Summary: Small x and Physics with eA

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The problem:

- Behaviour of QCD at high energies $A \equiv$ high partonic densities.

with implications on pp/pA/AA collisions and the small systems problem (thermalisation?; emergence of macroscopic properties?)
Our task:

What can we do with this while keeping an eye on this?
Talks:

- The Electron Ion Collider, Bernd Surrow, Wednesday morning.
- Impact of resummation on Higgs and other observables, Simone Marzani, Wednesday afternoon.
- Resummation, Amanda Cooper-Sarkar, Wednesday afternoon.
- Color fluctuations and photon-nucleus scattering, Mark Strikman, Wednesday afternoon.
- Exclusive vector meson production with eSTARLIGHT, Spencer Klein, Wednesday afternoon.
- Diffraction, Anna Stasto, Thursday morning.
- Elastic vector meson production, Heikki Mantysaari, Thursday morning.
- Open questions in QCD at high parton density (e+p, e+A, p+A), Cyrille Marquet, Thursday morning.
- How could heavy ion physics at the energy frontier profit from LHeC measurements (EXP point of view), Astrid Morreale, Thursday morning.
- How could heavy ion physics at the energy frontier profit from LHeC measurements (TH point of view), Elena G. Ferreiro, Thursday morning.

Thank you very much to all of them!!!
EIC: Study structure and dynamics of matter at high luminosity, high energy with polarized beams and wide range of nuclei

Whitepaper: arXiv:1212.1701

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

Understanding the glue that binds us all
EIC:

The EIC Physics Pillars

- EIC: Study structure and dynamics of matter at high luminosity, high energy with polarized beams and wide range of nuclei
- Whitepaper: arXiv:1212.1701

- EIC ↔ LHeC: complementarity in the kinematic region, detector aspects, and physics opportunities.

N. Armesto, 29.06.2018 - Summary: Small x and eA.
**EIC:**

The EIC Physics Pillars

- **QCD dynamics / Parton distributions in nuclei**

  $Q^2 (\text{GeV}^2)$

  **Strongly Correlated Quark-Gluon Dynamics**

  Confinement, Chiral Symmetry Breaking

  Non-linear evolution

  Linear evolution

  High-Density Gluon Matter

  $Q_s^2 (x)$

  Non-linear regime

  Perturbative

  Non-perturbative

  Hadrons

  Pomerons? Regge trajectories?

  Parton Density

  $1/x$

  **Study modifications of gluons in nuclear environment complementing LHC-AA and RHIC-AA programs.**

- **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!**

N. Armesto, 29.06.2018 - Summary: Small $x$ and $eA$.  

Electrons for the LHC - LHeC / FCCeh and Perle Workshop  
LAL-Orsay, France, June 27-29, 2018
The EIC Physics Pillars

- Transverse Momentum Distribution and Spatial Imaging
  
  \[ f(x, k_T) \quad 1+2D \]
  \[ \int d^2 b_T \quad W(x, b_T, k_T) \quad \int d^2 k_T \quad f(x, b_T) \quad 1+2D \]

  Transverse Momentum Distribution (TMD) → Wigner Distribution → Impact Parameter Distribution

- Spin-dependent 1+2D momentum space (transverse) images from semi-inclusive scattering

- Spin-dependent 1+2D impact parameter (transverse) images from exclusive scattering

Generalized Parton Distribution (GPD)

\[ H(x, 0, t) \quad \xi = 0 \]
\[ H(x, \xi, t) \quad \text{Fourier transf.} \quad b_T \leftrightarrow \Delta: t = -\Delta^2 \]
Small-x resummation:

PERTURBATIVE STABILITY

- NNLO and NNLO+NLLx differ quite dramatically
- one could question the reliability of the resummed procedure
- what gives us confidence we’re not talking rubbish?
- resummation cures perturbative instability of NNLO
Further study of the shapes of the gluon and the sea

In fixed order fits at NNLO the gluon dips below the sea at low-x as $Q^2$ is reduced.
This is a general feature of NNLO fits - not just of HERAPDF.

