Overview of recent developments on saturation physics at e-p and e-A colliders

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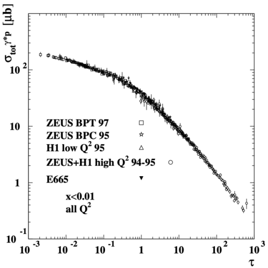
Motivation: why saturation is relevant at Hard Probes?

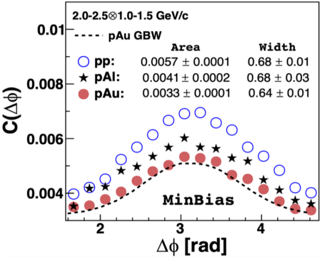
- We are all interested in QCD: consistent high energy limit?
  - Froissart–Martin bound: $\sigma_{\rm tot}(s) \leq \sigma_0 \ln^2(s)$ as $s \to \infty$
  - Saturation paradigm: non-linear gluon recombination effects tame the growth of the gluon distribution in proton and nuclei.
- Initial conditions in heavy-ion collisions depend on saturation physics.

Disclaimer: a theory biased overview on saturation

but synergy with experiments is crucial

- Since the observation of geometrical scaling in HERA data...





- ... recent hints for saturation effects in pA collision at RHIC. STAR Collaboration, 2111.10396
- Saturation is at the heart of the EIC Physics Program. EIC yellow report, 2103.05419
- Saturation physics at RHIC and at the LHC: see talks on Monday and during the week!

Outline

(1) New observables sensitive to saturation.

(2) Precision calculation in the saturation framework.

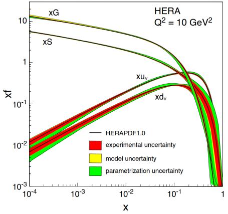
(3) Selected topics about the connection between saturation and AA physics.

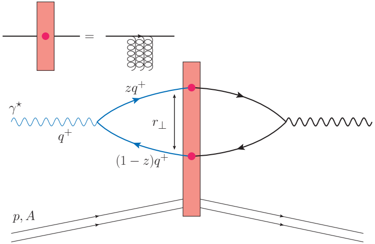
New observables in *ep* and *eA* for saturation physics

Saturation physics in a nutshell

- DIS at small $x_{\mathrm{Bj}} = Q^2/(2P \cdot q) \Leftrightarrow$ high energy $s \to \infty$ limit for fixed Q^2.
- Dipole picture of DIS: interaction between a $q\bar{q}$ dipole and the dense gluon field of the target.
- Large occupancy of gluons $\Rightarrow$ multiple scatterings and unitarization of the cross-section.
- Total DIS cross-section at small-x:

$$\sigma^{\gamma^\star A}(x, Q^2) \propto 2 \int d^2 r_\perp \int_0^1 dz |\psi^{\gamma^\star \to q\bar{q}}(r_\perp, Q^2, z)|^2 (1 - S_x(r_\perp))$$





Saturation physics in a nutshell

- Total DIS cross-section at small-x:

$$\sigma^{\gamma^\star A}(x, Q^2) \propto 2\int d^2 r_\perp \int_0^1 dz |\psi^{\gamma^\star \to q\bar{q}}(r_\perp, Q^2, z)|^2 (1 - S_x(r_\perp))$$

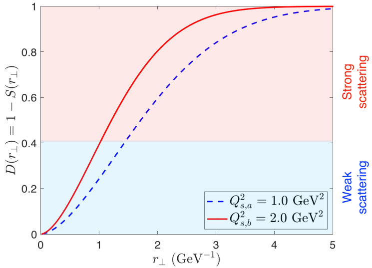
- $Q_s^2 \propto A^{1/3}$ transition scale between weak and strong scattering regime.
- Successful to describe HERA data.

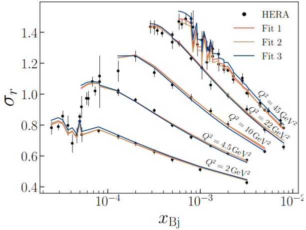
  NLO calculation and fit from Beuf, Hänninen, Lappi, Mäntysaari 2007.01645. See also Ducloué, Iancu, Soyez, Triantafyllopoulos, 1912.09196

- Total DIS cross-section sensitive to saturation when $Q^2 \sim 1/r_\perp^2 \lesssim Q_s^2 = \mathcal{O}(0.1 \div 1)$ GeV^2.
- **But** NP contamination for semi-hard Q^2.

