Electron-Ion Collisions at the LHeC and FCC-eh

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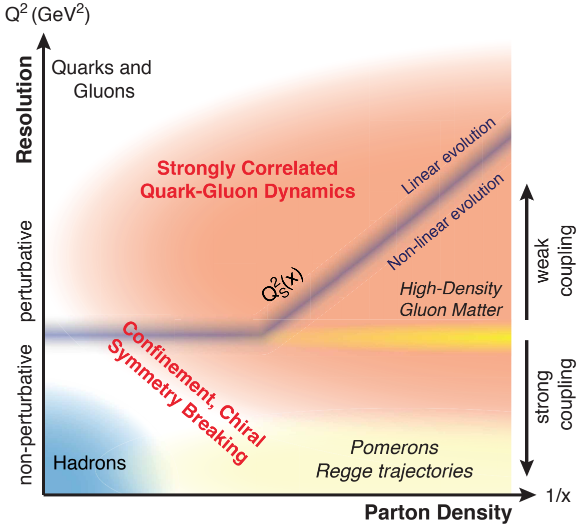
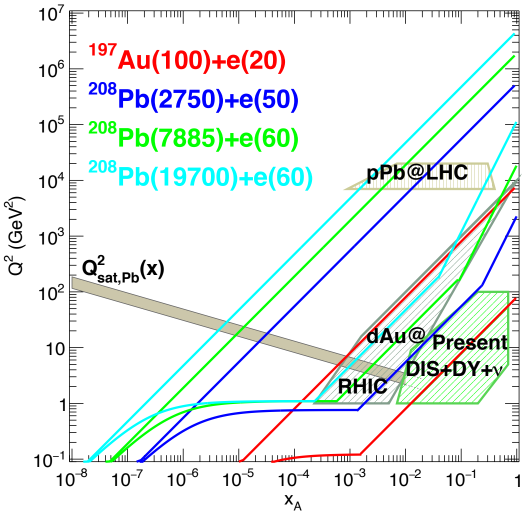
Motivation: “Cold QCD phase diagram”



- Gluon splitting: large parton densities at small x
- Non-linear regime of QCD
- LHeC and FCC:
  - Large $\sqrt{s} \Rightarrow$ small-x
  - With “nuclear oomph” $\sim A^{1/3}$
- LHeC and FCC-eh provide access to quantum field theory studies in the extremely non-linear regime
- More about the LHeC/FCC-eh project: see talk by Schwanenberger on Wednesday and plenary by Hobbs on Friday.

Aschenauer et al, arXiv:1708.01527

Wide kinematical lever arm



LHeC CDR update

- Wide range in x, Q^2
- Nuclear DIS down to $x \sim 10^{-7}$ at perturbative scales
- Non-linear dynamics in the region where Q_s^2 is a perturbative scale
- Saturation scale $Q_s^2 \sim$ scale where non-linear phenomena become important
- EIC project in the US: moving forward rapidly, but much more limited kinematics

Some eA physics highlights

CERN-ACC-Note-2020-0002
Geneva, July 28, 2020

The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group

Some physics highlights of the eA program

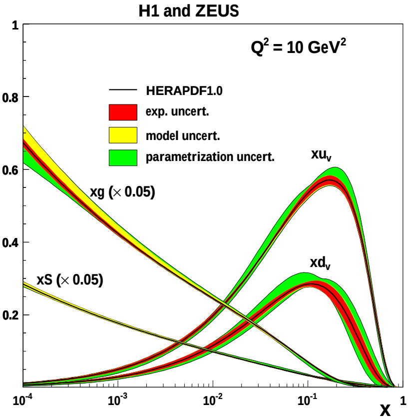
- Partonic structure of nuclei
- Exclusive processes
- Diffractive structure functions
- Non-linear QCD

Covered in detail in the LHeC/FCC-eh CDR update

Fundamentally interesting physics, with applications to e.g. Quark Gluon Plasma, Higgs, BSM etc. studies