These plots show the ratio of total sea $\Sigma$ to gluon vs x for various $Q^2$ for NNLO and NNLO+NLLx fits.
The ratio is much more stable with low x resummation

This arises from the behaviour of the $P_{qg}$ and $P_{gg}$ splitting functions.
At NNLO $xP_{qg}(x) > xP_{gg}(x)$ for $x \leq 10^{-3}$,
Whereas for NNLO+NLLx $xP_{qg}(x) < xP_{gg}(x)$

[Amanda Cooper-Sarkar]
Small-x resummation:

BFKL: THE GHOST OF CHRISTMAS YET-TO-COME

- small-x physics will be crucial at future circular colliders
- e (60 GeV) - p (7 TeV or 50 TeV) collisions
- to gauge the impact: fits including (resummed) pseudo-data

<table>
<thead>
<tr>
<th></th>
<th>$N_{\text{dat}}$</th>
<th>$\chi^2/N_{\text{dat}}$</th>
<th>NNLO</th>
<th>NNLO+NLLx</th>
<th>$\Delta\chi^2$</th>
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</thead>
<tbody>
<tr>
<td>HERA I+II incl. NC</td>
<td>922</td>
<td>1.22</td>
<td>1.07</td>
<td>-138</td>
<td></td>
</tr>
<tr>
<td>LHeC incl. NC</td>
<td>149</td>
<td>1.71</td>
<td>1.22</td>
<td>-73</td>
<td></td>
</tr>
<tr>
<td>FCC-eh incl. NC</td>
<td>98</td>
<td>2.72</td>
<td>1.34</td>
<td>-135</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1168</td>
<td>1.407</td>
<td>1.110</td>
<td>-346</td>
<td></td>
</tr>
</tbody>
</table>

N. Armesto, 29.06.2018 - Summary: Small x and eA.
Small-x resummation:

- TeV-scale ep to provide a decisive test of resummation.

BFKL: THE GHOST OF CHRISTMAS YET-TO-COME

- small-x physics will be crucial at future circular colliders
- $e^+ (60 \text{ GeV}) - p$ (7 TeV or 50 TeV) collisions
- to gauge the impact: fits including (resummed) pseudo-data

N. Armesto, 29.06.2018 - Summary: Small x and eA.
Small x:

A big open question

- is this relevant at today’s colliders?
  in other words: can we get away with using such a gluon distribution (with ad hoc cutoff if necessary)?
  or do we need to properly take into account the QCD dynamics at $k_T \sim Q_S$ and below?

the CGC phenomenology is successful for every collider process that involves small-$x$ partons and $k_T \sim Q_S$, i.e. for a broad range for high-energy observables:

- multiplicities in p+p, d+Au, Au+Au and Pb+Pb; forward spectra and correlations in p+p and d+Au; total, diffractive and exclusive cross sections in e+p and e+A, ...

- main limitation:
  - the applicability of the theory can be questioned when values of $Q_S$ start to drop below 1 GeV (e.g. p+p and peripheral d+Au at RHIC)
Small x:

A big open question

• is this relevant at today’s colliders?

in other words: can we use a gluon distribution to provide a lever arm and set the relevance of this phenomenon?

• TeV-scale ep and eA required to provide x and Q^2 lever arm and set the relevance of this phenomenon.

- multiplicities in p+p, d+Au, Au+Au and Pb+Pb; forward spectra and correlations in p+p and d+Au; total, diffractive and exclusive cross sections in e+p and e+A, …

• main limitation:
  - the applicability of the theory can be questioned when values of Q_s start to drop below 1 GeV (e.g. p+p and peripheral d+Au at RHIC)
Several observables can provide evidence of the high-density non-linear regime of QCD: correlations, different quark and sea evolution, diffraction,…

- Resummation is required for a stable small-x evolution.

