Signatures of gluon saturation from structure function (and diffractive) measurements

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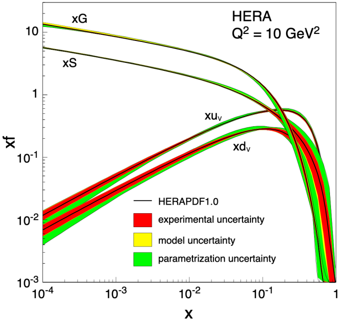
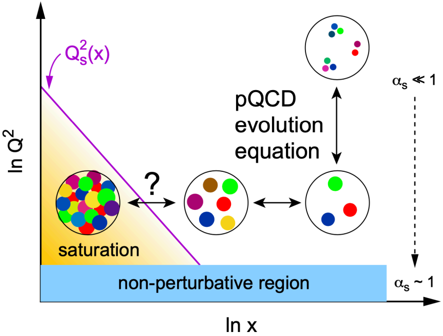
Lessons from HERA

HERA total $\gamma^* + p$ cross section data: parton densities $\sim x^{-\lambda}$, eventually violates unitarity



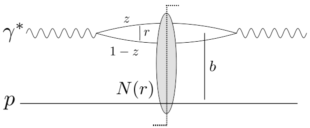


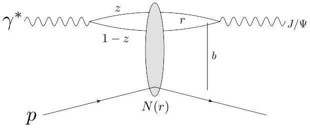
Non-linear QCD effects at small x (e.g. $gg \to g$) should tame this growth

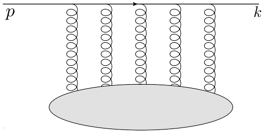
$\Rightarrow$ Saturated state of gluonic matter at small x and moderate Q^2

- Large densities $\sim A^{1/3}$ in nuclei
- Accessible also in p+A at the LHC (at smaller x), but γ^* a much cleaner probe

Different probes of gluon saturation







Inclusive cross section

Optical theorem:
$\sigma^{\gamma^* p} \sim \Psi^* \otimes \Psi \otimes N$
$\sim$ dipole N $\sim$ "gluon"

Exclusive process

Access to geometry
$\mathcal{A} \sim \int \mathrm{d}^2\mathbf{b} e^{-i\mathbf{b}\cdot\Delta} \Psi^* \otimes \Psi_V \otimes N$
$\sim \mathrm{FT}[\text{dipole } N]$, $\sigma \sim N^2$

Hadron production in $p+A$

q in amplitude, $\bar{q}$ in c.c. amplitude
$\sigma^{p+A\to\pi^0+X} \sim$ dipole N

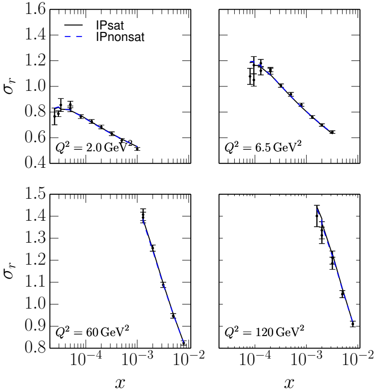
DIS (HERA, EIC) – LHC/RHIC complementarity

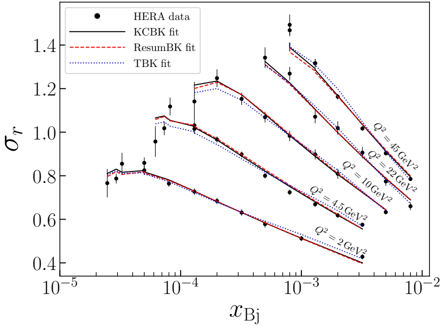
Dipole $N = 1 - \frac{1}{N_c} \mathrm{tr}\, V(\mathbf{x}) V^\dagger(\mathbf{y})$ is a convenient degree of freedom at high energy

- Resums multiple interactions with the target color field
- Energy (x_{Bj}) dependence: non-linear BK equation, needs a non-perturbative IC