LHeC CDR update: `arXiv:2007.14491 [hep-ex]`

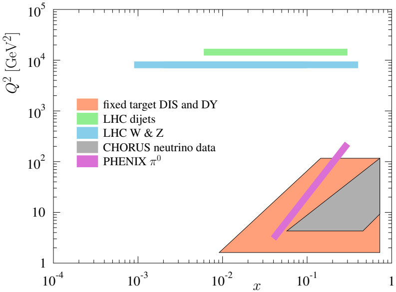
Nuclear parton distribution functions



H1 and ZEUS, JHEP 109 (2010)

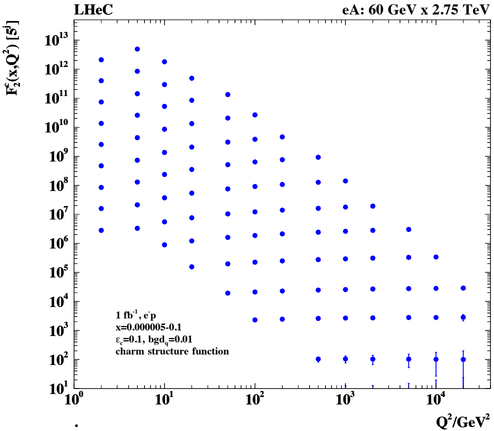
- HERA legacy: proton structure down to $x \sim 10^{-4}$
- (LHeC can help LHC studies by precise determination down to much smaller x!)
- No *eA* DIS data from colliders exist
  $\Rightarrow$ Partonic structure of nuclei at small x uncertain

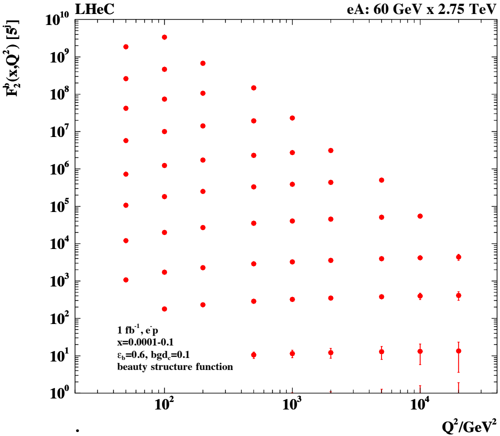
Data included in the EPPS16 fit: Eskola et al, arXiv:1612.05741



Nuclear parton distribution functions

Very precise structure function measurements (even for heavy quarks)