  Mäntysaari, Zurita, 1804.05311, Mäntysaari, Schenke, 1806.06783

Morreale, Salazar review 2108.08254



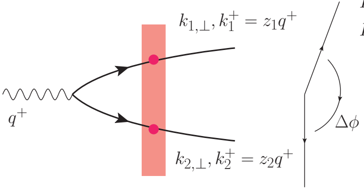


Interest of semi-inclusive processes: back-to-back dijets

- More than one transverse scale! For back-to-back dijet: $P_\perp \gg K_\perp$
- $P_\perp$ hard, $K_\perp \sim Q_s$ semi-hard
- Imprint of saturation on final state correlations.

  Dominguez, Marquet, Xiao, Yuan, 1101.0715, Dumitru, Lappi, Skokov, 1508.04438, Dumitru, Skokov, Ullrich, 1809.02615
- **But:** soft gluon radiation effects spoil this nice picture.

  Mueller, Xiao, Yuan, 1308.2993

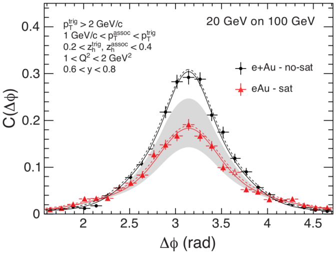


$P_\perp = z_2 k_{1,\perp} - z_1 k_{2,\perp}$

$K_\perp = k_{1,\perp} + k_{2,\perp}$

Ideal probe

Semi-inclusive observables with a hard scale, sensitive to Q_s through final state correlations not plagued by Sudakov effect.

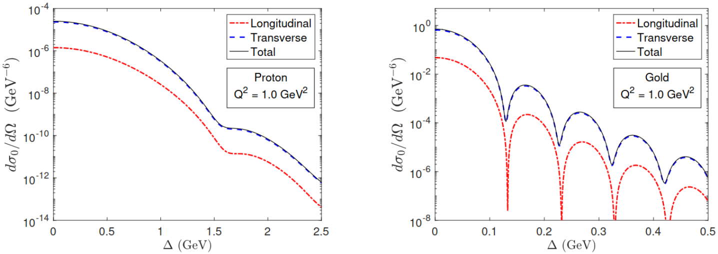


Zheng, Aschenauer, Lee, Xiao, 1403.2413

Diffraction in DIS: example of exclusive dijet production

- Diffractive events probes the strong scattering regime.
- Interesting opportunities if one measures final states correlations for $P_\perp \sim Q_s$.

  Altinoluk, Armesto, Beuf, Rezaeian, 1511.07452, Hatta, Xiao, Yuan, 1601.01585, Mäntysaari, Mueller, Schenke, 1902.05087, Salazar, Schenke, 1905.03763

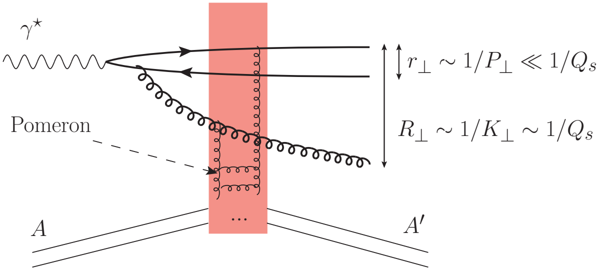


$\Rightarrow P_\perp = 1$ GeV in this plot! Challenging to measure.

- What about going to higher $P_\perp$? Problem: higher twist cross-section $\Rightarrow$ tiny cross-section at large $P_\perp \gg Q_s$ (color transparency).

2+1 diffractive jet production

- Hard $P_\perp \gg Q_s$ dijet + 1 semi-hard gluon jet $K_\perp \sim Q_s$ gives the dominant contribution to dijet diffractive events at large $P_\perp$.
- An $\mathcal{O}(\alpha_s)$ effect but leading twist!
- Strong sensitivity to saturation: effective gg dipole interacts strongly with the target.



