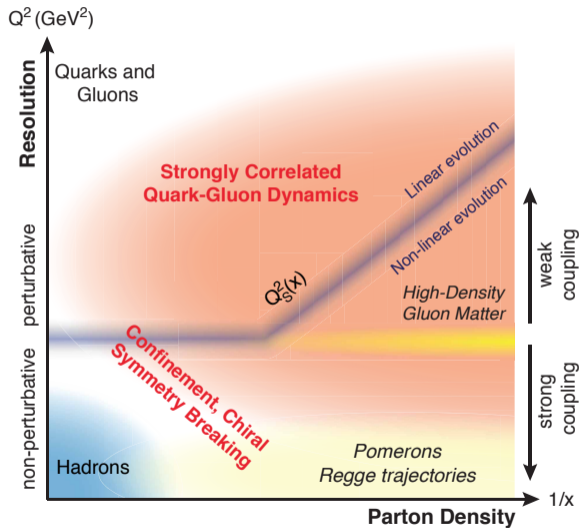


Electron-Ion Collisions at the LHeC and FCC-eh

Heikki Mäntysaari
LHeC Study Group

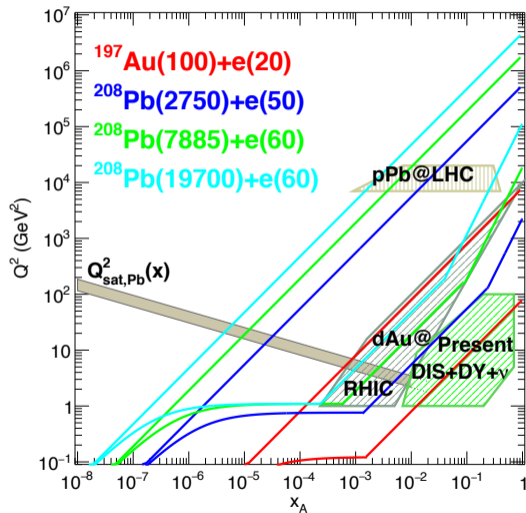
University of Jyväskylä, Department of Physics
Finland

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:
talk by Bernhard Holzer on Thursday

Wide kinematical lever arm



- 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
Version v2.0
Geneva, June 18, 2020



The Large Hadron-Electron Collider at the HL-LHC

LHeC Study Group



To be submitted to J.Phys. G

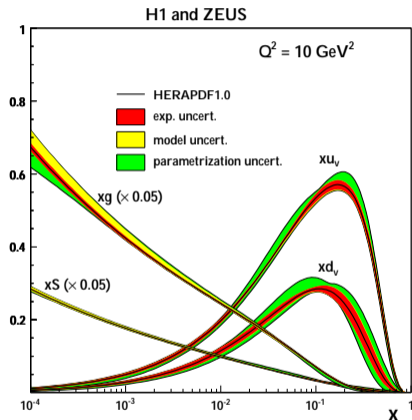
Some physics highlights of the eA program

- 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

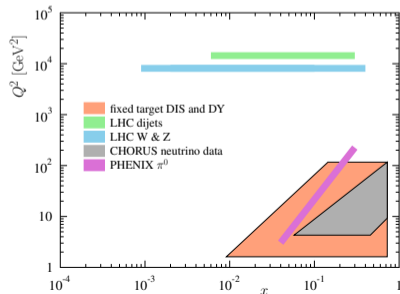
Nuclear parton distribution functions



H1 and ZEUS, JHEP 109 (2010)

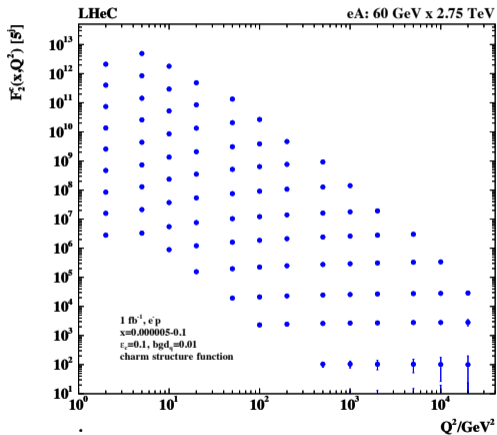
- HERA legacy: proton structure down to $x \sim 10^{-4}$
- (LHeC can help LHC studies by precise determination down to much smaller x !)
- No eA DIS data from colliders exist
 \Rightarrow Partonic structure of nuclei is poorly constrained