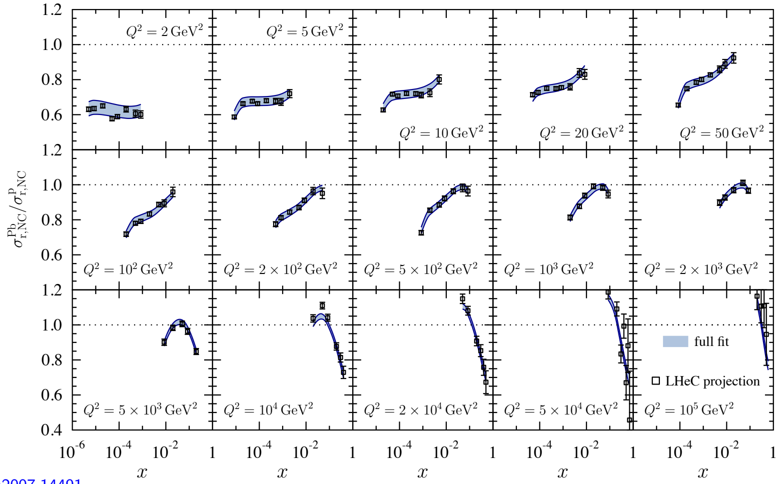
Charm: $x: 5\cdot 10^{-6} \to 0.1$

Bottom: $x: 10^{-4} \to 0.1$

LHeC CDR update arXiv:2007.14491

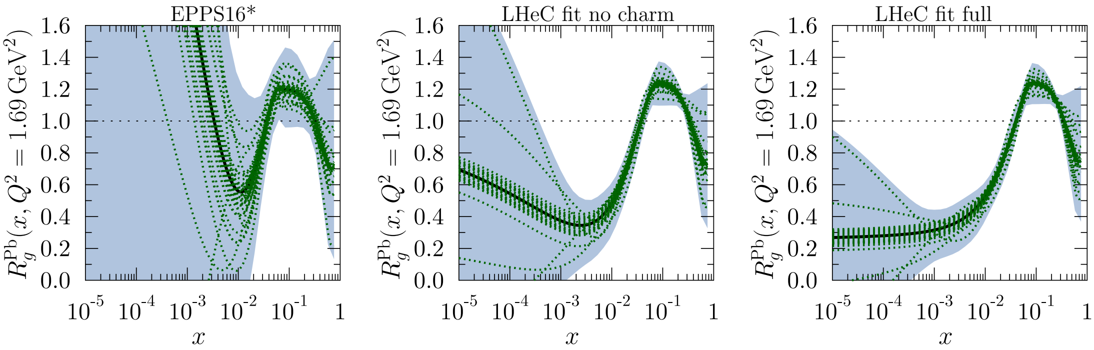
Nuclear suppression in structure function measurements

Pseudodata calculated assuming EPPS16 nuclear effects. High precision possible!



LHeC CDR update arXiv:2007.14491

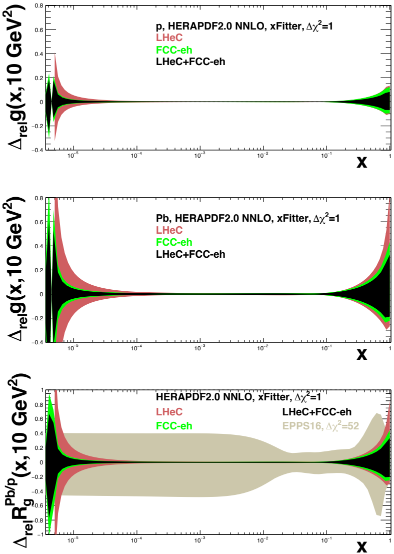
LHeC impact on global fits of nuclear parton distribution functions



- R_i: nuclear modification to the free nucleon parton distribution
- EPPS16*: flexible parametrization, large uncertainties in the region with no data
- LHeC structure function data (especially charm) provide strong constraints
- EPPS16* is a global fit, including also some LHC *pA* data!

LHeC CDR update arXiv:2007.14491 and Eur.Phys.J.C 77 (2017) 3

Ultimate precision in PDF determination



LHeC data allows for a direct determination of Pb PDF, no need to introduce e.g. A dependence

- Estimates ultimately achievable experimental precision
- In case of Pb, uncertainty $< 10\%$ down to $x \sim$ few $\times 10^{-5}$
- Huge improvement over the EPPS16 global fit
- Precision test for collinear factorization using nuclei

LHeC CDR update arXiv:2007.14491

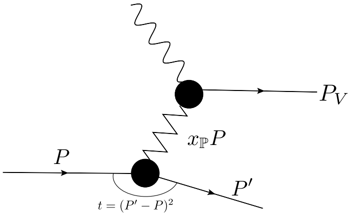
Diffraction I: Exclusive scattering

No net transfer of color charge: at least 2 gluon exchanged

- Especially sensitive to partonic structure at small x

Exclusive vector meson production: $\gamma A \to VA$

- Can also measure t (Fourier conjugate to b)
  $\Rightarrow$ access to the spatial dependence



Pocket formula for diffraction (2-gluon exchange, LO)

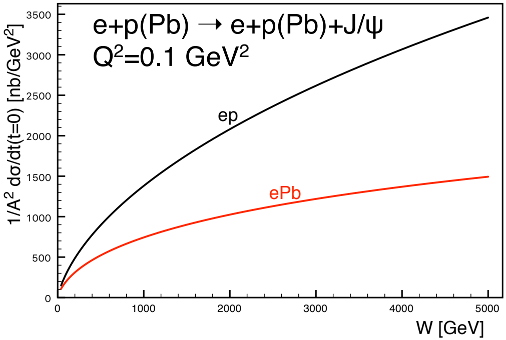
$$\left.\frac{\mathrm{d}\sigma^{\gamma^* A \to VA}}{\mathrm{d}t}\right|_{t=0} = \frac{16\pi^3 \alpha_s^2 \Gamma_{ee}}{3\alpha_{\mathrm{em}} M_V^5} \left[\mathbf{xg(x, Q^2)} \right]^2$$

