more controlled environment, separate **double**, **triple** scattering; spectator **tagging** on deuteron allows to study **SRC** and role of **gluons**

Passage of color charges through cold nuclear matter

- Modern theories of QCD in matter (such as $\mathrm{SCET_G}$ and $\mathrm{NRQCD_G}$) have enabled novel understanding of parton showers on matter. Capabilities to calculate higher order and resumed calculations in reactions with nuclei
- EIC will provide important input on **hadronization** mechanism in eA
- Different scenarios: **parton evolution in medium** or **hadron absorption**





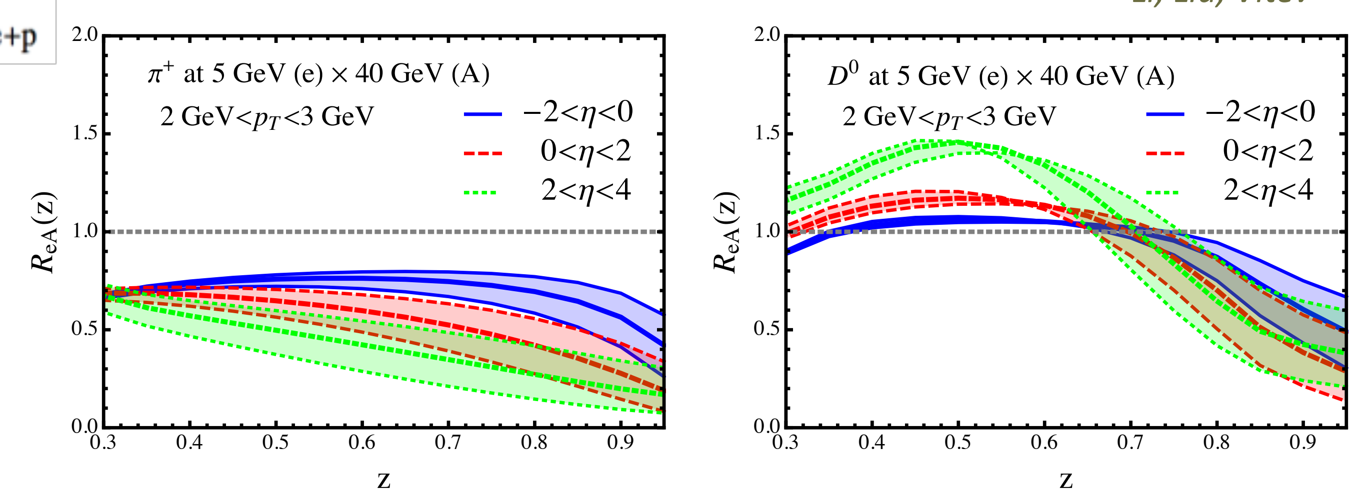
Parton energy loss and in-medium fragmentation function modification

$$\frac{d}{d\ln\mu^2}\tilde{D}^{h/i}(x,\mu) = \sum_j \int_x^1 \frac{dz}{z}\tilde{D}^{h/j}\left(\frac{x}{z},\mu\right)\left(P_{ji}(z,\alpha_s(\mu)) + P_{ji}^{\mathrm{med}}(z,\mu)\right)$$

$$R_{eA}^h(p_T,\eta,z) = \frac{\left.\frac{N^h(p_T,\eta,z)}{N^{\mathrm{inc}}(p_T,\eta)}\right|_{\mathrm{e+Au}}}{\left.\frac{N^h(p_T,\eta,z)}{N^{\mathrm{inc}}(p_T,\eta)}\right|_{\mathrm{e+p}}}$$

Modification (e+A vs e+p) of light vs heavy mesons vs the fragmentation fraction z

Li, Liu, Vitev



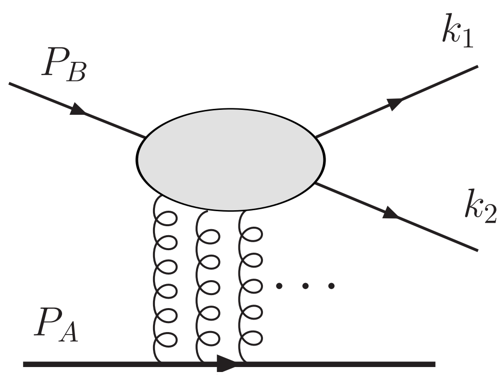
Constrain the space-time picture of hadronization.