Data included in EPPS16 fit: [Eskola et al, arXiv:1612.05741](https://arxiv.org/abs/1612.05741)

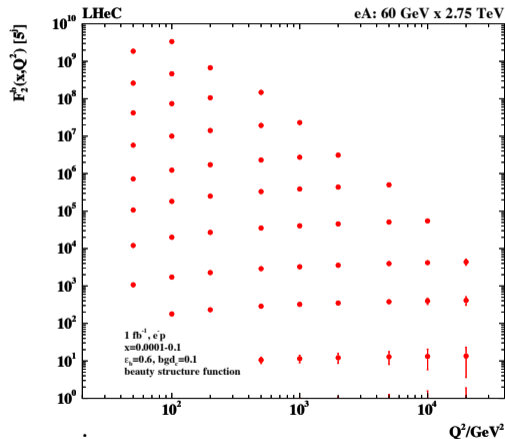


Nuclear parton distribution functions

Very precise structure function measurements (even for heavy quarks)



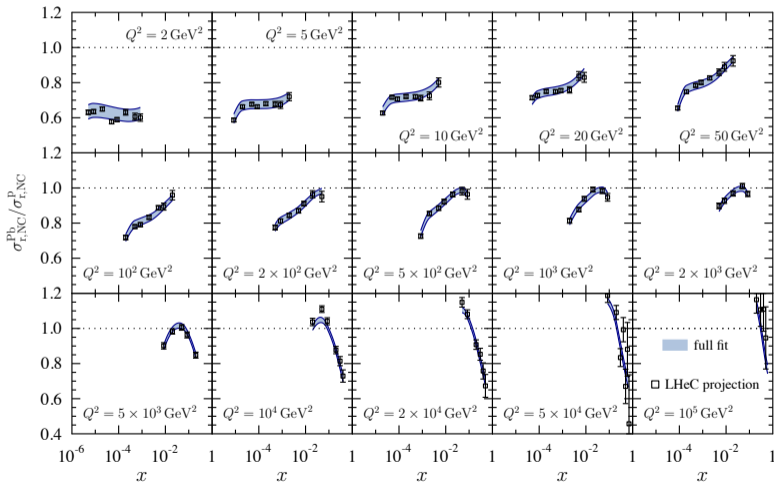
Charm: $x : 5 \cdot 10^{-6} \rightarrow 0.1$



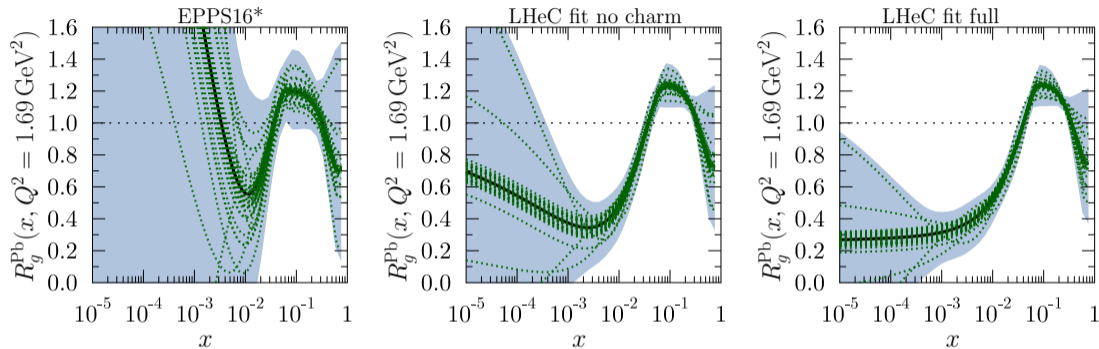
Bottom: $x : 10^{-4} \rightarrow 0.1$

Nuclear suppression in structure function measurements

Pseudodata calculated assuming EPPS16 nuclear effects. High precision possible!



