WG2: Small-x, Diffraction and Vector Mesons

Theory Summary

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Fits to DIS structure functions at small $x$

A. Stasto

- Fits of $F_2$ and $F_2^c$ using NLL BFKL with collinear resummation the CCSS scheme

- Exact kinematics is used in the high energy factorization formula

M. Sanhueza

- DIS fits using an approximate version of NLL BFKL with collinear resummations, and saturation effects

- Different models for large $b$ behavior of the saturation scale $Q_s$ are tested in the fits.
PDFs at small x

G. Chirilli

- Gluon Ioffe time distribution is computed in the high energy OPE.

- Gluon pseudo-PDFs and quasi PDFs are derived from this result.

- At low-x, very different behaviors for pseudo- PDF and quasi-PDF are observed.

- Pseudo-PDFs have the expected behavior at low-x.

- For Quasi-PDFs, the BFKL pomeron exponential is missing and higher twist power corrections are enhanced at low x.

K. Xie

- Comparison of DGLAP fits with either BFKL resummation or a choice of factorization scale simulating saturation effects

- Both give comparable description of HERA data

- At very small-x BFKL resummation leads to an enhancement of \( F_L \) whereas the saturation model reduces \( F_L \)
**Improvements of the NLO CGC**

**T. Lappi** - NLO structure functions in CGC at low-x with massive quarks in dipole factorization:

- Calculated in LFPT both for $\gamma^*_L$ and $\gamma^*_T$
- Required solving longstanding LFPT problem of mass renormalization
- All ingredients for fully accurate NLO CGC fits are now available

**L. Dai** - NLO JIMWLK with massive quarks:

- Contribution of massive quark loops to the NLO JIMWLK Hamiltonian calculated in LFPT.
- Two types of diagrams (quark loop either across or fully outside the shock)
- Massive quark loops can induce gluon mass in LFPT but a specific counter term can prevent this issue.

**P. Korcył** - Collinearly improved JIMWLK equation

- Numerical study of the Langevin form of JIMWLK
- New lattice implementation with finite volume and lattice spacing effects fully under control.
- Collinear improvement of JIMWLK implemented numerically for the first time. However, extremely demanding in computing power.
Further studies of nonlinear low-x evolution

**L. Motyka** - Twist decomposition of non-linear effects in BK evolution
- Twist decomposition of the proton structure functions from LL BK equation is performed with a single iteration of the nonlinear term
- Strong effect of gluon saturation corrections at twist 2
- Nonlinear evolution introduces small higher twist correction in $F_2$ and moderate corrections in $F_L$

**M. Lublinsky** - Reggeon Field Theory in zero transverse
- Toy model study in order to understand unitarity constraints and the transition from dilute to dense for the incoming hadrons
- Construction of a unitarized toy model with multiple emissions to approach the dense-dense regime in RFT

**S. Bondarenko** - Balitsky hierarchy from Lipatov effective action
- Expansion of Wilson lines around a classical background and calculation of the propagator of fluctuations in the background
- This formalism in principle can be extended to derive further corrections to low-x evolution (NNLL BFKL?)
CGC beyond eikonal accuracy

A. Tymowska - DIS dijet production at NEik order

- Calculation of the full NEik corrections from the gluon background field
- NEik correction beyond infinite time dilation of the target considered for the first time, allowing light-cone momentum exchange with the target.
- NEik corrections stemming from transverse motion within the target is accounted for, beyond the shockwave approximation

M.G. Santiago - Boer-Mulders TMDs at small-x

- Low-x evolution equation for the Boer-Mulders TMD is derived
- In the non-singlet case solution is shown to scale at low-x as

\[ h^{\perp NS}_{1}(x, k_{\perp}) \propto \left( \frac{1}{x} \right)^{-1} \]

Naive sub-sub-eikonal scaling unchanged by \( \alpha_s \) correction

R. Boussarie - Twist expansion for DDVCS

An interpolating expression between the Regge-Gribov and Bjorken limits is derived for DDVCS amplitude.

It involves a GTMD defined from decorated Wilson loop with \( F^{i-} \) insertions.
Semi-inclusive DIS observables in the CGC

**F. Salazar** - DIS dijet production at NLO

- Cancellation of soft and UV divergences between diagrams
- Collinear divergences treated with jet definition in small R limit
- Rapidity divergences treated with JIMWLK evolution of quadrupoles and dipoles.
- Sudakov double logs with the wrong sign are obtained in the back-to-back limit in the absence of kinematical improvement of JIMWLK

**E. Iancu** - Diffractive production of 2+1 jets in DIS

\[ k_{1\perp}, k_{2\perp} \sim Q \gg k_{3\perp} \sim Q_s \]

- TMD-like factorization obtained in this regime involving Pomeron UGD
- Strong sensitivity to gluon saturation

**J. Jalilian-Marian** - DIS dihadron production at NLO

- Similar calculation as dijet production with the same diagrams. / - Collinear divergences are absorbed into fragmentation functions instead of jets.
Exclusive vector meson production (1)

J. Penttala

- Full NLO calculation with massive quarks of the exclusive heavy vector meson production in the CGC
- Vector meson Light Front wave function obtained from nonrelativistic expansion in NRQCD
- First relativistic correction is also included in the computation

C. Flett

- Implementation of NLO collinear factorization + NRQCD to exclusive photoproduction of $J/\Psi$ in Pb-Pb UPCs
- Large scale dependence encountered
- At mid-rapidity, quarks dominate at NLO due cancelation of gluon contributions
- Some ideas have been proposed to resolve these issues
Exclusive vector meson production (2)

F. Celiberto

- Exclusive forward $\rho$-meson production is computed in BFKL formalism and results for HERA and EIC are presented.