High energy: quark propagating at $\mathbf{x}$ picks up a Wilson line $V(\mathbf{x})$

Looking for gluon saturation at HERA/EIC: structure functions





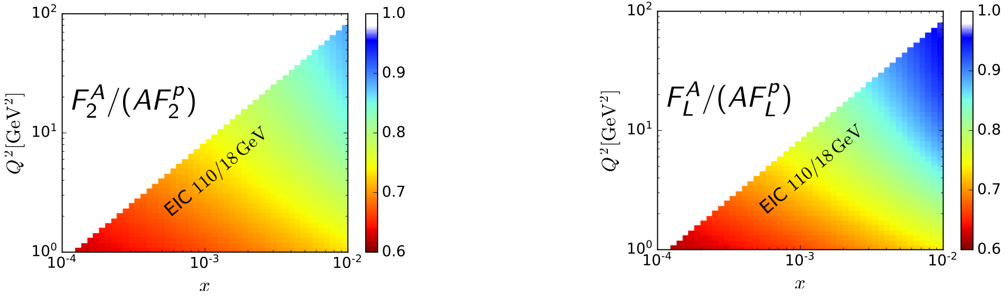
- Fit initial condition to small-x evolution
- Equally good description with and without non-linear dynamics H.M, P. Zurita, 1804.05311

- CGC calculations entering NLO era
- Good agreement with HERA data

Beuf, Hänninen, Lappi, H.M, 2007.01645

HERA data does not seem to require non-linear dynamics

Non-linear QCD dynamics in inclusive cross section: nuclear targets

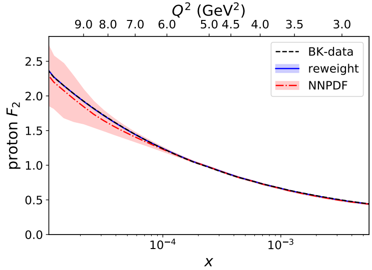


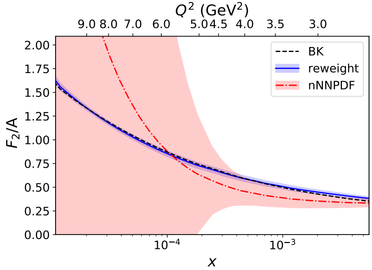
Based on Lappi, H.M, 1309.6963

- Clear nonlinear effect expected for nuclei ($Q_s^2 \sim cA^{1/3}$)
- F_L probes more directly dipole sizes $r \sim 1/Q \Rightarrow$ stronger Q^2 and x dependence
- F_2 is sensitive to non-perurbatively large dipoles, so F_L and $F_{2,c}$ theoretically better

Maximally large x, Q^2, A lever arm is important (e.g. close to $y = 1$)

Extracting genuine signals of saturation from QCD evolution





Both DGLAP (no saturation) and BK (saturation) based calculations can usually be fitted to a one set of data
How precise measurements are needed to distinguish the two?

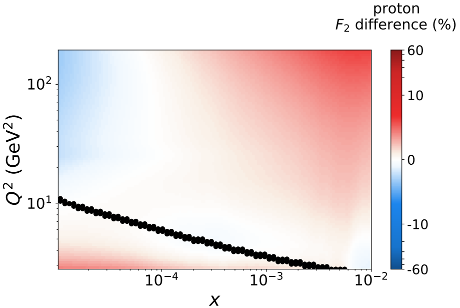
Remove the effect of the non-perturbative initial condition:

- Require $F_2(\mathrm{BK}) = F_2(\mathrm{DGLAP})$ at $Q^2 = 10 Q_s(x)^2$: Both approaches expected to be valid in this kinematics
- Technically: reweight PDF sets
- Construct DGLAP evolution that matches BK at $Q^2 = 10 Q_s(x)^2$
- Probe genuine differences in evolution when moving away from the matching line

