Motivation and Perspective on the ep and eA physics at future colliders

1. Motivation and short review of HERA physics
   HERA experiments were designed for high $Q^2$ physics
   unexpected findings came mainly from the low-$x$ region
   ➤ low-$x$ is dominated by gluonic structures, they dominate the high energy behavior and are well accessible to experimental investigations

2. Optimized detector for the low-$x$ physics
3. Optimized HERA machine

main goal: Understand the properties of gluonic fields
why? Gluons are the most important components of high energy collisions involving nucleons or nuclei
Gluons keep everything together

H. Kowalski, EMMI-Darmstadt, 22 November 2010
Goal oriented motivation:

Precise knowledge of Gluon Density is necessary to fully exploit the physics potential of LHC

  e.g. Higgs production, \( m_H < 150 \text{ GeV} \), any deviation from the SM value of the Higgs x-section is a sign of BSM

General motivation:

Gluon density is a basic QCD quantity. Its study should help to understand how matter arises from the QCD interactions of quarks and gluons.
Can we really derive all properties of matter from the QCD Lagrangian?

Lattice Calculations successfully reproduces the values of hadron masses starting from the QCD Lagrangian. It is, however, not clear how masses emerge.

For example, the mass relations have only a limited sensitivity to the way how the chiral invariance is approached or what is the role of instantons (private communication A. Schaefer).

It is characteristic for QCD that clear structures are emerging due to effects of multiple $gg$ and $qg$ interactions. An example is isospin symmetry, another is the formation of Regge trajectories.

From QED it is known that the derivation of emergent phenomena from the Lagragian is very difficult (e.g superconductivity).
Motivation

The study of high energy behavior of strong interactions was the original motivation to do high energy physics. The hope was that at high energies the structure of strong interactions simplifies and can be understood from first principles.

This hope was first fulfilled at HERA where it was observed that, in the low-\(x\) limit, the rise of the DIS cross sections is due to the rise of the Gluon Density. Indeed, at low-\(x\), due to the time dilatation, the strong interactions of QCD simplify to a many body problem with clear structures.

For example, theoretically, in addition to \(q \rightarrow qg\) and \(g \rightarrow gg\) transitions, quarks are forming dipoles or two gluons are forming highly correlated, quasi-bound, states. Multiple gluons condensate to a novel state of matter and gluonic soliton states should appear. These structures give also rise to directly observed effects like the strong rise of the DIS cross sections or diffraction. A new structure of this type is, presumably, a recently observed CMS correlation.
Motivation

These phenomena are forming the Gluon Density and allow to study its properties experimentally. Theoretically its properties can be studied with the sophisticated QCD equations like DGLAP, BFKL, BK or BKP.

Gluon Density is analog to black body radiation in QED. The structure of atoms was not revealed by the investigation of atoms. The decisive step came from the study of the radiation properties with the help of precision measurements.

HERA has shown that Gluon Density is well measurable but its experiments were not designed for the precision measurements of the gluon density. Although impressive results where achieved it is very likely that only the surface was scratched and much more can be learned from high precision measurements. The challenging question is what are the degrees of freedom of the gluonic field or what is its space of states.
Determination of Gluon Density

GD is determined from the increase of $F_2$ with $x$ and $Q^2$ in low-$x$ region

Recent progress, precision of $F_2$ increased by more than a factor 2

DGLAP describes data very well but deviations are seen when the low $Q^2$ cut change from 2 to 5 GeV:

$\chi^2 [818/806 \to 698/771]$

Today precision of GD $O(10)\%$

e.g.: valence quark contribution varies by about 5 to 10% in low-$x$, substantial differences between v.q contributions for MSTW, CTEQ or HERAPDF
In the low-$x$ region gluon density dominates valence quarks.
another sign of a problem with DGLAP at small $x$, negative gluons in addition to higher $\chi^2$ of fits

a solution has to involve matching of BFKL or BK equations with DGLAP

matching requires high precision data
e.g.
recent BFKL analysis of HERA data by HK, Lipatov, Ross. Watt, arXiv(1005.0355);

BK analysis by Albacete et al
BFKL+DGLAP, Thorn and White

The rate of rise $\lambda$

$F_2 \sim (1/x)^2$

The first successful pure BFKL description of the $\lambda$ plot.