Differentiate **energy loss** and **hadron absorption** models (based on ability to measure heavy flavors)

Lower energy beams better for this process

Testing saturation through (de)correlations of hadrons

Azimuthal (**de)correlations of two hadrons** (dijets) in DIS in eA: direct test of the **Weizsacker -Williams unintegrated gluon distribution**



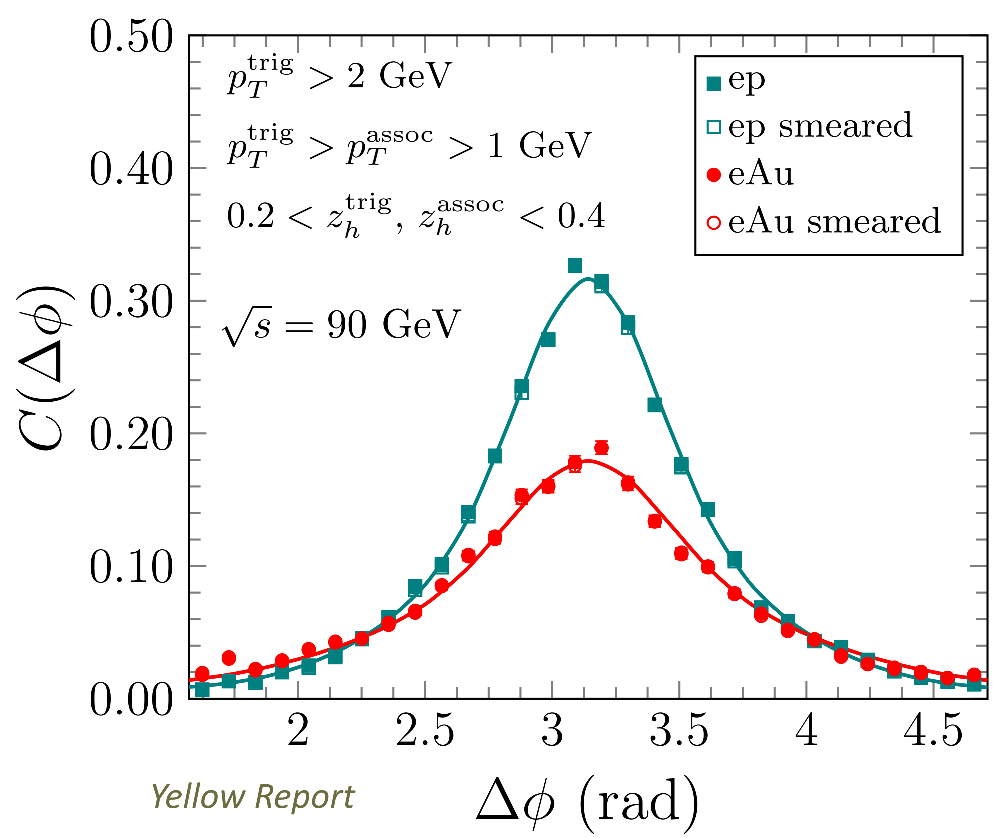
$$C(\Delta\phi) = \frac{1}{\frac{d\sigma_{\text{SIDIS}}^{\gamma^*+A\to h_1+X}}{dz_{h1}}} \frac{d\sigma_{\text{tot}}^{\gamma^*+A\to h_1+h_2+X}}{dz_{h1}dz_{h2}d\Delta\phi}$$

$$\frac{d\sigma^{\gamma^*+A\to h_1+h_2+X}}{dz_{h1}dz_{h2}d^2p_{h1T}d^2p_{h2T}} \sim \mathcal{F}(x_g,q_T)\otimes\mathcal{H}(z_q,k_{1T},k_{2T})\otimes D_q(z_{h1}/z_q,p_{1T})\otimes D_q(z_{h2}/z_q,p_{2T})$$

- Clear differences between the ep and eA: **suppression** of the correlation peak in **eA** due to **saturation** effects (including the **Sudakov resummation)**

- Further observables: azimuthal correlations of dihadrons/dijets in diffraction, photon+jet/dijet.