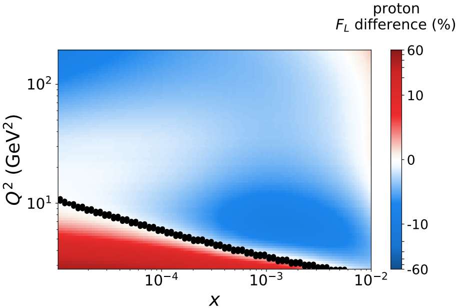
Details: NNPDF 3.1 for protons, nNNPDF2.0 for nuclei, 1000 MC replicas reweighted

Armesto, Lappi, H.M, Paukkunen, Tevio, 2203.05846

Evolution dynamics I: protons



$$\frac{F_2^{\mathrm{BK}} - F_2^{\mathrm{Reweight}}}{F_2^{\mathrm{BK}}}$$

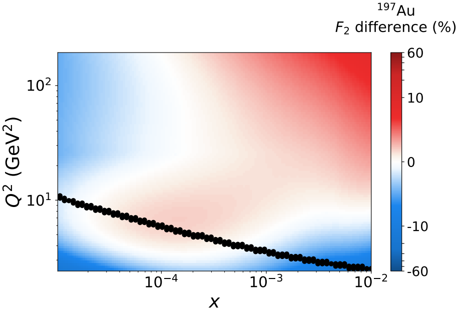


- Quantify differences in evolution when moving away from the matching line
  $\Rightarrow$ how precisely $F_{2,L}$ need to be measured to see signals of non-linear dynamics
- Only $\sim$ few percent differences in F_2 in the EIC energy range
- F_L more sensitive, differences up to $\sim 10\%$ at the EIC – but more difficult to measure

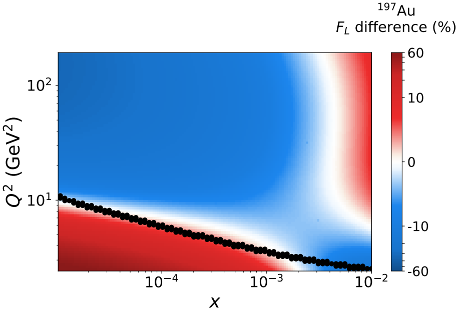
Interested in absolute values? See backup for 1d plots

Armesto, Lappi, H.M, Paukkunen, Tevio, 2203.05846

Evolution dynamics II: nuclei



$$\frac{F_2^{\mathrm{BK}} - F_2^{\mathrm{Reweight}}}{F_2^{\mathrm{BK}}}$$



- Larger effects in nuclei, as $Q_s^2 \sim A^{1/3} \Rightarrow$ stronger non-linear phenomena
- F_2 is needed in $\sim 10\%$ precision in EIC kinematics, for $F_L \sim 15\%$ accuracy is enough
- Again: Q^2, x, A systematics and lever-arm important!

Armesto, Lappi, H.M, Paukkunen, Tevio, 2203.05846

Looking for gluon saturation at the EIC 2: diffraction

Exclusive processes: no net color transfer, rapidity gap around the produced particle

Coherent diffraction

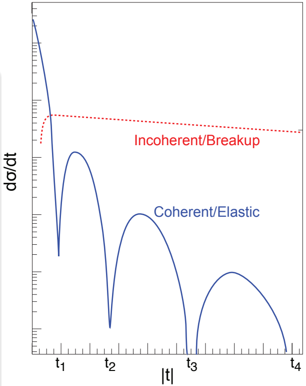
- Target remains in the same quantum state, e.g. $\gamma + p \to J/\Psi + p$
- FT coordinate $\Rightarrow$ momentum space: access to geometry
- Coherent–incoherent separation? Chang et al, 2108.01694

$$\frac{\mathrm{d}\sigma^{\gamma^* A \to VA}}{\mathrm{d}t} \sim |\langle \mathcal{A}^{\gamma^* A \to VA} \rangle_\Omega|^2$$