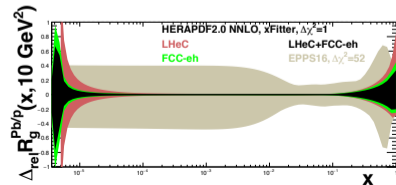
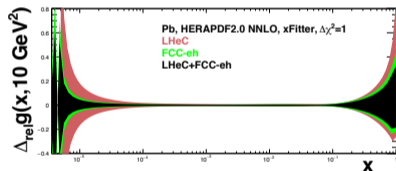
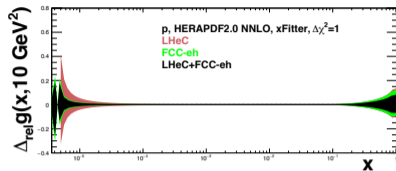
LHeC impact on global fits of nuclear parton distribution functions



- 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!

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 $x \sim \text{few} \times 10^{-5}$
- Huge improvement over the EPPS16 global fit
- Precision test for collinear factorization using nuclei

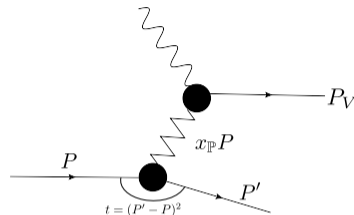
Diffraction I: Exclusive scattering

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

- Especially sensitive to partonic structure at small x

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

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



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

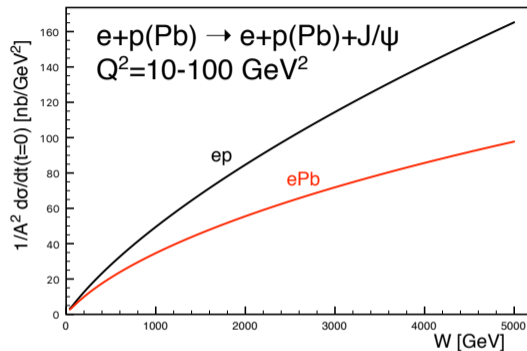
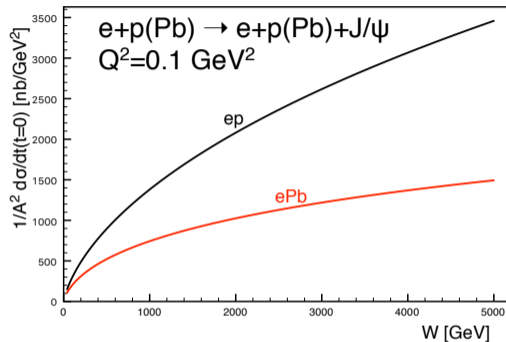
$$\left. \frac{d\sigma^{\gamma^* A \rightarrow VA}}{dt} \right|_{t=0} = \frac{16\pi^3 \alpha_s^2 \Gamma_{ee}}{3\alpha_{em} M_V^5} \left[xg(x, Q^2) \right]^2$$

Ryskin, 1993

In practice not exactly 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



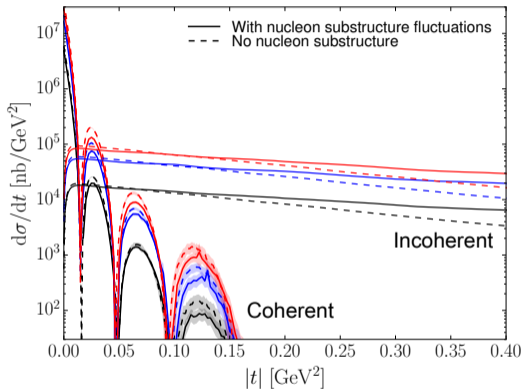
Exclusive production at $t = 0$ scales as A^2

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 \Rightarrow perturbative (but not too large: still sensitive probe)

Differential imaging with exclusive processes

$$\gamma + \text{Pb} \rightarrow J/\Psi + \text{Pb}, Q^2 = 0 \text{ GeV}^2$$



Coherent: Pb remains intact

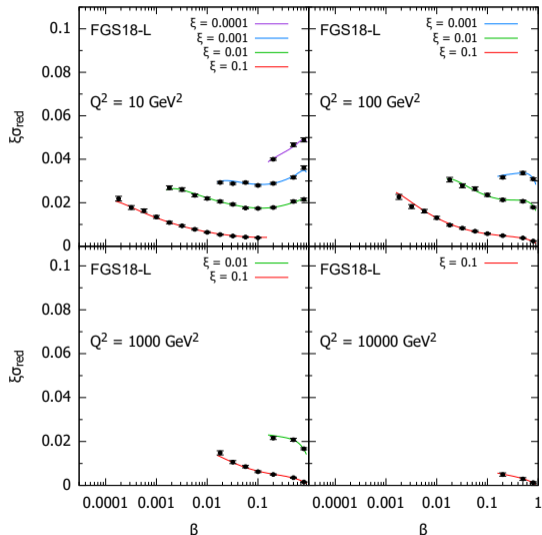
Incoherent: target breakup

$W = 0.1, 0.813, 2.5 \text{ TeV}$

- Fourier transform coherent spectra
→ 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. Nucleon shape fluctuations: H.M, Schenke, PRL 117 (2016) 052301, see also review arXiv:2001.10705