For many years it was claimed that BFKL analysis was not applicable to HERA data because of the observed substantial variation of $\lambda$ with $Q^2$.

H. Kowalski, L.N. Lipatov, D.A. Ross and G. Watt
arXiv 1005.0355
accepted for EPJC
BFKL is a quasi-Schroedinger eq. The solution is build from the quasi-bound, two-gluon states given by the eigenfunctions.

EF’s are the degrees of freedom of the gluonic fields.

Novel property: EF connects the extreme high energy behavior with low energies.

Data precision was crucial for finding a consistent solution.
$F_L$ measurements
combined H1 and ZEUS data

$F_L$ more directly connected to gluon density than $F_2$
at HERA I+II measurement precision of $F_L$ much worse than of $F_2$

$F_L$ measurement at HERA suffers from systematic errors of small angle electron measurement
Partons vs Dipoles

Infinite momentum frame: Partons

F$_2$ measures parton density at a scale Q$^2$

\[ F_2 = \sum_f e_f^2 \, x q(x, Q^2) \]

Proton rest frame: Dipoles - long living quark pair interacts with the gluons of the proton
dipole life time \( \approx 1/(m_p \, x) \)

\[ = 10 - 1000 \text{ fm at } x = 10^{-2} - 10^{-4} \]

\[ \sigma_{\gamma^* p} = \int \Psi^* \sigma_{qq} \Psi \; ; \; \; \; F_2 = \frac{Q^2}{4\pi^2 \alpha_{em}} \sigma_{\gamma^* p} \]

for small dipoles, at low-x, dipole picture is equivalent to the QCD parton picture
The same, universal, gluon density describes the properties of many reactions: $F_2$, $F_L$, inclusive diffraction, exclusive J/Psi, Phi and Rho production, DVCS, diffractive jets.

\[
\sigma_{\text{tot}}^{\gamma^* p} = \int \Psi^* \sigma_{qq} \Psi
\]

$\sigma_{\text{tot}}^{\gamma^* p} = \int \Psi^* \sigma_{qq} \Psi$  \quad \text{Optical Theorem}  \quad \frac{d\sigma^{\gamma^* p \rightarrow Vp}}{dt} \sim \left| \int d^2 b \Psi^*_V \Psi e^{-i\vec{b} \cdot \vec{\Delta}} \frac{d\sigma_{qq}}{d^2 b} \right|^2$

\[
\frac{d\sigma_{qq}}{d^2 b} \sim r^2 \alpha_s xg(x, \mu^2) T(b)
\]

for small gluon density
Vector Mesons

Note: educated guesses for VM wf are working very well
In focus: Exclusive J/psi production

Note:
J/psi x-section grows almost like
\[ \sigma \propto (x \ g(x,\mu^2))^2 \]
no valence quarks contribution

➢ the determination of gluon density with J/psi would be more precise than by \( F_2 \) or \( F_L \) (MRT) if J/psi would have small systematic errors

Educated guess for VM wf is working very well for J/psi and phi and DVCS

Equally good description of Q2 and \( \sigma_L/\sigma_T \) dependences for J/psi and phi and DVCS
Extracting Proton Shape using dipoles

$$\frac{d\sigma_{qq}}{d^2b} = 2 \left( 1 - \exp\left(-\frac{\pi^2}{2N_C} r^2 \alpha_s(\mu^2) x g(x, \mu^2) T(b) \right) \right)$$

for larger gluon density

v.g. description of B for all VM and DVCS with the same wf ansatz ➞ determination of the gluonic proton radius, $r_{gg} = 0.6$ fm is smaller than the quark radius $r_p=0.9$ fm

sys. errors due to different t-dep. of proton diss. reaction
The size of interaction region $B_D$ for various VM

Modification by Bartels, Golec-Biernat, Peters

$$e^{ib \cdot \Delta} \Rightarrow e^{i(b + (1-z)\vec{r} \cdot \vec{\Delta})}$$

For $J/\psi$, $B_D - B_G = 0.6 +/- 0.2 \text{ GeV}^{-2}$
Saturation models of HERA DIS data and inclusive hadron distributions in p+p collisions at the LHC