$\langle \, \rangle_\Omega$: average over target configurations Ω

$\mathcal{A} \sim \int \mathrm{d}^2\mathbf{b} e^{-i\mathbf{b}\cdot\Delta} \Psi^* \otimes \Psi_V \otimes N$

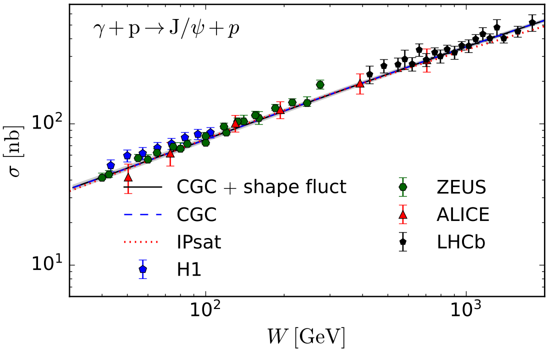
Incoherent (target breakup) also interesting (backup)



Good, Walker, PRD 120, 1960
Miettinen, Pumplin, PRD 18, 1978
Kovchegov, McLerran, PRD 60, 1999
Kovner, Wiedemann, PRD 64, 2001
Caldwell, Kowalski, PRC 81, 2010

H.M., Rept. Prog. Phys. 83, 2020

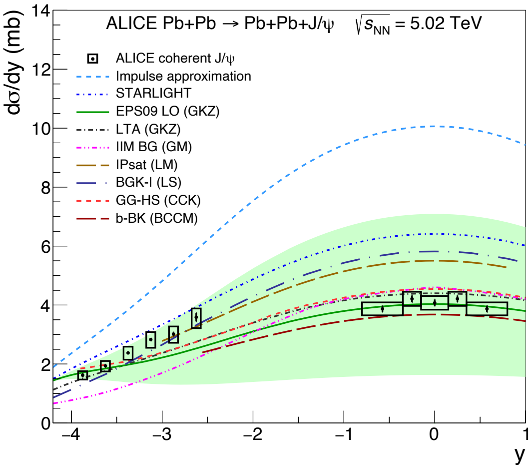
Center-of-mass energy dependence: protons



H.M, F. Salazar, B. Schenke, 2207.03712

- Coherent cross section measured up to very large W (UPC pA)
- No clear deviation from the W^δ extrapolation from HERA energies
- Compatible with CGC calculations, but no clear signal of saturation with proton targets

Significant nuclear effects already seen, with some open questions



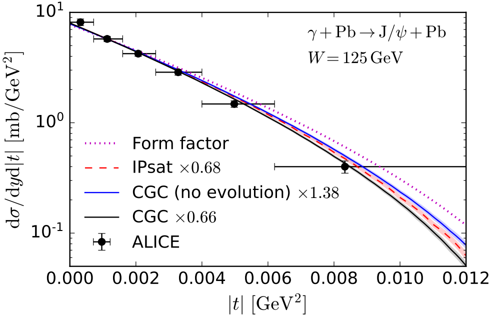
$$x = \frac{M_{J/\Psi}}{\sqrt{s}} e^{\pm y}$$

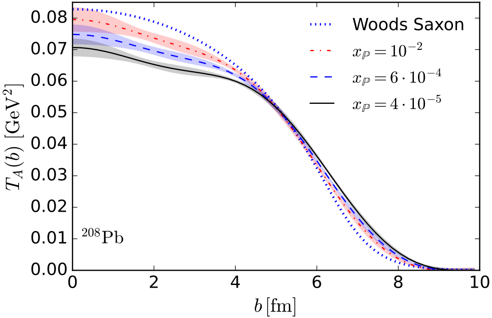
ALICE: 2101.04577

- Extensively studied in UPCs at the LHC by CMS, ALICE, LHCb
- Impulse approximation $=$ scaled $\gamma + p$ from HERA $\Rightarrow$ large nuclear effect
- CGC based calculations (e.g. *IPsat (LM)*) relatively successful
  - But y dependence?
  - Not enough suppression?
- EIC advantages:
  - No two-fold ambiquity in kinematics
  - Q^2, A (and some $x_{\mathbb{P}}$) lever arm $\Rightarrow$ systematics
  - Coherent-incoherent separation?
  - Access to photon k_T, no interference

Saturation effects on nuclear geometry – more differential measurements!