NLO DGLAP cannot simultaneously accommodate $F_2$ and $F_L$ at LHeC data if saturation sets in according to current models. (the same cannot be said for the lower energy EIC CM, R-Moldes and Zurita (2017))
Spin physics without polarised beams, requires dedicated studies.

the Weizsäcker-Williams H function can be extracted at the LHeC in di-jet/di-hadron production with non-zero $Q^2$ and/or heavy quarks produced

we can still be sensitive to gluon polarization

unpolarized gluon TMD

linearly-polarized gluon TMD

[Metz and Zhou (2011)]

Spin physics without polarised beams, requires dedicated studies.
Inclusive diffraction:

Phase space: HERA to LHeC to FCC-eh

\[ E_e = 60 \text{ GeV} \]

- \( E_p = 7 \text{ TeV} \) vs. HERA
  - \( x_{\min} \) down by factor \( \sim 20 \)
  - \( Q^2_{\max} \) up by factor \( \sim 100 \)
- \( E_p = 50 \text{ TeV} \) vs. 7 TeV
  - \( x_{\min} \) down by factor \( \sim 10 \)
  - \( Q^2_{\max} \) up by factor \( \sim 10 \)
Huge extension of the kinematic plane with respect to HERA, requires large acceptance (or smaller $E_e$).

- $E_p = 7$ TeV vs. HERA
  - $x_{\text{min}}$ down by factor $\sim 20$
  - $Q^2_{\text{max}}$ up by factor $\sim 100$
- $E_p = 50$ TeV vs. 7 TeV
  - $x_{\text{min}}$ down by factor $\sim 10$
  - $Q^2_{\text{max}}$ up by factor $\sim 10$

$E_e = 60$ GeV

[Anna Stasto]
Inclusive diffraction:

[Anna Stasto] DPDFs error bands

$Q^2_{\text{min}} \approx 5 \text{ GeV}^2$

- Extraction robust under changes in $Q^2_{\text{min}}$, inclusion of top, statistics,…
- Precise determination of DPDFs in a new kinematic domain.

Electrons for the LHC-LHeC/FCC-eh and Perle workshop, LAL-Orsay, June 28, 2018
Inclusive diffraction:

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● 1st analysis for diffraction in ePb, never measured before, extraction of nuclear DPDFs possible.

[Anna Stasto]

Electrons for the LHC-LHeC/FCC-eh and Perle workshop, LAL-Orsay, June 28, 2018

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Elastic VMs:

Two components – two target averages

Coherent diffraction:
Target remains in the same quantum state
Probes average density

$$\frac{d\sigma^{\gamma^* p \rightarrow Vp}}{dt} \sim |\langle A^{\gamma^* p \rightarrow Vp}\rangle|^2$$

Incoherent/target dissociation:
Total diffractive – coherent cross section
Target breaks up

$$\frac{d\sigma^{\gamma^* p \rightarrow Vp^*}}{dt} \sim \langle |A^{\gamma^* p \rightarrow Vp}|^2 \rangle - |\langle A^{\gamma^* p \rightarrow Vp}\rangle|^2$$

Variance, measures the amount of fluctuations!
\langle \rangle: average over target configurations \[\mathcal{N}(r, b)\]

[Heikki Mantysaari]

Good, Walker, PRD 120, 1960
Miettinen, Pumplin, PRD 18, 1978
Kovchegov, McLerran, PRD 60, 1999
Kovner, Wiedemann, PRD 64, 2001
Elastic VMs:

Energy evolution

Bjorken-x evolution by solving perturbative JIMWLK equation
Initial state geometry is lost in the evolution

- Incoherent vs. coherent diffraction gives information about hot spots in the proton.
- Most relevant for hadronic collisions.

$W = 75$ GeV:

$W = 680$ GeV

[Heikki Mantysaari]

Note: parameters fixed at $W = 75$ GeV, the rest is prediction

H.M. B. Schenke, arXiv:1806.06783

Heikki Mantysaari (JYU) Elastic VM production

June 28, 2018 6/16
Elastic VMs:

Scaling exponents: dense ↔ dilute transition

\[ \sigma_{\gamma+A \rightarrow J/\Psi+A} \sim Q^\gamma \]
\[ \gamma^* + \text{Au} \rightarrow V + \text{Au}, \ x_P = 0.01 \]

- Lever arm in \( Q^2 \) at small \( x \) required to establish the relevance of non-linear phenomena.