Iancu, Mueller, Triantafyllopoulos, 2112.06353

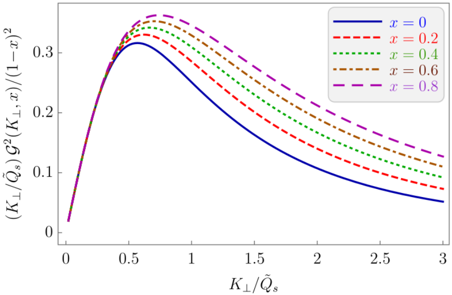
2+1 diffractive jet production

- Admits TMD factorization at leading order.

Iancu, Mueller, Triantafyllopoulos, Wei, 2207.06268, see also Hatta, Xiao, Yuan, 2205.08060

$$x_{\mathbb{P}} \frac{d\sigma^{\gamma^\star A \to q\bar{q}A'+X}}{d^2P_\perp d^2K_\perp dx_{\mathbb{P}}} = \overbrace{\mathcal{H}(P_\perp^2, Q^2)}^{\text{hard factor}} \times \underbrace{xG_{\mathbb{P}}(x, x_{\mathbb{P}}, K_\perp^2)}_{\text{UGD of the Pomeron}}$$

$$x_{\mathbb{P}} = x_{\rm Bj}/\beta \quad , \beta = \frac{Q^2}{Q^2 + M_{q\bar{q}g}^2}$$



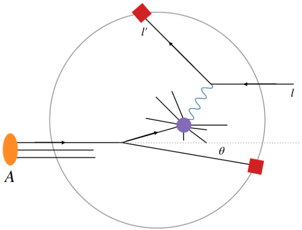
- UGD counts the number of gluon with a given x in the Pomeron.
- Fast decrease $K_\perp^{-4}$ of the Pomeron UGD at large $K_\perp$ $\Rightarrow$ maximal sensitivity to Q_s, even after integrating over $K_\perp$ to **remove Sudakov effects**.

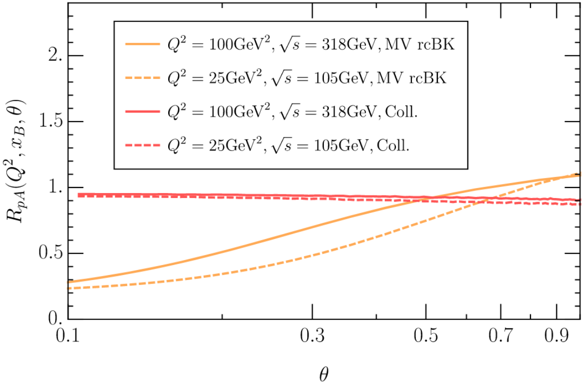
Nucleon energy-energy correlators

- Many talks on EEC at this conference!
- Very promising observable to see saturation effects as well.

  Liu, Zhu, 2209.02080, Liu, Liu, Pan, Yuan, Zhu, 2301.01788

- Nucleon EEC $\sim$ partonic angular distribution induced by intrinsic transverse momentum in nuclei.
- $\Sigma(\theta) = \int d\sigma(x_{\rm Bj}, Q^2, p_i)\frac{E_i}{E_N}\delta(\theta-\theta_i)$





Towards precision small-x physics in the saturation regime

Ingredients of N^{p}LO small-x calculation

Universal non linear N^{p}LL BK/JIMWLK evolution equation

- Process independent, resum $\alpha_s^{p+n} \ln^n(1/x_{\mathrm{Bj}})$ to all orders.
- Recents results on spin dependent small-x evolution, NLL JIMWLK with massive quarks.

  See Cougoulic, Kovchegov, Tarasov, Tawabutr, 2204.11898 and Dai, Lublinsky, 2203.13695

Process dependent N^p LO impact factors

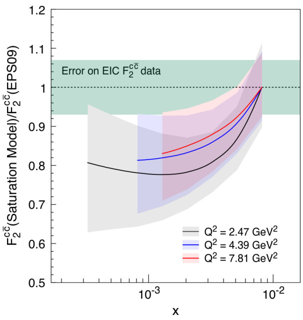
- **Non**-exhaustive list of recent NLO results in eA or ep
  - Dijet+photon in DIS Roy, Venugopalan, 1911.04530
  - Inclusive dijets PC, Salazar, Venugopalan, 2108.06347, inclusive dihadrons Bergabo, Jalilian-Marian, 2207.03606
  - Structure functions for massive quarks. Beuf, Lappi, Paatelainen, 2112.03158
  - Exclusive heavy-vector production. Mäntysaari, Penttala 2204.14031
  - Diffractive structure functions. Beuf, Hänninen, Lappi, Mulian, Mäntysaari, 2206.13161

