Strong interaction physics at future eA colliders

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1. Introduction.

2. Partonic structure of the nucleus.

3. New dynamics at small $x$.

4. Nuclear effects in the final state.

5. Summary/recommendations.

Note: this is a selection of topics; for additional discussions and supplementary material (e.g. on spin, relations with other fields,...), see the talks by Daniel Boer, David d’Enterria, Thomas Gehrmann, Uta Klein, Jean-Philippe Lansberg, Tanguy Pierog, Gavin Salam, Gunar Schnell, Johanna Stachel and Urs Wiedemann, and the backup.

Main contributions: 159 (LHeC/FCC-eh), 99 (US-based EIC) and 103 (DIS).

Many thanks to Daniel Boer, Elena Ferreiro, Max and Uta Klein, Guilherme Milhano, Paul Newman and Bernd Surrow for information and feedback.
Nuclear structure functions:

- Bound nucleon ≠ free nucleon: search for process independent nPDFs that realise this condition, within collinear factorisation.

\[
\sigma_{\ell+\text{A} \rightarrow \ell+X}^{\text{DIS}} = \sum_{i=q,\bar{q},g} f_i^A(x, \mu^2) \otimes \hat{\sigma}_{\ell+i \rightarrow \ell+X}^{\text{DIS}}(\mu^2)
\]

- Flavor dependence?; relation with shadowing and coherence

- Short versus long range correlations, pion cloud, intrinsic charm,...

- Multiple scattering, saturation, ...; high-energy QCD

- Fermi-motion

- EMC-effect

- Superfast quarks

**How much does the structure of a hadron change when it is immersed in a nuclear medium?**

\[
R = \frac{f_i^A}{Af_i^p} \approx \text{expected if no nuclear effects}
\]

ePb at LHeC/FCC-eh
eAu at EIC

Strong interaction physics at future eA colliders: 1. Introduction.
Small-x physics:

- HERA found $xg \propto x^{-0.3}$.
- Present data can be described by:
  - Linear evolution approaches, either DGLAP or resummation at low $x$.
  - Non-linear approaches - weak coupling but high density: saturation.

- Theory: at high energies (i.e. small $x$), non-linear dynamics must be present.

**Where is it?** At HERA:
- Hints of failure of DGLAP at small $x$, $Q^2$, resummation?
- No ridge azimuthal structures yet found.

- Saturation is density-driven: $\downarrow x/\uparrow A \Rightarrow ep&eA + large range in 1/x & Q^2$ essential for full understanding.

\[ xG_A(x, Q^2_s) \approx 1 \implies Q^2_s \propto A^{1/3}x^{-0.3} \]

Strong interaction physics at future eA colliders: 1. Introduction.

N. Armesto, 15.05.2019
Implications on pA/AA:

- Nucleus ≠ Zp+(A-Z)n.
- Particle production at large scales similar to pp (dilute regime).
- Medium behaves very early like a low viscosity liquid: macroscopic description.
- Medium is very opaque to coloured particles traversing it.

- Lack of information about small-x partons, correlations and transverse structure.
- We do not understand the dense regime.

- How isotropised the system becomes?
- Why is hydro effective so fast, which dynamics?
- Dynamical mechanisms for such opacity? Weak or strong coupling?
- How to extract accurately medium parameters?

- eA: nuclear WF and mechanism of particle production.
- eA: initial conditions; how small can a system become and still show ‘collectivity’?
- eA: in-medium QCD radiation, cold nuclear effects on hard probes.

Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

Strong interaction physics at future eA colliders: I. Introduction.
Strong interaction physics at future eA colliders: 1. Introduction.

- Projects of eA colliders with $E_{cm} \sim \mathcal{O}(0.1) \text{ TeV/A}$ (EICs at US and China) and $\mathcal{O}(1) \text{ TeV/A}$ (LHeC and FCC-eh at CERN) addressing different physics.
The EIC Physics Pillars

QCD dynamics / Parton distributions in nuclei

- Strongly Correlated Quark-Gluon Dynamics
- Linear evolution
- Non-linear evolution
- High-Density Gluon Matter
- Confinement, Chiral Symmetry Breaking
- Non-linear regime
- Pomerons? Regge trajectories?