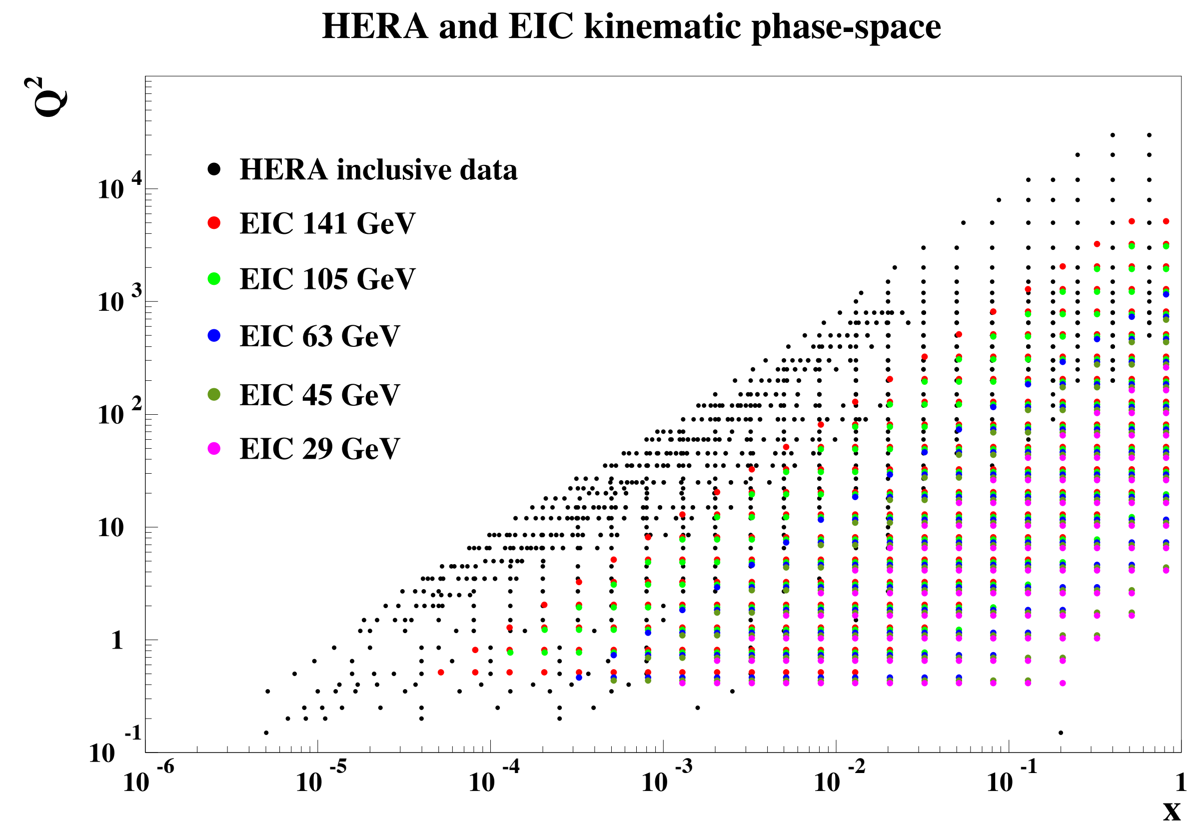
- Possibility to test various **CGC correlators**