Large \( Q^2 \) lever arm needed to see the transition, and to probe the \( x \) dependence!
 Monte Carlo for photoproduction and electroproduction of vector mesons at an EIC
  - Here, photoproduction is $Q^2 < 1 \text{ GeV}^2$, while electroproduction is $Q^2 > 1 \text{ GeV}^2$

 Physics model follows STARlight UPC event generator, but covers photons with arbitrary $Q^2$

 A fast, complete, reasonably accurate model of vector meson production, not a sophisticated theoretical calculation
  - For detector simulations....
  - Electron (or positron) -> $\gamma^*$ -> vector meson -> final state
  - Vector meson polarization and decay angular distribution
  - Based on data where possible, phenomenology elsewhere
    - Some extrapolations required

 Designed to be easily extensible

Monte Carlo for photoproduction and electroproduction of vector mesons at an EIC

- Here, photoproduction is $Q^2 < 1 \text{ GeV}^2$, while electroproduction is $Q^2 > 1 \text{ GeV}^2$

- Physics model follows STARlight UPC event generator, but covers photons with arbitrary $Q^2$

- A fast, complete, reasonably accurate model of vector meson production, not a sophisticated theoretical calculation
  - For detector simulations…
  - Electron (or positron) $\rightarrow \gamma^* \rightarrow$ vector meson $\rightarrow$ final state

- Tools under development, essential for:
  - detector design (large acceptance);
  - proposing new observables (exotic spectroscopy, diffractive $t\bar{t}$bar,…).
**eSTARLIGHT:**

[Spencer Klein] **Rapidity and Angular distributions**

- Vector meson production over a wide rapidity range
  - **N. b. unscaled distributions here**

- Electrons scattering angle is small (no surprise)

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N. Armesto, 29.06.2018 - Summary: Small x and eA.
Colour fluctuations:

We will refer fluctuations of the strength of interaction of nucleon, photon,.. as color fluctuations of interaction strength - studying them allows to go beyond single parton 3-D mapping of the nucleon.

Color fluctuations in photon - nucleus collisions

Photon is a multiscale state:

Probability, $P_\gamma(\sigma)$ for a photon to interact with nucleon with cross section $\sigma$, gets contribution from point - like configurations and soft configurations (VM like)

$$P_\gamma(\sigma) \propto 1/\sigma \text{ for } \sigma \ll \sigma(\pi N) \quad P_\gamma(\sigma) \propto P_\pi(\sigma) \text{ for } \sigma > \sigma(\pi N)$$

● Understanding correlations of partons inside particles essential for hadron averages in CGC, MPIs,…

[Mark Strikman]
Colour fluctuations:

Calculation of distribution over the number of wounded nucleons

(a) Color fluctuation model

\[
\sigma_\nu = \int d\sigma P_\gamma(\sigma) \left( \frac{A}{\nu} \right) \times \int d\tilde{b} \left[ \frac{\sigma_{\text{in}}(\sigma)T(b)}{A} \right]^\nu \left[ 1 - \frac{\sigma_{\text{in}}(\sigma)T(b)}{A} \right]^{A-\nu} 
\]

\[
p(\nu) = \frac{\sigma_\nu}{\sum_{1}^{\infty} \sigma_\nu}.
\]

(b) Generalized Color fluctuation model (includes LT shadowing for small \( \sigma \))

Interaction of small dipoles is screened much stronger than in the eikonal model

Evidence from J/psi production - next slide

\[
P_\gamma(\sigma) \left( \frac{A}{\nu} \right) \times \frac{\sigma_{\text{in}}}{\sigma_{\text{eff}}} \int d\tilde{b} \left[ \frac{\sigma_{\text{eff}}T(b)}{A} \right]^\nu \left[ 1 - \frac{\sigma_{\text{eff}}T(b)}{A} \right]^{A-\nu}
\]

\[
\sigma_{\text{eff}}/\sigma \quad \text{calculated in the LT nuclear shadowing theory for small } \sigma
\]

[Mark Strikman]
Colour fluctuations:

Tuning strength of interaction of configurations in photon using forward (along $\gamma$ information). Novel way to study dynamics of $\gamma$ & $\gamma^*$ interactions with nuclei

- A full picture requires lever arm in $x$ and $Q^2$ to select configurations leading to stronger or weaker interaction.