- Ratio $R(x,Q^2)$ of PDF's of Pb/p - Significant reduction of uncertainties of nuclear sea quarks / gluons with EIC
- Explore QCD landscape in various aspects over a wide range in $x$ and $Q^2$ - Heavy nuclei at high energy critical to explore high-density gluon matter!
Strong interaction physics at future eA colliders: 1. Introduction.
Kinematics:

- **LHeC-FCC-eh**: extension of 4-5 orders of magnitude in $x$ and $Q^2$ w.r.t. existing DIS data.

- **DIS versus hh**:
  - $\rightarrow$ pA/AA covers largest range in kinematics.
  - **DIS offers**:
    - A clean experimental environment - low multiplicity, no pileup, fully constrained kinematics $x,Q^2$ reconstructing the outgoing lepton;
    - A more controlled theoretical setup - many first-principles calculations, factorisation tests.
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nPDFs: status

- Large uncertainties for $x<0.01$ and for large $x$ glue (parametrisation biases, weakly constrained flavour decomposition and impact parameter dependence); small impact of present LHC data.
- Few data for any single $A$ e.g. Pb (15 DIS+30 pPb+$\nu A$): $A$-dependence of initial conditions.
- Sizeable impact on precision in hard probes of the QGP.
- HL-LHC to provide additional constrains, see 1812.06772: W/Z, jets, heavy quarks (including top) and quarkonium (inclusive, and exclusive in UPCs) under study; FT@LHC for large $x$.
- eA will provide precise nPDFs to be contrasted with $pA/AA$: checks of factorisation in the nuclear environment required for hard probes of the QGP.

\[ R_{i/A}(x, Q^2) = \frac{f_{i/A}(x, Q^2)}{A f_{i/p}(x, Q^2)} \]

EPPS16

unconstrained

unconstrained
nPDFs: fits to a single nucleus

- LHeC/FCC-eh ePb included in EPPS16-like global fits and HERAPDF DIS-only fits: large reduction of uncertainties in a completely new kinematical region.

- Fit to a single nucleus: no A-dependence modelling.

- Charm, beauty, c-tagged CC for strange (not yet in) ⇒ complete unfolding of different parton species.

NA at DIS2019, LHeC CDR update to appear

uncertainty on the gluon

proton

Pb

presently unconstrained

Pb/proton

Strong interaction physics at future eA colliders: 2. Partonic structure of the nucleus.

N. Armesto, 15.05.2019
3D - GPDs and TMDs:

- The extraction of 3D-structure (GPDs and TMDs and their evolution equations) is a huge undergoing program: scarcely known in the proton, **mostly unknown in nuclei**.

- Coherent exclusive production \((\gamma/\text{VM}) \Rightarrow q/g\) with GPDs, transverse profile.
- Incoherent exclusive production yields information about fluctuations: hot spots \(\Rightarrow\) MPIs.

- It can be done at the LHeC/FCC-eh in a large range of \(x\) and \(Q^2\) \(\Rightarrow\) evolution.
3D - GPDs and TMDs:

- The extraction of 3D-structure (GPDs and TMDs and their evolution equations) is a huge undergoing program: scarcely known in the proton, **mostly unknown in nuclei**.

**Coherent exclusive production** ($\gamma^*/\text{VM}$) ⇒ $q/g$

GPDs, transverse profile.

- Incoherent exclusive production yields information about fluctuations: hot spots ⇒ MPIs.

- It can be done at the LHeC/FCC-eh in a large range of $x$ and $Q^2$ ⇒ evolution.
Nuclear diffractive PDFs:

- Diffractive PDFs give the conditional probability of measuring a parton in the hadron with the hadron remaining intact: \( \sim 10\% \) events at HERA are diffractive!
- Never measured in nuclei, incoherent diffraction dominant above relatively small \(-t\): interplay between multiple scattering and survival probability of the colourless exchange (rapidity gap), relation between diffraction in ep and nuclear shadowing \( \Rightarrow \) MPIs, CEP.