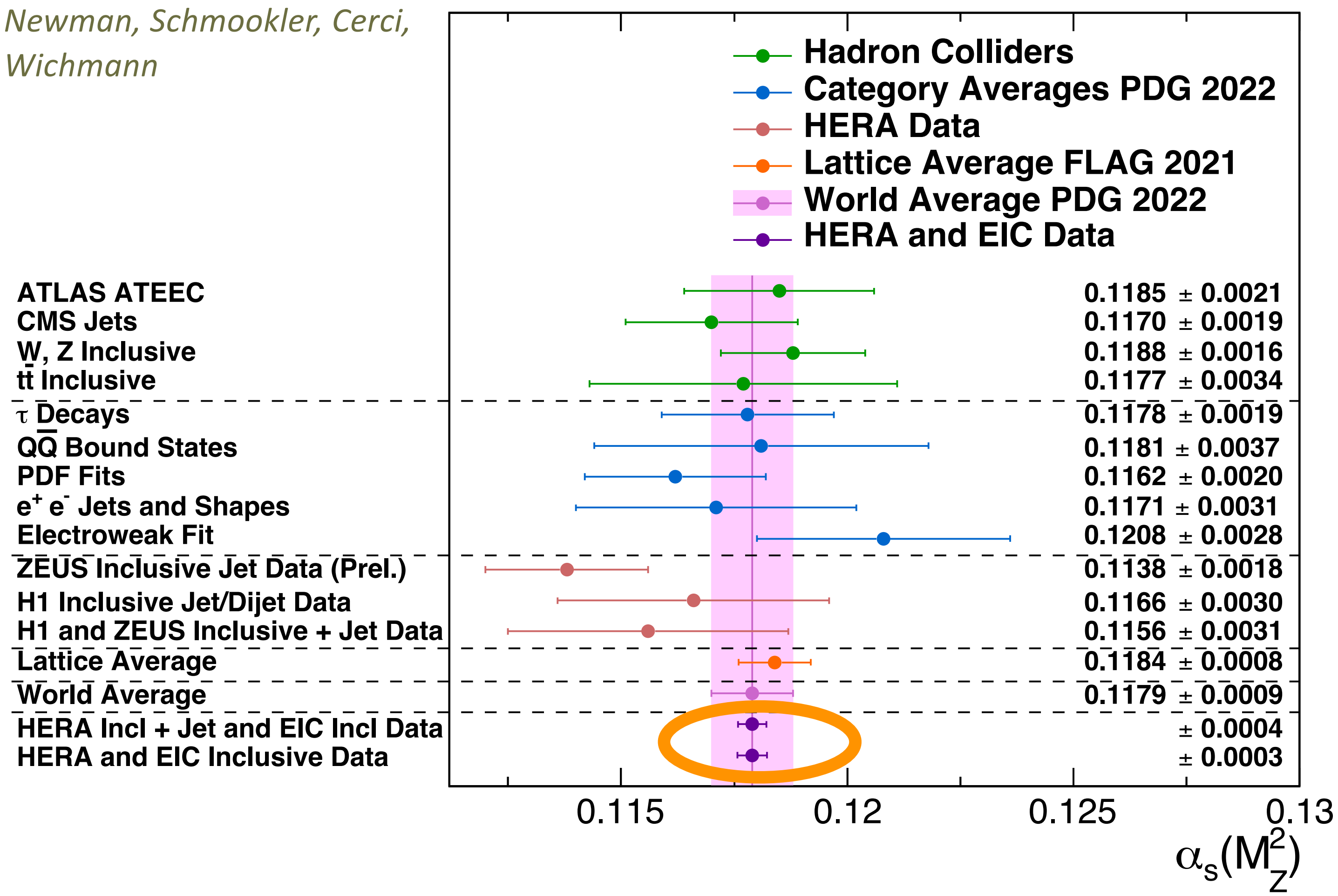
Yellow Report

Extraction of α_s from HERA and EIC

- Inclusive DIS cross section sensitive to α_s
- Need to know with **high precision**, α_s essential for **SM** calculations, and for constraints on **BSM**
- EIC complementary to HERA



Cerci, Demiroglu, Deshpande, Newman, Schmookler, Cerci, Wichmann



HERA inclusive (or inclusive + jets) + EIC inclusive data allows for **determination of α_s** with **unprecedented precision : $\leq 0.3\,\%$**

$$\alpha_s(M_Z^2) = 0.1161 \pm 0.0003\ (\text{exp}) \pm 0.0001 (\text{model} + \text{param})\ {}^{+0.0002}_{-0.0001}\ (\text{scale})$$

Jets as probes of cold nuclear matter

Jets emerged as a premier diagnostic tool for **hot** nuclear matter at RHIC and LHC

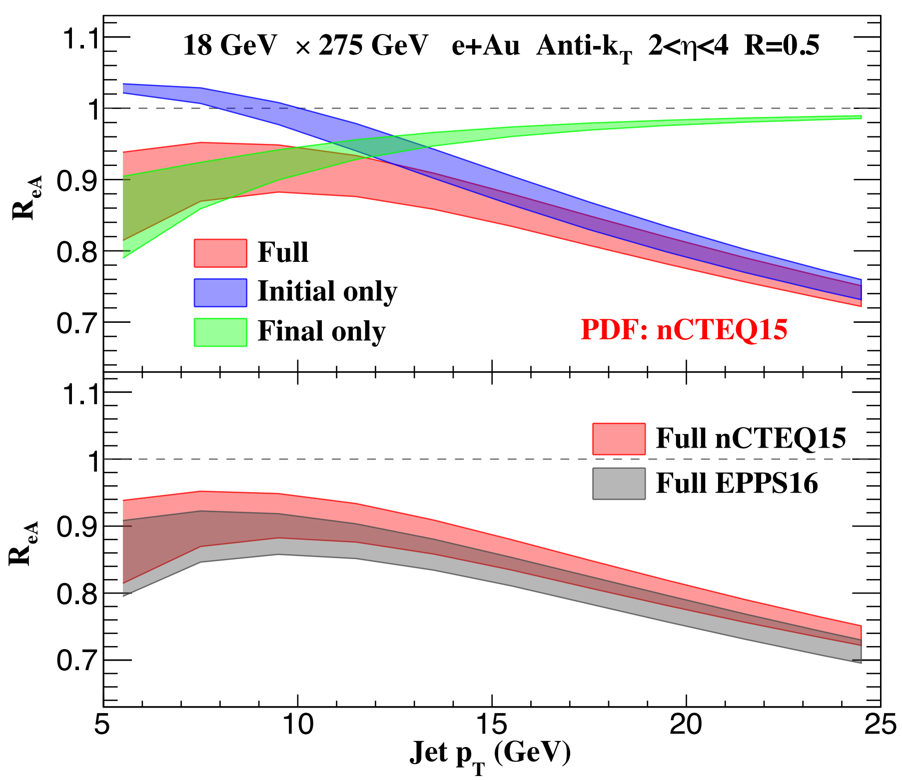
Also excellent probes for **cold** nuclear matter. Using jets, elucidate the properties of in-medium parton showers.