ALICE UPC: extracted $\gamma + \mathrm{Pb} \to \mathrm{J}/\psi + \mathrm{Pb}$ from $\mathrm{Pb} + \mathrm{Pb} \to \mathrm{Pb} + \mathrm{Pb} + \mathrm{J}/\psi$





H.M, F. Salazar, B. Schenke, 2207.03712. Data: 2101.04623.

Normalized: $\int \mathrm{d}^2 b T_A(b) = 1$

- Naive expectation/linearized calculation:
  $\mathrm{d}\sigma/\mathrm{d}t \sim \mathcal{F}[\text{Woods-Saxon}]^2$ (*Form factor*), but a steeper t spectrum seen
- Center of the nucleus closer to the black disc limit, stronger nonlinear effects
  $\Rightarrow$ Good description of the data (except lowest $|t|$) + effect on geometry/t spectrum

Conclusions

Inclusive DIS

- Clear nuclear effects expected in the EIC energy range
- Determine initial condition for the small-x evolution: crucial input for phenomenology
- Important to minimize the effect of the fitted non-perturbative initial condition

Diffraction

- Stronger nuclear effects, but theoretically more complicated (e.g. meson structure)
- More differential measurements (e.g. spectra, e-J/ψ correlations, ...) are powerful

Everything is connected

- x, Q^2, A systematics is important to distinguish linear and non-linear evolution
- Nuclear DIS at the EIC and p+A collisions at the LHC: complementary probes
- Eventually a global analysis is likely required to “discover” saturation

Backups

Gluon saturation and the Color Glass Condensate

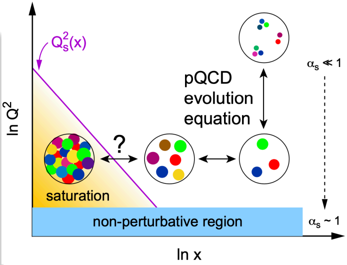
- Very high occupation number $xg(x, Q^2)$, apparent size $1/Q^2$

Non-linear dynamics important when

$$\pi R_p^2 = \alpha_s xg(x, Q^2)\frac{1}{Q^2}$$

Emergent saturation scale $Q^2 = Q_s^2 > \Lambda^2_{\mathrm{QCD}}$
Characterizes the target wave function

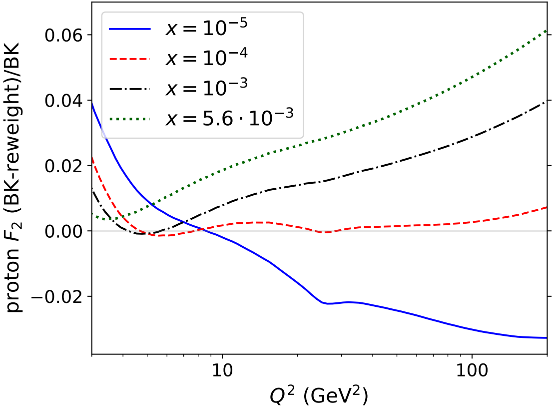
- DIS or particle production in $p + A$: scale Q^2 or $p_T^2 \sim Q_s^2$: probe transition to saturated region