- At the LHeC/FCC-eh, extractable in nuclei with the same accuracy as in proton.

See Uta Klein’s talk
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Search for new parton dynamics at small $x$:

- **Saturation modifies evolution**: tension between the description in DGLAP analyses of different inclusive observables (with different sensitivities to glue and sea, e.g. $F_2$ and $F_L$ or $\sigma_r^{HQ}$), if enough lever arm in $Q^2$ at small $x$ available.

- High scales are small $x$ at the FCC-AA: e.g. top production in pPb sensitive to $x \sim 0.02-0.2$ at HL-LHC and 0.0002-0.2 at the FCC-hh (1501.05879).

See LHeC CDR 1206.2913 and 1203.1043

Strong interaction physics at future eA colliders: 3. New dynamics at small $x$. N. Armesto, 15.05.2019
Diffractive observables:

- Saturation (the approach to the black disk limit) affects both the energy and the t (impact parameter)-dependence of coherent exclusive VM production: smaller energy dependence, shrinking of the diffractive peak.

\[
e+p(Pb) \rightarrow e+p(Pb)+J/\psi
\]
\[
Q^2=0.1 \text{ GeV}^2
\]

Mantysaari in DIS2018; LHeC CDR update to appear

\[
e+p(Pb) \rightarrow e+p(Pb)+J/\psi
\]
\[
Q^2=10-100 \text{ GeV}^2
\]

Strong interaction physics at future eA colliders: 3. New dynamics at small x.
Correlations:

- Dihadron azimuthal decorrelation: currently discussed at RHIC as suggestive of saturation.
- To be studied at LHeC/FCC-eh far from kinematical limits.

**Nuclear and saturation effects on usual BFKL signals** (e.g. dijet azimuthal decorrelation, Mueller-Navelet jets) has not been extensively addressed: A-dependence contrary to linear resummation?

- HL-LHC and higher energy hh/AA colliders: many of these signals can be considered (nuclear modification factors at small-x, exclusive vector meson production in UPCs, particle and jet decorrelation), but larger uncertainties will remain: collectivity, factorisation,... **DIS would be decisive to set the existence of a new regime of QCD.**
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Jets:

- Jet observables in AA: energy loss + response of the medium must be disentangled for characterisation of the medium.
- Jets not suppressed in pPb @ LHC: compatibility with softer observables? → **small systems**.
- Jets (inclusive and diffractive) abundantly produced in eA up to sizeable $E_T$, they can be used to test factorisation and for precision studies of changes of QCD radiation in the nuclear environment ⇒ hard probes of the QGP.
Fragmentation functions:

- eA: dynamics of QCD radiation and hadronization for light and heavy particles (energy loss of light and heavy, and quarkonium production and suppression), **relevant for particle production off nuclei** (nPDF determination in pA) and for QGP analysis in AA.

  → High energy: partonic evolution altered in the nuclear medium.

  → Low energy: hadronization inside formation time, (pre-)hadronic absorption,...

\[
R^h_A(z, \nu) = \frac{1}{N^e_A} \frac{dN^h_A(z, \nu)}{d\nu \, dz} / \frac{1}{N^e_D} \frac{dN^h_D(z, \nu)}{d\nu \, dz}
\]

LHeC CDR 1206.2913

- Ratio of FFs A/p
  
  \[ z = p_{\text{hadr}} / p_{\text{parton}} \]
  
  \[ \nu = E_{\text{hadron rest frame}} / E_{\text{struck parton}} \]

**Strong interaction physics at future eA colliders: 4. Nuclear effects in the final state.**
• eA: dynamics of QCD radiation and hadronization for light and heavy particles (energy loss of light and heavy, and quarkonium production and suppression), **relevant for particle production off nuclei** (nPDF determination in pA) and for QGP analysis in AA.

→ **High energy**: partonic evolution altered in the nuclear medium.