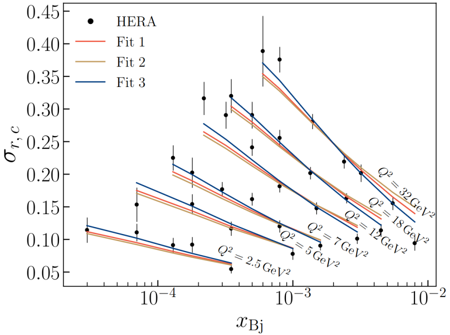
- Topic not covered here: sub-eikonal corrections suppressed by powers of x_{Bj}.

  See e.g. Altinoluk, Beuf, Czajka, Tymowska, 2212.10484, Altinoluk, Armesto, Beuf, 2303.12691

DIS structure functions for massive quarks

- Less sensitive to non-perturbative dipole sizes as the charm mass regulates the IR.
- Recent calculation of the NLO impact factor for massive $q\bar{q}$ pair in light-cone perturbation theory. Beuf, Lappi, Paatelainen, 2112.03158, Hänninen, Mäntysaari, Paatelainen, Penttala, 2211.03504
- Reduces theoretical uncertainties on saturation models.





Albacete, Armesto, Milhano, Salgado, 0902.1112

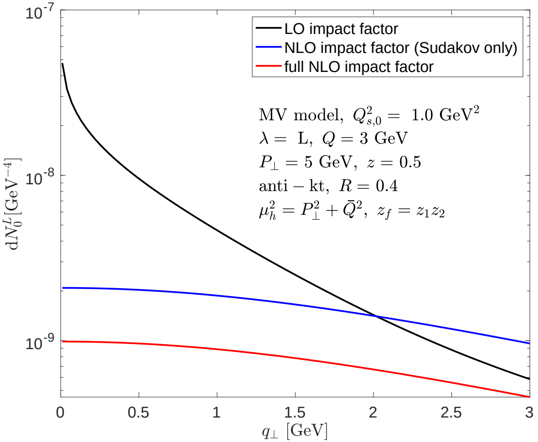
Inclusive dijet production in DIS

PC, Salazar, Schenke, Venugopalan, 2208.13872, PC, Salazar, Schenke, Stebel, Venugopalan, to appear

- Full NLO calculation in the CGC in PC, Salazar, Venugopalan, 2108.06347
- Focus on back-to-back kinematics: $P_\perp \gg q_\perp$.
- Sudakov double and single logarithms.
  $S \sim 1 - \alpha_s s_{\rm DL} \ln^2(\mathbf{P}_\perp^2/\mathbf{q}_\perp^2) - \alpha_s s_{\rm SL} \ln(\mathbf{P}_\perp^2/\mathbf{q}_\perp^2)$
- Weisäcker-Williams TMD factorization at NLO!

$$\frac{\mathrm{d}\sigma}{dP_\perp dq_\perp} = \left[\mathcal{H}^{ij,\lambda=\mathrm{L}}_{\mathrm{LO}}(\mathbf{P}_\perp) + \alpha_s \mathcal{H}^{ij,\lambda=\mathrm{L}}_{\mathrm{NLO}}(\mathbf{P}_\perp, x_f)\right] \times \int \frac{\mathrm{d}^2\mathbf{r}_{bb'}}{(2\pi)^4} e^{-i\mathbf{q}_\perp\cdot\mathbf{r}_{bb'}} \underbrace{x_f \hat{G}^{ij}(x_f, \mathbf{r}_{bb'})}_{\mathrm{WW gluon TMD}} \mathcal{S}(\mathbf{P}_\perp^2, \mathbf{r}_{bb'}^2)$$