Prithwish Triedy and Raju Venugopalan
Saturation of gluon density is characterized by the size of the dipole, $r_s$, which, at a given $x$, starts to interact multiple times

$$
\frac{d\sigma_{q\bar{q}}}{d^2b} = 2 \left[ 1 - \exp \left( -\frac{\pi^2}{2N_C} r^2 \alpha_s x g(x, \mu^2) T(b) \right) \right] = 2(1 - \exp(-1/2))
$$

Saturated gluons form a new state of matter, CGC?

$$ Q_S^2 = \frac{2}{r_S^2} $$

$A^{1/3}$ increase of saturation expected in nuclei

\begin{align*}
(Q_S)^2 &= 0.5 \text{ GeV}^2 \text{ at } x=10^{-3} \\
0.8-1.8 \text{ GeV}^2 \text{ at } x=10^{-5} \\
(Q_{S-LHC})^2 &= 9/4 (Q_{S-HERA})^2
\end{align*}

strong correlations expected between momenta of saturated gluons

CMS correlation?
Strong rise of DIS cross sections

Photoproduction cross section shows the same universal behavior as the rise of hadronic cross sections, pp, Kp or πp, $\sigma \sim s^{1.08}$. It is a clear sign of the universality of saturation.

➤ Solve the impact parameter dependent BK equation. Connection to confinement?

work in progress by AS, KGB, GS, RV ..
Dipole projectiles are excellent tools to investigate nuclear matter. Measurement precision matches the precision of nuclear physics experiments.

σ\text{diff} and σ\text{tot} approach saturation in a different way. Sensitivity increase due to 
\[ d\sigma_{\text{diff}}/dt \propto (x \ g(x,\mu^2))^2 \]
and
\[ d\sigma_{\text{diff}}/dt|t=0 \sim A^2 \]
\[ \sigma_{\text{tot}} \sim A \]
Saturation scale in nuclei

The graphs show the behavior of various nuclei at different impact parameters (b). The y-axis represents the AT(b) values, and the x-axis represents the impact parameter (b) in units of (GeV)^{-1}. Different curves represent different nuclei, with Au, Ca, C, and D being distinguishable. The lower graph focuses on the relationship between Q^2 (GeV^2) and 1/x for different nuclei at b=0 GeV^{-1}.
Exclusive, Diffractive J/psi production at t=0

Large saturation or shadowing effects on nuclei consistent with KLV - PRL 100 022303
Saturation effects in the incoherent region
Measurement problems of ZEUS and H1

- Missing detector coverage in 3 units of rapidity
- Poor electron identification
- Large systematic errors of $F_2$, $F_L$ at low $Q^2$ and small $x$
- Systematic errors of diffractive $x$-sections $O(20)$ %, no long range correlation measurement
main source of information about GD today: $F_2$, $F_2^{charm}$
best signatures: $F_L$, diffractive processes ($J/\psi$...) and long range correlations

example: exclusive $J/\psi$ photoproduction,
  $x$-section for $J/\psi \to ee$ or $\mu\mu$ is $O(1)$ nb
the statistical errors of $\sim 1\%$ would require $L = 1\text{fb}^{-1}$
$\rightarrow$ expected # events $O(10^6)$

requirement: no systematic errors due to missing proton remnant,
good momentum resolution for $J/\psi$ measurements
in $O(10)$ units of rapidity (HERA had $\sim 2$)

detector should cover the full rapidity range with tracking
and/or calorimetry

Such a detector can also measure very well $F_L$, all other diffractive processes and long range correlations

Note: particle identification is of secondary importance $\rightarrow$ lower cost
BAGHERA
Best Acceptance for Gluons at HERA

conceptual detector

10m for tracking
The J/Psi energy versus W

CTD Acceptance

proton direction

electron direction
HERA I
\(E_e = 27.5 \text{ GeV}, \ E_p = 920 \text{ GeV}, \ \text{peak L}=1.4 \cdot 10^{31} \text{ cm}^2/\text{sec}\)
integrated lumi \(O(0.1) \text{ fb}^{-1}\)