→ **Low energy**: hadronization inside \( \rightarrow \) formation time, (pre-)hadronic absorption,...

\[
R_A^h(z, \nu) = \frac{1}{N_A^{e^+}} \frac{dN_A^h(z, \nu)}{d\nu \, dz} \bigg/ \frac{1}{N_D^{e^+}} \frac{dN_D^h(z, \nu)}{d\nu \, dz}
\]

**EIC example**

1212.1701

<table>
<thead>
<tr>
<th>D0 mesons</th>
<th>x &gt; 0.1</th>
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<tr>
<td>25 GeV^2 &lt; Q^2 &lt; 45 GeV^2</td>
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<td>140 GeV &lt; x &lt; 150 GeV</td>
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<td>( \int L dt = 10 \text{ fb}^{-1} )</td>
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</table>

\( z \) fraction of virtual photons energy carried by hadron.
Summary / recommendations:

- eA colliders offer huge possibilities for QCD physics in new kinematic and dynamics domains:
  - Determination of nuclear partonic structure with high precision: collinear nuclear PDFs, nuclear GPDs/TMDs (3D-structure), diffractive nuclear PDFs, to be contrasted with those in pA and AA.
  - Searches of signals of a new regime of QCD - saturation - in inclusive and diffractive observables, and through correlations; both ep & eA are required to discover it and understand the underlying dynamics.
  - Modifications of particle production, hadronisation and QCD radiation in the nuclear environment.

Support further studies of the eA physics case at the largest possible energy and its implications on pp/pA/AA.

- The EIC and the LHeC are complementary:
  - PDFs for future AA colliders and the study of saturation demand the highest possible energy.
  - 3D-structure and hadronisation/QCD radiation will be studied in complementary domains.
  - The EIC will have a unique role in spin.

Support the exploitation of synergies and complementarities between the EIC and the LHeC/FCC-eh.

- All these aspects are relevant for the heavy-ion program:
  - Benchmarking of hard probes.
  - Initial conditions for collective behaviour.
  - Understanding of the onset of collectivity: small systems, MPIs, ...

Encourage the development of a broad QCD program for the 2030’s comprising pp/pA/AA and ep/eA.

Strong interaction physics at future eA colliders.
Backup
Purpose:

- **To cover:** Prospects and Challenges for Electron-Ion Collider, also from the perspectives of the US-EIC, to trigger our understanding of the rich variety of structures at the subatomic scale.

- **Related contributions submitted to the ESPPU:**

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<thead>
<tr>
<th>ID</th>
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<tbody>
<tr>
<td>159</td>
<td>LHeC/PERLE</td>
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<td>152</td>
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<td>135</td>
<td>QCD/HI at FCC-hh and FCC-eh</td>
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<td>NuPECC</td>
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<td>21</td>
<td>INFN hadron</td>
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<tr>
<td>114</td>
<td>MC generators</td>
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<td>33</td>
<td>Germany HEP</td>
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Consider the process of lepton (e, \( \mu \), \( \nu \)) scattering on a proton (or neutron or nucleus).

For charged lepton scattering and neglecting \( Z \) exchange,

\[
\frac{d^2\sigma_{NC}}{dx dQ^2} = \frac{2\pi \alpha^2 Y_+}{Q^4} \cdot \sigma_{r,NC} \\
\sigma_{r,NC} = F_2 + \frac{Y_+}{Y_+} x F_3 - \frac{y^2}{Y_+} F_L, \\
\sigma_{r,CC} = W_2^+ + \frac{Y_+}{Y_+} x W_3^+ - \frac{y^2}{Y_+} W_L^+ \\
F_2^+ = F_2 + \kappa_Z (-v_e \mp P a_e) \cdot F_2^Z + \kappa_Z^2 (v_e^2 + a_e^2 \pm 2Pv_e a_e) \cdot F_2^Z \\
x F_3^+ = \kappa_Z (\pm a_e + P v_e) \cdot x F_3^Z + \kappa_Z^2 (\mp 2v_e a_e - P(v_e^2 + a_e^2)) \cdot x F_3^Z
\]
## nPDFs: status