- Further constraints on UGD is possible with this process.

M. Hentschinski

- Energy dependence of the ratio of $\psi(2s)$ over $J/\Psi$ exclusive cross sections found to depend noticeably on gluon saturation.

- Flat for linear BFKL evolution

- Rising with $W$ for nonlinear BK evolution

M. Krelina

- Photoproduction of heavy quarkonium on nuclei

- $t$-dependent calculation in the dipole formalism including various corrections in particular gluon shadowing and shorter lived higher Fock components in the photon. 
**Proton shape fluctuations**

Fluctuating proton necessary in order to describe both coherent and incoherent exclusive VM production at HERA: *hot-spot model*

\[ \sigma_{\text{coherent}} \sim |\langle A \rangle_{\Omega}|^2 \quad \text{and} \quad \sigma_{\text{incoherent}} \sim \langle |A|^2 \rangle_{\Omega} - |\langle A \rangle_{\Omega}|^2 \]

**H. Mantysaari** - First Bayesian analysis to extract hot-spot model parameters from diffractive J/Psi data.

- Allows to control uncertainty propagation.

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

**T. Toll** - Test of energy dependence of parameters of the hot-spot model vs HERA data

- Preference for hot-spot number or proton size growing with energy.
Other DIS / photoproduction observables

A. Kumar

- DIS processes with leading neutron can give accesses to DIS on pion.

- By comparison to HERA data at low-x, the same dipole cross section is then obtained for pions and proton up to the normalization: universality of hadron structure at small-x.

- t-dependence of exclusive vector meson production with leading neutron can probe both the spatial distribution of gluons in pion at large-t and the pion cloud of the proton at small t.

S. Nabeebaccus

- $2 \rightarrow 3$ exclusive process with $\rho_T$ production allows to access so far unknown chiral-odd twist 2 GPDs

- Models for this transversity GPDs have been used to make predictions at JLab kinematics

M. Siddikov

- Production of quarkonia pairs with opposite C-parity is dominated by photon-Pomeron fusion: Cross-section is not so small.

- This process is calculated in the dipole model and the predictions for EIC, UPCs at LHC, LHeC and FCC have been presented.
Saturation vs Sudakov in 2-particle correlations in hadronic collisions

Gluon saturation alone describes the suppression of the back-to-back peak in forward particle production. However, leads to a too narrow peak. Need for Sudakov resummation in the vicinity of the back-to-back limit.

Cyrille Marquet - Forward di-hadron/dijet back-to-back correlations

Sanjin Benic - Photon-hadron correlations

- At large pt: Sudakov resummation erase the sensitivity to saturation.
- At small pt: Sudakov resummation is non-perturbative and leads to large uncertainties.

\( R_{pA} \)

2.7 < y < 4
28 < \( p_{t1,2} \) < 35 GeV

\( R_{pA} \) mostly sensitive to CGC+S non-pert
\( R_{pA} \) mostly sensitive to S Sud

\( \Delta \phi \)

ATLAS measured the di-jet correlation function at forward rapidities.

\( \Delta y = 0, 2 \) TeV
\( \Delta p_t = 2, 90 \) GeV

CGC+Sudakov, pp
CGC+Sudakov, pA

van Hameren, Kotko, Kutak and Sapeta (2019)
similar conclusions obtained with the MC model
Jet production in low-x hadronic collisions

H. Liu - Forward single jet production at NLO in CGC

- Jet production beyond the small R limit is implemented for the first time in the CGC.

- Full fledged anti-kt jet algorithm is used.

- Numerical study shows that small R jet definition is a good approximation for an extended domain in pt and in R.

- In the small R approximation the same semi-inclusive quark jet function is obtained as in collinear factorization.

*Special thanks to Meijian Li for making this talk possible after all.

A. van Hameren - Hybrid $k_T$ factorization at NLO

- Off-shell leg in an amplitude can be defined via auxiliary on-shell parton.

- NLO corrections to partonic cross sections with one off-shell leg are studied.

- Cancellation of the infrared poles requires small momentum fraction $x$ carried by the off-shell leg.

- HEF emerge from $k_T$-dependent factorization in the auxiliary parton method at NLO.
Inclusive heavy quarkonium production

M. Nefedov - $\eta_c$ and $\eta_b$ inclusive hadroproduction, ...

- NLO cross section in collinear factorization is unstable due to high energy logs
- HEF partonic cross section valid only in part of the integration range
- Matching between HEF and NLO CF is always required.

M. Fucilla - Inclusive $J/\Psi$ and $\Upsilon$ production in hybrid HEF/Collinear factorization

- Quarkonium production from single parton fragmentation as well as collinear PDF included in the impact factors
- Azimuthal angle correlation between quarkonium and jet is studied.
- Due to the weak dependence on renormalization/factorization scale, it is a promising channel to study BFKL physics.
Correlations and entanglement in hadron wave function

A. Dumitru - C-odd color charge correlators:

- Model for proton state including perturbative \(|qqqg>\) component in addition to the \(|qqq>\) component:

- C-odd three color charge correlator is computed in this model.
- Should contribute to Odderon exchange and T-odd gluon TMDs.

M. Li - Bose correlations in DIS trijet production

Demonstration that diffractive quark-antiquark singlet dijet + gluon jet in DIS has near-side ridge correlation that originates from the Bose correlations in the nuclear wave function.

K. Kutak - Conjecture of maximal entanglement at low-x:

“Hadronic entropy from charged particle multiplicity distribution is related log of the number of partons in the proton”

\[ S(x, Q^2) = \ln \left( n \left( \ln \frac{1}{x}, Q \right) \right) \]

Indeed, observed at HERA for quark+gluon distributions with low-x resummation.