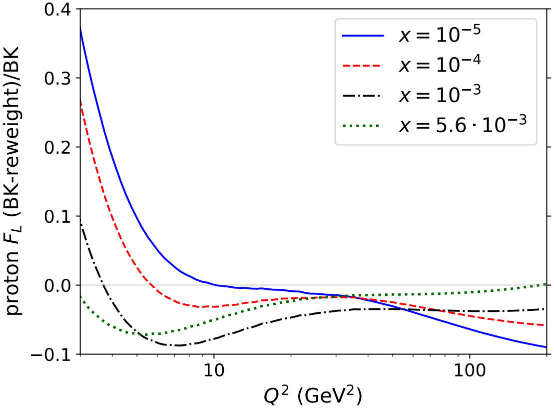


Color Glass Condensate

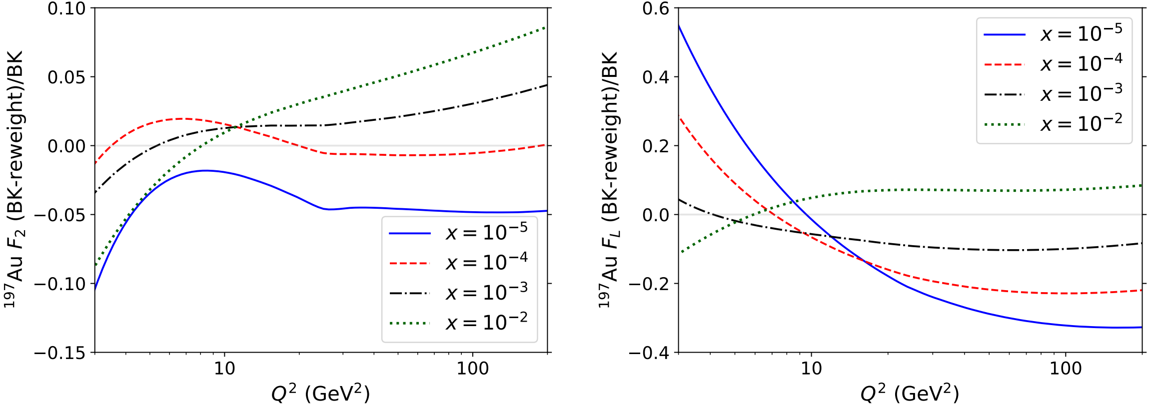
- Effective theory of QCD in the high energy limit
- Large x: static color charge ρ, small x: classical gluon field A_μ
- Unitarity built in, relevant d.o.f. is dipole-target amplitude $N \leq 1$

Relative differences: proton F_2 and F_L



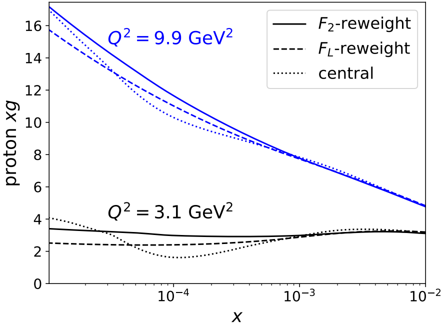


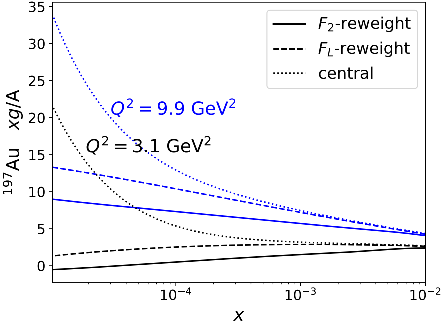
Relative differences: nuclear F_2 and F_L



Connection to PDFs

Result of the reweighting procedure: (n)PDFs that match BK evolution



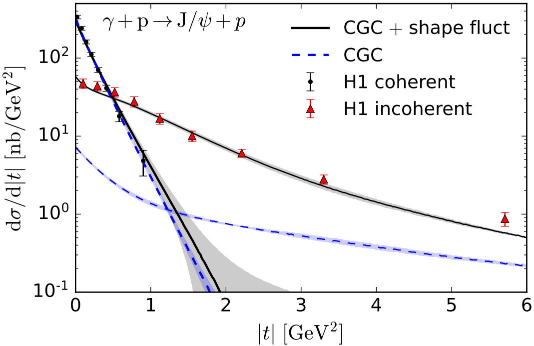


- Matching/reweighting using either BK-evolved F_2 (solid) or F_L (dashed)
- Small effect on proton PDFs – setups describe the HERA data in this kinematical domain
- Significant reduction of nuclear gluon at small x