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<td>comments</td>
<td>Δχ²=50, ratios, huge</td>
<td>Δχ²=30, ratios, medium-modified FFs for π₀</td>
<td>Δχ²=35, PDFs, valence flavour sep., not enough sensitivity</td>
<td>PDFs, deuteron data included</td>
<td>Δχ²=52, flavour sep., ratios, LHC pPb data</td>
<td>NNPDF methodology, isoscalarity assumed</td>
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</tbody>
</table>

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N. Armesto, 15.05.2019
**nPDFs: status**

\[
R = \frac{f_i/A}{Af_i/p} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}
\]

- Lack of data \(\Rightarrow\) large uncertainties for the nuclear glue at small scales and \(x\): problem for benchmarking in HIC in order to extract medium parameters.

\(1506.03981\)
nPDFs: status

- nCTEQ15 vs. EPPS16: note the parametrisation bias.

- Presently available LHC data seem not to have a large effect: large-$x$ glue (baseline=no $\nu$, no LHC data).
Strong interaction physics at future eA colliders: 2. Partonic structure of the nucleus.

- LHeC/FCC-eh ePb and EIC eAu pseudodata included in EPPS16-like global fits: large impact.

- Inclusion of charm has sizeable impact (on glue).
- Not yet included: beauty, c-tagged CC for strange.

\[
\begin{align*}
\text{LHeC/FCC-eh} & \quad \text{EIC} \\
\text{ePb and EIC eAu} & \quad \text{pseudodata} \\
\text{included in} & \quad \text{EPPS16-like} \\
\text{global fits:} & \quad \text{large} \\
\text{impact.} & \quad \text{large} \\
\end{align*}
\]

- Inclusion of charm has sizeable impact (on glue).
- Not yet included: beauty, c-tagged CC for strange.

\[
\begin{align*}
10^2 & \quad 10^3 & \quad 10^4 & \quad 10^5 & \quad 10^6 & \quad 10^7 \\
Q^2 (\text{GeV}^2) & \quad LHC & \quad NC+CC, \ EPPS16^*, \ Pb \\
& \quad \text{LHeC charm, EPPS16}, \ Pb \\
& \quad \text{LHeC NC+CC, xFitter, Pb} \\
& \quad \text{FCC-eh NC+CC, xFitter, Pb} \\
\end{align*}
\]
Presently, only dijet and W/Z data from pPb at the LHC are used in global fits.

- Use of heavy quarks (including top) and quarkonium under study.

- Also exclusive vector meson production in UPCs - additional assumptions are required.

- **nPDFs from eA to be contrasted with pA/AA:** precise checks of factorisation in the nuclear environment.

See [1812.06772]
New kinds of factorisation (or lack of it), new evolution equations.  
Directly related with spin.  
Most of these quantities can be ideally explored in the EIC and the LHeC; they also can be explored in fixed target programs (talks by Lansberg and Schnell) and UPCs (at Q=0).
Quark and gluon GPDs:

\[ \int \frac{d^2w}{2\pi} e^{-i\mathbf{P} \cdot \mathbf{w}} \left( P' | T \bar{\psi} \left(0, \frac{1}{2} w^-, 0_T \right) \frac{1}{2} \psi \left(0, -\frac{1}{2} w^-, 0_T \right) | P \right) \]

- Coherent exclusive production of \( \gamma \) and VM yields information about quark and gluon GPDs.

**EIC, 1212.1701**

**LHeC 1206.2913**
Quark and gluon GPDs:

- Coherent exclusive production of $\gamma$ and VM yields information about $q$ and $g$ GPDs.

\[
\int \frac{d\omega}{2\pi} e^{-i\omega \cdot \mathbf{w}} \left( \rho_p \frac{1}{2} T_\psi j \left( 0, \frac{1}{2} w^-, 0_T \right) \frac{1}{2} \bar{\psi}_j \left( 0, -\frac{1}{2} w^-, 0_T \right) \right) \left| p \right|^c
\]

\[
\text{Mantysaari, DIS 2018, LHeC CDR update to appear}
\]
Quark and gluon GPDs:

\[ \int \frac{d\omega^+}{2\pi} e^{-i\omega^+ p^+} \left( P^+ \Gamma \psi_j \left( 0, \frac{1}{2} w^-, 0_T \right) \frac{\gamma^+}{2} \bar{\psi}_j \left( 0, -\frac{1}{2} w^-, 0_T \right) \right) \left| P \right| C \]