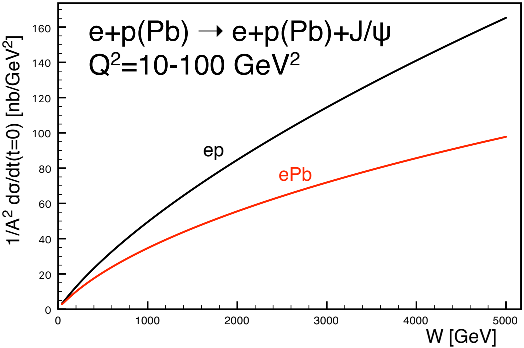
Ryskin, 1993

In practice not excatly proportional to the squared PDF, as PDFs are inclusive by definition

See however Guzey, Zhalov arXiv:1307.4526

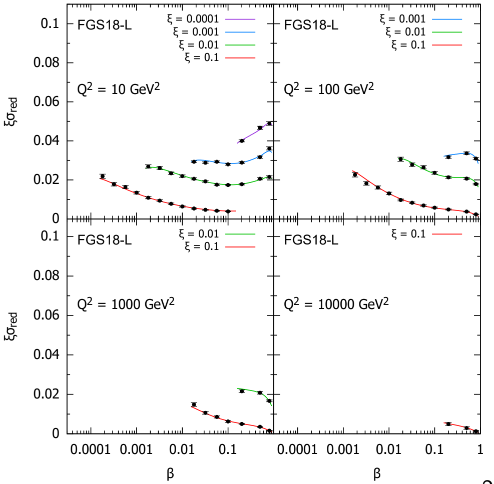
Nuclear effects in exclusive J/Ψ production





Exclusive production at $t = 0$ scales as A^2 If no nuclear effects: identical curves

- Exclusive J/Ψ production is highly sensitive to the nuclear environment at small x
- Note advantage of J/Ψ: high enough mass ⇒ perturbative (but not too large: still sensitive probe)



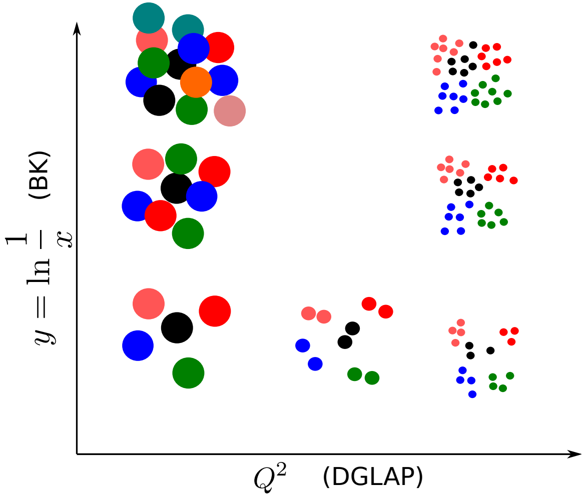
($\xi = x$ in diffraction, small $\beta \sim$ large M_X^2)

LHeC CDR update arXiv:2007.14491

Production of a system with mass M_X^2, no net color charge transfer

- Diffractive PDFs probed when target is left intact in the process
- Never measured for nuclei
- Can be determined from global fits (with DGLAP) to diffractive structure functions
- High precision measurements possible at the LHeC/FCC-eh
- Stringent test for models: simultaneous description of nuclear effects in inclusive and diffractive events