PDF — partonic cross section — jet function

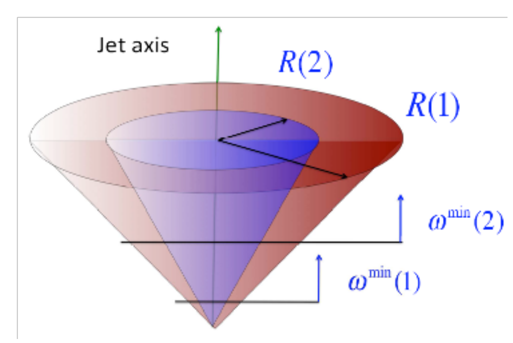
$$d\sigma \sim f_a(z,\mu) \otimes H_{ab}(x,z;p_T,\eta) \otimes J_b(z,\mu,R)$$

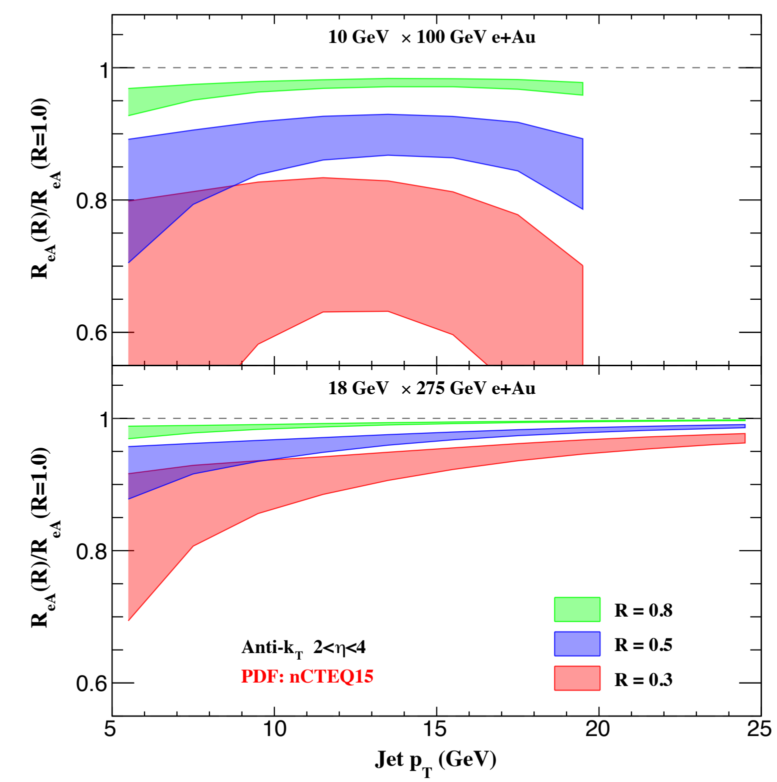
initial — final

Yellow Report



- IS (large and small p_T) vs FS (small p_T) contributions to nuclear ratio
- Small nPDF effects
- Ratios with different jet cone allow to separate parton shower effects





Li, Vitev

- Pioneer jet **substructure** studies with heavy quark initiated jets performed in a EIC regime very different from the one probed in heavy ion collisions *Li, Liu, Vitev*
- Pave the way to a qualitatively new level of understanding of the role of **heavy quark mass**

Parametrisation for fitting the pseudodata: full 4D fit IP+IR

- Treat the Pomeron and Reggeon contributions as symmetrically as possible
- Light quark separation not possible with only inclusive NC fits
- For both $I\!P$ and $I\!R$ fit the gluon and the sum of quarks
- Generic parametrization at $Q_0^2 = 1.8\ \mathrm{GeV}^2$:

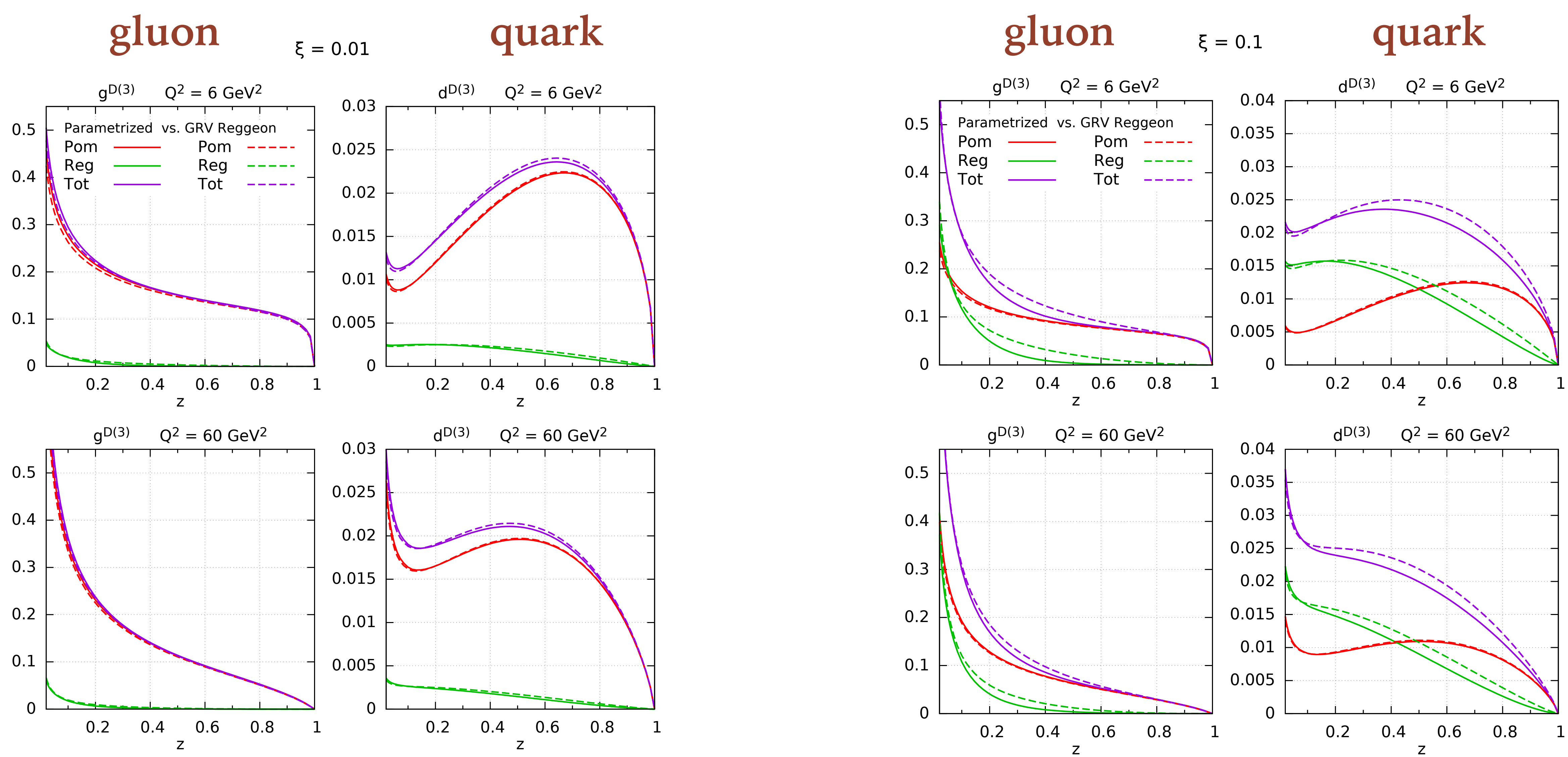
$$f_k^{(m)}(x, Q_0^2) = A_k^{(m)}\, x^{B_k^{(m)}} (1-x)^{C_k^{(m)}} (1 + D_k^{(m)}\, x^{E_k^{(m)}})$$

where $k = q, g$ and $m = I\!P, I\!R$

- Following sensitivity studies a suitable choice is:
  - $f_q^{I\!P}$ has A,B,C parameters
  - $f_g^{I\!P}$ has A,B,C parameters
  - $f_q^{I\!R}$ has A,B,C,D parameters
  - $f_g^{I\!R}$ has A,B,C parameters
- In addition fit for the parameters of the fluxes for $I\!P$ and $I\!R$: $\alpha(0), \alpha', B$

$$\frac{e^{B^{(m)}t}}{\xi^{2\alpha^{(m)}(t)-1}} \qquad \alpha^{(m)}(t) = \alpha^{(m)}(0) + \alpha'^{(m)} t$$