Optimized HERA

Ring - Ring option \((\text{study by D. Pitzl et al.})\)
modified electron ring in the arcs - shorter dipoles, more quadrupoles:  \textit{emittance decrease by a factor} \(\sim 8\)

proton cooling with an additional ring:
\textit{emittance decrease by a factor} 3 to 5

peak \(L = 1\) to \(5 \cdot 10^{32} \text{ cm}^2/\text{sec}\)
integrated lumi \(O(0.8)\) to \(O(4) \text{ fb}^{-1}\)

Nuclear measurements \(\rightarrow\) dedicated Ion injector

ERL-Ring option: BNL design - further increase of lumi by \(O(10)\)
Conclusions

Optimized detector, operating on the optimized ep or eA machine, can precisely measure observables directly connected to the gluon density, like $F_L$, exclusive diffractive Vector Mesons, DVCS, jets and forward energy and multiplicity fluctuations.

Precise determination of the gluon density is necessary to fully exploit the LHC physics potential.

As in the case of black body radiation, precise GD will allow to determine what is the space of states of the gluonic field.

The nuclear measurements will give access to the substantially enhanced gluon saturation effects. Clear observation of saturation allows the study of properties of the strong gluonic fields.
Backup
1. $F_2$ and $F_L$ measurements combined H1 and ZEUS data

- Precision increase by more than factor 2
- DGLAP describes data very well but deviations are seen at lower $Q^2$
- Consequences for LHC are under investigations
1. Combined H1 and ZEUS data

**Averaged $F_L$**

$F_L$ more directly connected to the gluon density than $F_2$

at HERA I+II measurement precision of $F_L$ much worst than of $F_2$
Vector Mesons

\[ \gamma^* p \rightarrow J/\psi\ p \]

\[ \gamma^* p \rightarrow \phi\ p \]

- **H1** \(40 < W < 160\) GeV
- **ZEUS** \(W = 90\) GeV

- **Boosted Gaussian** \(\Psi_V\)
- **Gaus-LC** \(\Psi_V\)
DVCS

\[ \gamma^* p \rightarrow \gamma p \]

\( \sigma \) (nb)

\( W = 82 \text{ GeV} \)
- H1 (HERA I)
- H1 (HERA II)
- ZEUS

- b-Sat model
- b-CGC model

\( Q^2 \) (GeV\(^2\))

\[ Q^2 = 8 \text{ GeV}^2 \]
- H1
- ZEUS

\( \sigma \) (nb)

\( W \) (GeV)

(a)

(b)
Conceptual beam pipe design

\[ \Delta l = \frac{0.3 \cdot l^2 B}{2p} \frac{m^2 T}{GeV} \]
Measurement of momenta of J/ψ decay muons

Expected resolution of drift chambers:

\[
\frac{\sigma_{p_T}}{p_T}_{\text{meas}} = \frac{p_T \sigma_{r\phi}}{0.3L^2B} \sqrt{\frac{720}{N + 4}}
\]

\[
\frac{\sigma_{p_T}}{p_T}_{\text{MS}} = \frac{0.05}{LB\beta} \sqrt{1.43 \frac{L}{X_0} [1 + 0.038 \log(L/X_0)]}
\]

**TPC parameters**

1. outer radius \( R = 2 \text{ m} \)
2. solenoidal field \( B = 3.5 \text{ T} \)
3. gas density \( X_0 = 450 \text{ m} \)
4. point resolution \( \sigma = 100 \text{ \mu m} \)
5. measurement \( N = 200 \) points.

\[
\frac{\sigma_{p_T}}{p_T} = 0.005 \cdot p_T \oplus 0.045/\beta \ %
\]

\[\Delta p_T < 1 \text{ MeV with } p_T = 2 \text{ GeV}\]
Electron hemisphere with 14 tracking planes up to 480 cm

The design is symmetric around the interaction point.

Each plane is approximately 40 cm x 40 cm, consisting of two double-sided silicon detectors plus support.

Proton hemisphere with 14 tracking planes up to +480 cm

HERA III LOI