- Coherent exclusive production of $\gamma$ and VM yields information about $q$ and $g$ GPDs.
- Incoherent exclusive production yields information about fluctuations: hot spots.

\[ \text{Pb} + \text{Pb} \rightarrow J/\psi + \text{Pb} + \text{Pb}, \sqrt{s} = 5.02 \text{ TeV}, \gamma = 0 \]

\[ \text{Geometric and } \xi, \text{ fluctuations in the nucleus} \]

\[ \text{No subnucleon fluctuations: } 1703.09256 \]
Spin:

\[
\frac{1}{2} = \text{Spin of Quarks} + \text{Spin of Gluons} + \text{Angular Momentum of Quarks} + \text{Angular Momentum of Gluons}
\]

- The origin of proton spin has been an open issue for several decades: schematically speaking, quarks account for ~30%, gluons for ~20% (known in a limited x-range), the rest?

Inclusive Measurement: \( e+p \rightarrow e'\pi X \)

\[
\frac{1}{2} \left[ \frac{d^2\sigma^\uparrow}{dx\,dQ^2} - \frac{d^2\sigma^\downarrow}{dx\,dQ^2} \right] \approx \frac{4\pi\alpha^2}{Q^4} y(2-y) g_1(x, Q^2)
\]

Leading Order:

\[
g_1(x, Q^2) = \frac{1}{2} \sum_q c_q^2 [\Delta q(x, Q^2) + \Delta\bar{q}(x, Q^2)]
\]

\[
\Delta\Sigma(Q^2) = \int_0^1 dx\, g_1(x, Q^2)
\]

Higher Order:

\[
\frac{dg_1}{d\log Q^2} \propto \Delta g(x, Q^2)
\]

- Inclusive measurements with both e and p polarised (EIC): huge improvement at low x.
Several TMDs to be determined by different observables: beyond inclusive DIS, further possibilities are SIDIS (FFs required), CC,…

Besides, polarised light nuclei, diffraction,…

TMD factorisation can be tested in non-polarised collisions: dijets, charm,… Relation at small x with CGC.
The EIC Physics Pillars

Tomography (p/A)
Transverse Momentum Distribution and Spatial Imaging
Spin and Flavor Structure of the Nucleon and Nuclei
Parton Distributions in Nuclei
QCD at Extreme Parton Densities - Saturation

EICUG: ~ 860 people (1/3 from Europe)
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1212.1701

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LHeC & EIC: synergies and complementarities

- **EIC versus LHeC/FCC-eH: different kinematics and different focus of the physics programs - even on the QCD side.**

- **Synergies:**
  - Detector studies: forward instrumentation for diffraction?
  - QCD Monte Carlo simulators.
  - Analysis frameworks?
  - Theoretical developments: higher orders e.g. N^3LO DGLAP.

- **Complementarities:**
  - Kinematics: Q^2 < 1 GeV^2 and large x and not so large Q^2 to be studied at the EIC; evolution to be obtained at the LHeC/FCC-eH.
  - Detector optimisation: EIC more focused to PID and low transverse momentum.
  - Nuclear species: in principle, more flexibility at the EIC, but proposals for lighter ions at the LHC in the 2030's have been done in the context of the HL/HE-LHC studies (see 1812.06772).
Relation with other fields:

- **String theory (AdS/CFT correspondence):** models for QCD at strong coupling at zero and finite temperature, applied to model DIS at low $Q^2$.

- **Cosmic ray physics,** see Tanguy Pierog’s talk.

- **Information theory:** how to reconcile the parton picture with the proton/nucleus as a pure quantum state? Relation with:
  - The physics of open quantum systems.
  - Entropy produced in hadronic and nuclear collisions.
  - Wigner distributions: TMDs, GPDs.
  - Entropy in QCD radiation: jets.