[Mark Strikman]

“2D strengthomometer” - EIC & LHeC - $Q^2$ dependence - decrease of role of “fat” configurations, multinucleon interactions due to LT nuclear shadowing

Comment: Forward $\gamma A$ & $\gamma p$ physics at the LHC mostly within acceptance of central ATLAS, CMS detectors
eA for heavy ions:

Old paradigm: the three systems (understanding before 2012)

- **Pb-Pb**
- **pp**
- **p-Pb**

- **eA** to provide key information for a full understanding of the findings in AA whose interpretation is under revision: small systems.

**Hot QCD matter:**
This is where we expect the QGP to be created in central collisions.

**QCD baseline:**
This is the baseline for “standard” QCD phenomena.

**Cold QCD matter:**
This is to isolate nuclear effects in absence of QGP, e.g. nuclear pdfs.

● eA to provide key information for a full understanding of the findings in AA whose interpretation is under revision: small systems.

N. Armesto, 29.06.2018 - Summary: Small x and eA.
Nuclear PDFs:

\[ f^A_i(x, Q^2) = R^A_i(x, Q^2) f_i(x, Q^2) \]

\[ Q^2 = 2 \text{ GeV}^2 \]

\[ R_{AA} \]

- eA for a reduction of the uncertainties in the initial state: nuclear WF, nuclear PDFs.

The improvement after adding the LHeC pseudodata at \( Q^2 = 10 \text{ GeV}^2 \)

[Elена Ferreiro]
Jet quenching:

- eA for a reduction of the uncertainties in the final state: QCD branching and hadronisation in the nuclear medium.
Striking similarities and a smooth transition between pp, pPb and PbPb (QGP-like features in small systems) ⇒ new paradigm that all systems become equally interesting: QGP in small systems (final state interactions) or properties of the initial state? [emergence].

N. Armesto, 29.06.2018 - Summary: Small x and eA.
Small systems:

Flow in small systems?

These effects have not been seen at LEP nor HERA.

N. Armesto, 29.06.2018 - Summary: Small x and eA.
Small systems:

- Top energy ep and eA to check how small the system can become and still show collective features.

These effects have not been seen at LEP nor HERA.
The ridge:

Collisions of Aligned Flux Tubes produce high multiplicity events: Ridges

Brown, Glazek, Goldhaber, sbj

Ridge Production at the LHeC

- ep and eA to check these (and other) ideas.

Flux tube aligned with the plane of the scattered electron

Ridges of produced hadrons will correlate with scattering plane of proton!

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eA for heavy ions:

New paradigm: small systems

Totally unexpected:
- the discovery of correlations –ridge, flow- in small systems pA & pp
- Smooth continuation of heavy ion phenomena to small systems and low density
- Small systems as pA and pp show QGP-like features

Two serious contenders remain today:
- **initial state**: quantum correlations as calculated by CGC
- **final state**: interactions leading to collective flow described with hydrodynamics => equilibration?

The **old paradigm** that
- we study hot & dense matter properties in heavy ion AA collisions
- cold nuclear matter modifications in pA
- and we use pp primarily as comparison data appears no longer sensible

We should examine a **new paradigm**, where the physics underlying soft collective signals can be the same in all high energy reactions, *from e+e− to central AA*

It becomes fundamental to have access to ep & eA collisions

N. Armesto, 29.06.2018 - Summary: Small x and eA.
Many aspects of the hadron wave function to be probed in ep/eA.
QCD on the light front:

\[ ep \rightarrow e'cgX, \quad ep \rightarrow e'bgX, \]

- Intrinsic charm.
- Flavour dependent antishadowing.

**LHeC:** Measure \( c(x,Q), b(x,Q) \) at large \( x \)

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**Stanley Brodsky**

N. Armesto, 29.06.2018 - Summary: Small \( x \) and \( eA \).
To end:

- Beautiful discussions and results presented here.
- The physics case is clear, interplay with detector design (acceptance, forward instrumentation) essential for its success.
- Irrespective of what exactly we find, the LHeC will change our field, and the knowledge that we gain is essential for the physics programmes in hadronic colliders.

THANK YOU

TO THE SPEAKERS AND TO YOU ALL!

if we have seen further it is only by standing on the shoulders of giants

N. Armestro, 29.06.2018 - Summary: Small x and eA.