Non linear QCD

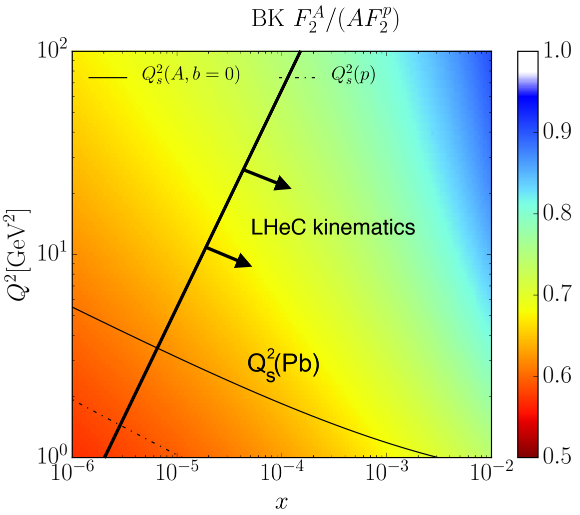


Comprehensive physics program to discover non-linear QCD dynamics

- Nuclear suppression:
  Inclusive and exclusive scattering
- Two particle correlations
  - Azimuthal angle
  - Rapidity
- Collective dynamics (flow)
- Hadronization in nuclear medium
- ...

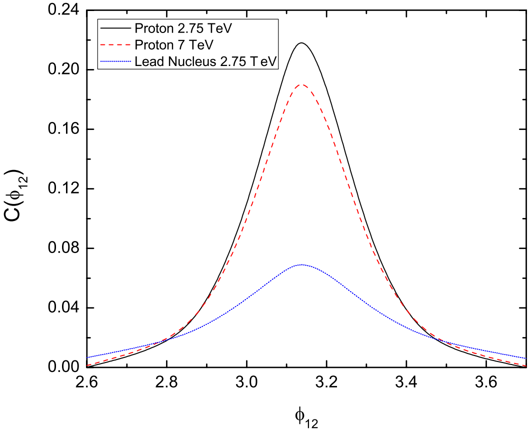
Potential to study non-linear QFT!
With implications to e.g. LHC physics

Dilute-dense transition



- Saturation effects important at scales $\lesssim Q_s^2 \sim A^{1/3} x^{-0.2}$
- Wide x, Q^2 coverage: can study transition to the saturation region at perturbative scales at small x
- Tension in DGLAP fits not including non-linear dynamics?

Color Glass Condensate prediction based on H.M, T. Lappi, arXiv:1309.6963



$e + A \rightarrow h + h + X$ LHeC CDR arXiv:1206.2913

Power of more differential measurements, e.g.

- Azimuthal correlations of hadrons
- Gluon saturation: gluons have $p_T \sim Q_s \sim A^{1/3} x^{-\lambda}$
- Prediction: back-to-back peak disappears:
  - Increasing A
  - Decreasing x / increasing $\sqrt{s}$
- Power of nuclei: Huge nuclear *oomph*

Conclusions

- High energy nuclear DIS at LHeC and FCC-eh, with center-of-mass energies in TeV range
- High precision and large kinematical coverage enable a comprehensive physics program
- eA collisions is a central part of the physics program
  - Nuclear PDF, diffractive PDF, exclusive processes, non-linear QCD
- Probe QCD in high density region with multiple probes to reveal non-linear dynamics

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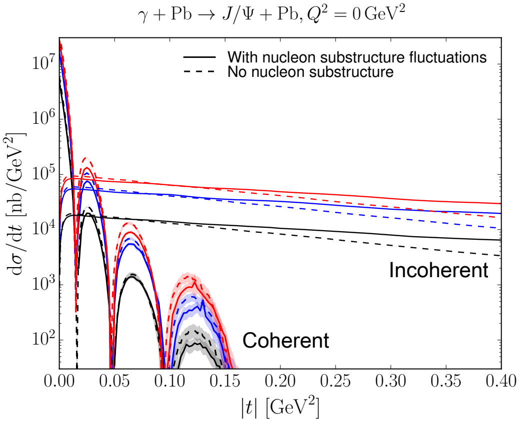
See also other LHeC/FCC-eh talks

- *BSM Physics at the LHeC and the FCC-eh*: Tuesday
- *The ERL Facility PERLE at Orsay*: Tuesday
- *Determination of the Parton Densities in the Proton at the LHeC*: Wednesday
- *The Large Hadron-electron Collider at CERN: Status and Plans*: Wednesday
- *The LHeC as Part of the HL-LHC Programme*: Thursday
- *Top physics at the LHeC and the FCC-eh*: Thursday
- *Higgs physics at the LHeC and the FCC-eh*: Thursday
- *Precision electroweak measurements at the LHeC and the FCC-eh*: Thursday
- *Small-x physics at the LHeC and FCC-eh*: Thursday