Diffraction II: inclusive diffraction

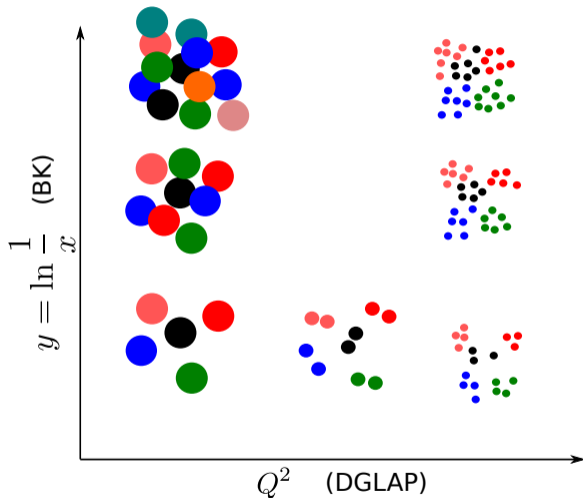


($\xi = x$ in diffraction, small $\beta \sim$ large M_X^2)

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

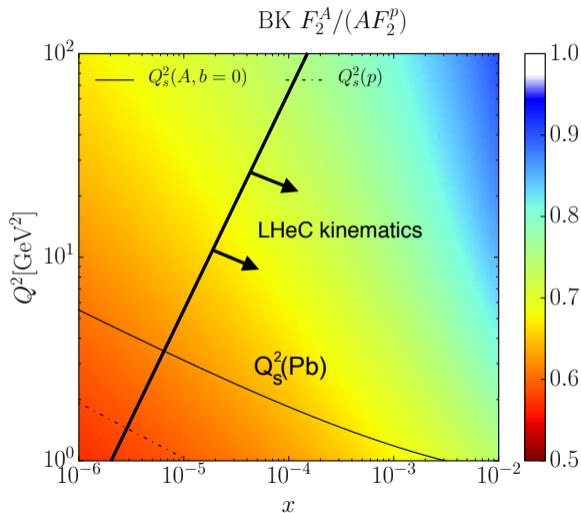


Comprehensive physics program to discover non-linear QCD dynamics

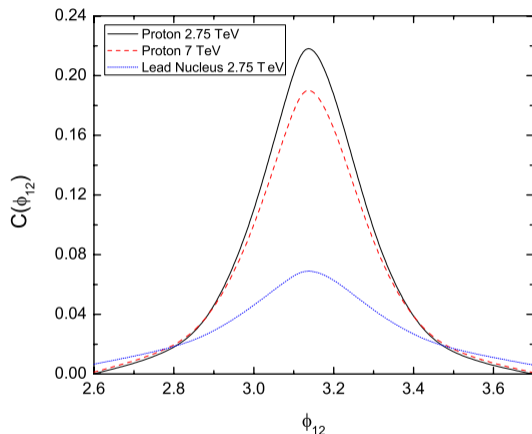
- Nuclear suppression:
Inclusive and exclusive scattering
- Two particle correlations
 - Azimuthal angle
 - Rapidity
- Collective dynamics (flow)
- Hadronization in nuclear medium
- ...

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?



$e + A \rightarrow h + h + X$ [LHeC CDR arXiv:1206.2913](#)

Power of more differential measurements

- 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

- *Precision QCD at the LHeC and the FCC-eh*: Tuesday 18:30
- *BSM Physics at the LHeC and the FCC-eh*: Wednesday 15:30
- *Energy Frontier DIS at CERN: the LHeC and the FCC-eh*: Thursday 8:20
- *Higgs physics at the LHeC and the FCC-eh*: Wednesday 16:42
- *The Updated LHeC Detector*: Friday 8:15
- *Precision Top and EW measurements at the LHeC and the FCC-eh*: Friday 12:15