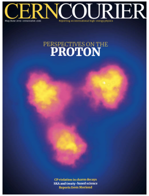
Armesto, Lappi, H.M, Paukkunen, Tevio, 2203.05846

Large geometry fluctuations required by the HERA data ($x_{\mathbb{P}} \approx 0.001$)

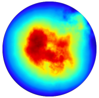
Study simultaneously coherent ($\sim$ average interaction) and incoherent ($\mathcal{A}$ variance)



CGC + shape fluct



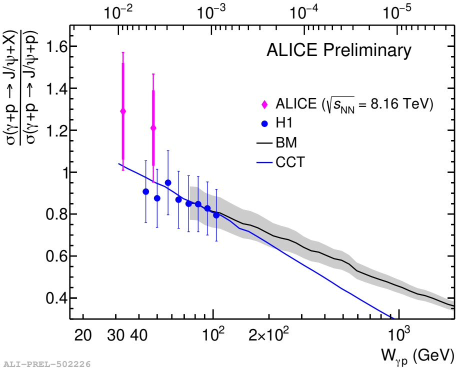
CGC



- Parametrize e-b-e fluctuating geometry, fit parameters to data
- Incoherent σ: substructure geometry or color charge fluctuations depending on $|t|$

Orignal: H.M, B. Schenke, 1607.01711 (PRL), recent: 2202.01998 (HM, Schenke, Shen, Zhao), similar setup e.g.: Bendova, Cepila, Contreras; Cepila, Contreras, Krelina, Takaki; Traini, Blaizot; Kumar, Toll; Demirci, Lappi, Schlichting

Towards small x: $\gamma + p \to J/\psi + p^*$



Small-x evolution

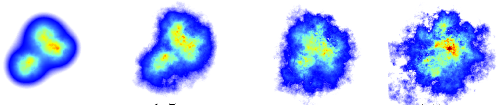
- Evolve proton structure by solving evolution perturbatively (JIMWLK) *BM*

  Schlichting, Schenke, 1407.8458, H.M., Schenke, 1806.06783

- Parametrize the W dependence of the proton density & num. of hot spots *CCT*

  Cepila, Contreras, Takaki, 1608.07559

Constrained by HERA F_2 and J/ψ data.

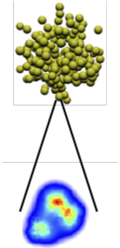


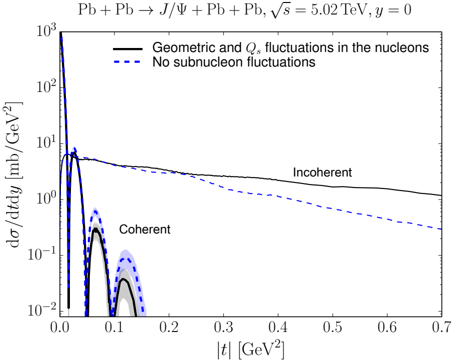
Smoother proton at small x, coherent cross section dominates

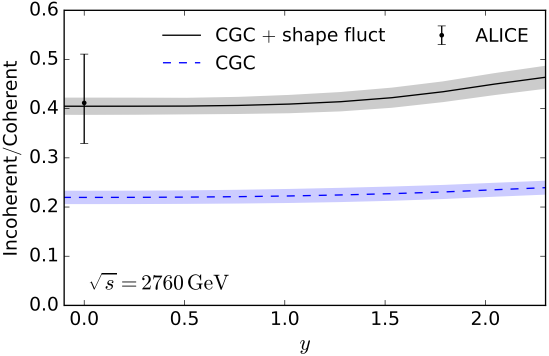
EIC: x, Q^2, A dependence of substructure fluctuations. Important e.g. for 3D hydro!