At LO, see Dominguez, Marquet, Xiao, Yuan, 1101.0715

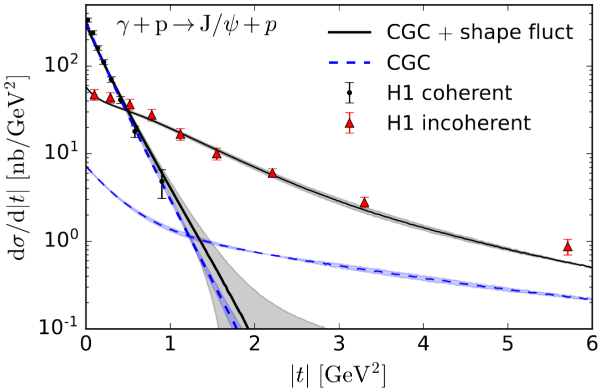


Selected topics about the connection between saturation and AA physics

Constraining initial conditions to small system collisions

- Incoherent exclusive vector meson production interesting to probe subnuclear fluctuations.

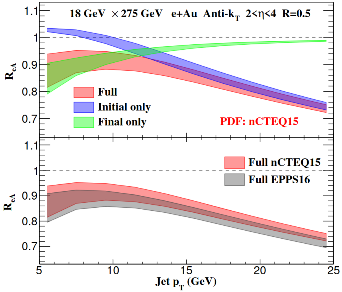
Lappi, Mäntysaari, 1011.1988,
Mäntysaari, Schenke, 1603.04349
Demirci, Lappi, Schlichting, 2206.05207
See also Cepila, Contrerasa, Tapia Takaki, 1608.07559 (photoproduction)

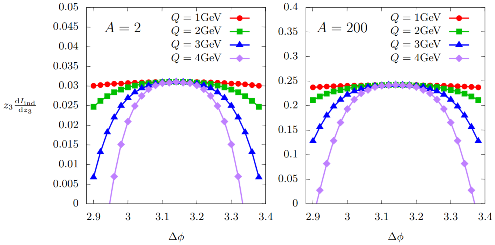


- Constraining power of fluctuating nucleon substructure within CGC based IP-Glasma model. Schenke, Tribedy, Venugopalan, 1202.6646

Jet quenching in eA?

- Calculations in collinear factorization, with a $\hat{q}$ for cold nuclear matter $\sim Q_s^2/L$
  Li, Vitev, 2010.05912





Bergabo, Jalilian-Marian, 2108.10428

- At small-x, negligible jet energy loss "inside the medium" $\Delta E_{mie} \sim \alpha_s^2 Q_s^2 L \ll E$.
  Coherent energy loss should dominate:

$$R_{pA} < 1 \text{ for jets at small } x?$$

Quantum evolution of $\hat{q}$

Synergy between small-x and jet quenching physics

- $\hat{q}$ receives double log corrections from fluctuations with formation time $\tau \ll L$.
  Liou, Mueller, Wu, 1304.7677, Blaizot, Mehtar-Tani, 1403.2323
  Iancu 1403.1996

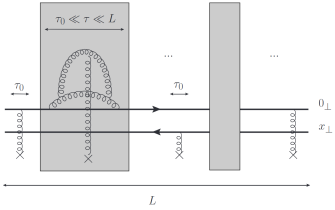
  Kang, Wang, Wang, Xing 1407.8506, 1409.1315

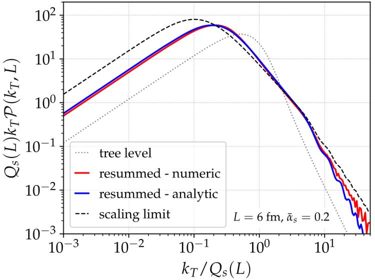
- Many recent studies of quantum corrections to $\hat{q}$:
  Arnold, Gorda, Iqba, 2112.05161, Arnold 2111.05348
  Ghiglieri, Weitz, 2207.08842

  PC, Mehtar-Tani, 2109.12041, 2203.09407

- Improved initial conditions to BK, including radiative corrections "inside the shockwave".

- Improved jet quenching pheno.





Concluding remarks

- A taste of **some** of the recents developments in saturation physics.
- Many things I did not have the time to cover, especially works in the BFKL/dilute approaches or saturation physics in pA collisions.
- Many opportunities for saturation in photoproduction at the LHC.
  See next talk by Vadim Guzey.

THANK YOU!