Recovering the Pomeron and Reggeon inputs

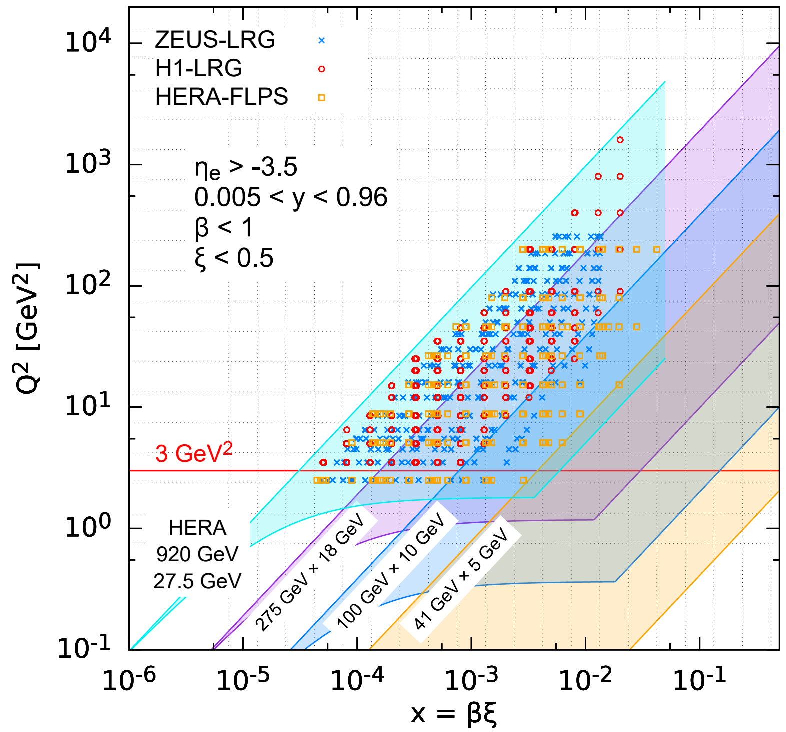


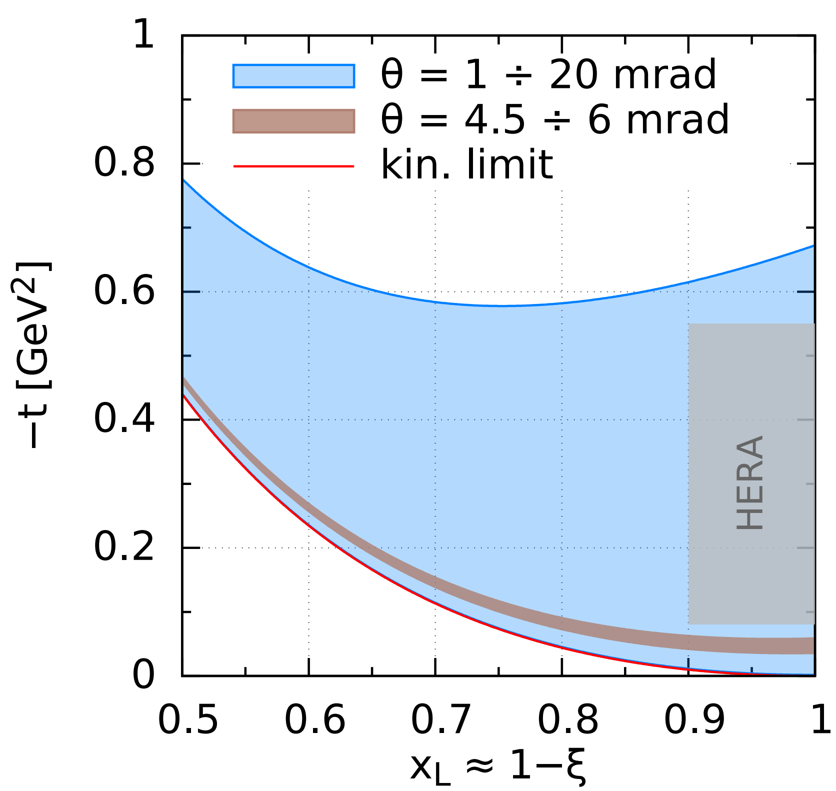
Fit results with free Reggeon parametrization (solid) made to the pseudodata based on the GRV pion structure function (dashed)