Backups

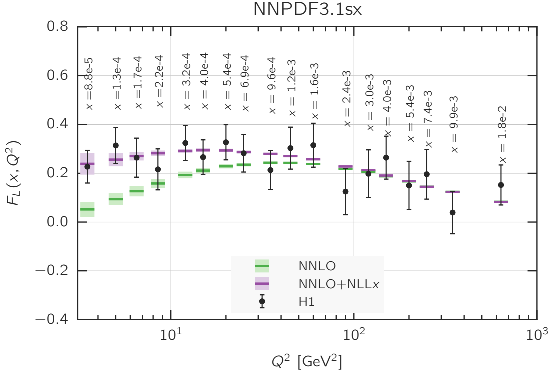
Differential imaging with exclusive processes



Coherent: Pb remains intact
Incoherent: target breakup
$W = 0.1, 0.813, 2.5$ TeV

- Fourier transform coherent spectra $\to$ spatial distribution of small-x gluons
- Incoherent cross section: sensitive to e-b-e fluctuations of the scattering amplitude
- Dashed line: only nucleon positions fluctuate, solid: also nucleon substructure
- Substructure fluctuations: large effect at large $|t|$ (small length scale)
- LHeC/FCC-eh kinematical coverage: study x evolution of fluctuations

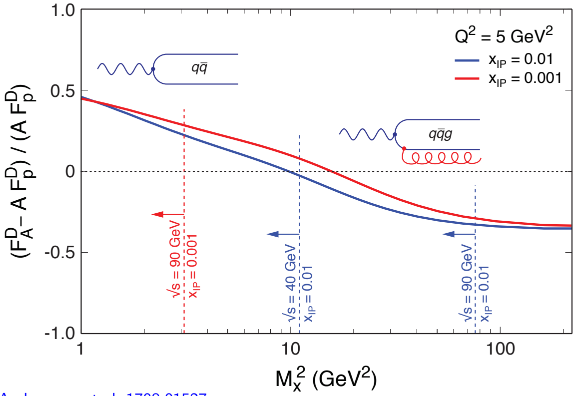
Figure: LHeC CDR update arXiv:2007.14491. Nucleon shape fluctuations: H.M, Schenke, PRL 117 (2016) 052301, see also review arXiv:2001.10705



Ball et al, arXiv:1710.05935

- At small-x, gluon density $\sim 1/g$
- Resumming large logs $\alpha_s \ln 1/x$ necessary
- HERA F_L data seems to prefer NNLO calculation with resummation
- Expect much larger effect at the LHeC/FCC-eh kinemaitcs

Importance of wide kinematical domain



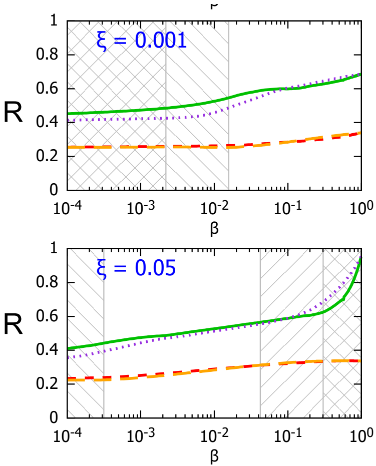
Aschenauer et al, 1708.01527

- Large M_X^2: nucleus absorbes $q\bar{q}g$ dipole more strongly, nuclear suppression
- Small M_X^2: todo why

This transition at small x is accessible only with high $\sqrt{s}$; EIC at the US is borderline, LHeC can do MUCH better

Nuclear effects in inclusive diffraction

Nuclear suppression factor in inclusive diffraction (1 = no nuclear effects)



$(\xi \sim x_B,\ \beta\ \sim 1/M_X^2)$

- Prediction: large suppression observable in a wide kinematical window
- Nuclear effects potentially different compared to inclusive scattering
- Multiple probes of the high density nuclear matter
- Hatched area: kinematically excluded in LHeC/FCC-eh

LHeC CDR update and 1901.09076