Reggeon reproduced reasonably well

Pomeron reproduced almost perfectly

Low energy scenario: 5 GeV x 41 GeV





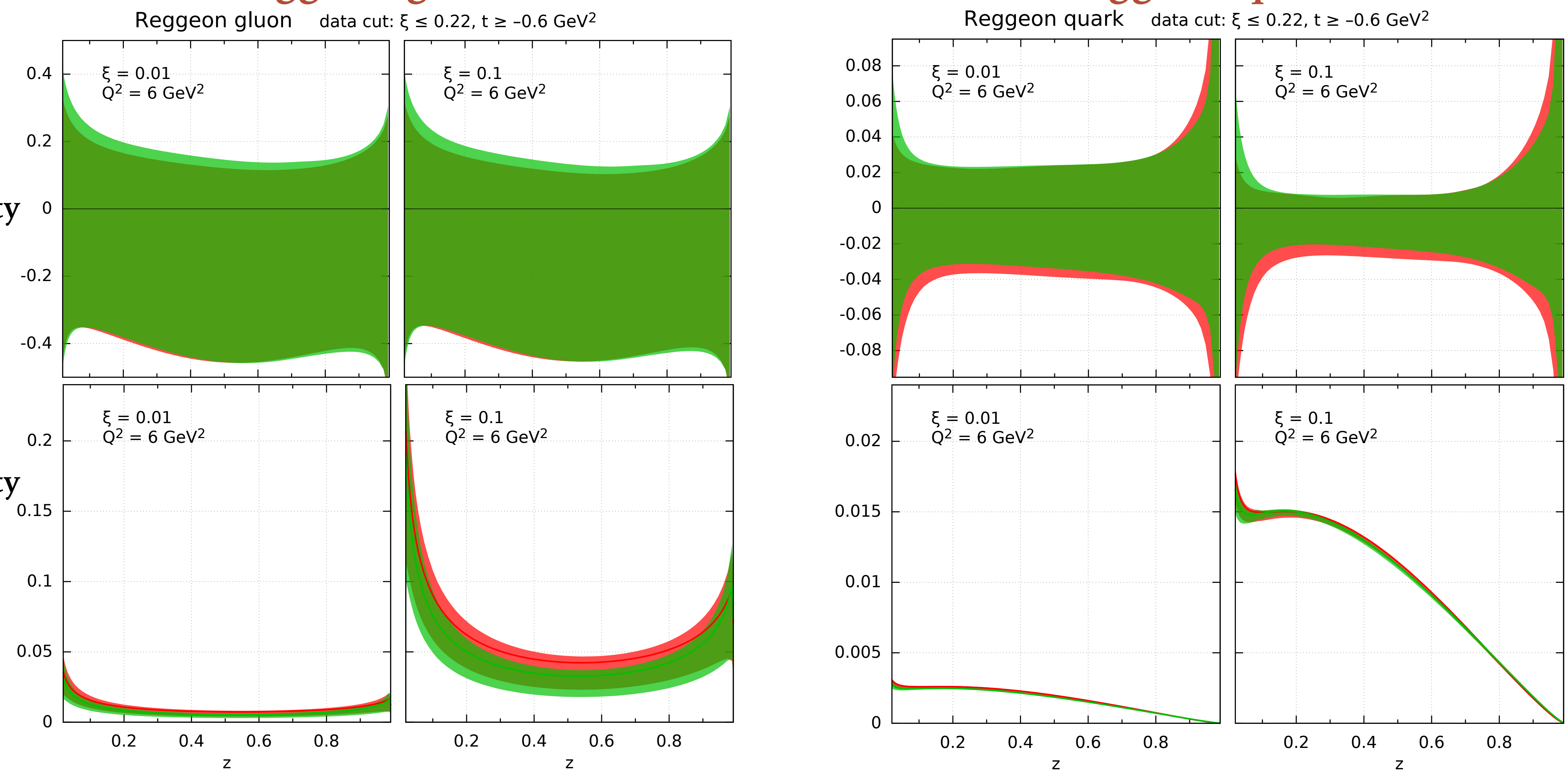
- Low energy scenario: $E_e = 5\,\text{GeV} \times E_p = 41\,\text{GeV}$
- Kinematics restricted:
  - $\xi \geq 0.01$, by cms energy
  - $t \geq -0.6\ \text{GeV}^2$, forward detector acceptance
- Reggeon dominated
- Fix Pomeron from HERA and fit only Reggeon
- Luminosity $\mathscr{L} = 10\,\text{fb}^{-1}$

Low energy: Reggeon DPDFs and uncertainties

Reggeon gluon Reggeon quark

relative uncertainty

PDF with uncertainty



- Quark Reggeon constrained very well
- Larger uncertainty for Reggeon gluon which is much smaller than Pomeron gluon
- Two bands indicate sensitivity to two Monte Carlo samples: small variation

Low energy data at EIC can already determine Reggeon