Event-by-event fluctuations at small-x: nuclei

- Small $|t| \lesssim 0.25\text{GeV}^2$: long length scale, fluctuating nucleon positions
- Large $|t| \gtrsim 0.25\text{GeV}^2$: short length scale, fluctuating nucleon substructure







Subnucleon fluctuations preferred by ALICE data

H.M, B. Schenke, 1703.09256 + H.M, Salazar, Schenke, 2207.03712

EIC: nuclear effects on nucleon shape fluctuations as a function of x, A, Q^2

ALICE: 1305.1467

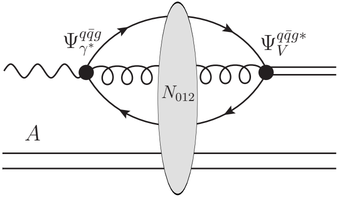
Theory developments: towards NLO

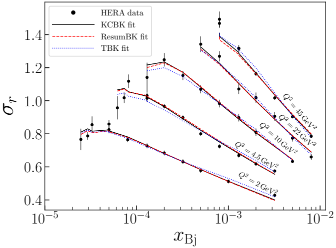
Most of the CGC phenomenology so far: LO (resumming $\alpha_s \ln 1/x$)

Recent progress to calculate exclusive processes at NLO

Ingredients

- Photon wave function at NLO Beuf, Hänninen, Paatelainen, Lappi 2018-2022
- Heavy vector meson wave function at NLO Escobedo, Lappi, 1911.01136
- Relativistic corrections to wave function: H.M, Lappi, Penttala, 2104.02349
- Small-x evolution equations Balitsky 0710.4330
- Initial condition fitted to F_2 data Beuf, Hänninen, Lappi, H.M, 2007.01645





Cross sections for exclusive processes

- Light meson at NLO H.M, Penttala, 2203.16911 , Boussarie et al, 1612.08026
- Heavy meson at NLO H.M, Penttala, 2204.14031, 2104.02349

Also much more progress towards NLO not listed here

Dipole amplitude from the CGC

Color charge distribution at $x = 0.01$

- Event-by-event random color charge distribution ρ^a
- McLerran-Venugopalan model $\langle \rho^a(\mathbf{x}) \rho^b(\mathbf{y}) \rangle \sim \delta^{ab} \delta(\mathbf{x} - \mathbf{y}) g^4 \mu^2$
- $g^4 \mu^2 \sim Q_s^2(\mathbf{b}) \sim T_p(\mathbf{b})$ e.g. from HERA data

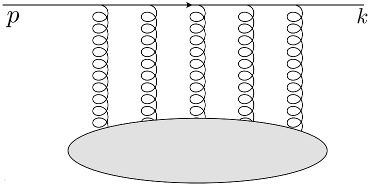
Small-x evolution

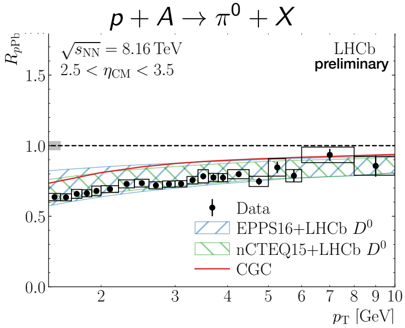
- Perturbative JIMWLK evolution (event-by-event)
- Infrared regulator to suppress gluon emission at long distance

Dipole-target amplitude

- $N(\mathbf{r} = \mathbf{x} - \mathbf{y}) = 1 - \frac{1}{N_\mathrm{c}} \langle V^\dagger(\mathbf{x}) V(\mathbf{y}) \rangle$
- $V(\mathbf{x}) = P \exp \left(-ig \int \mathrm{d}x^- \frac{\rho(\mathbf{x})}{\nabla^2 - m^2} \right)$

Connection to inclusive particle production





LHCb, 2204.10608 and talk at QM2022

- LO CGC: $1 \to 1$ process (note: LO = resum $\alpha_s \ln 1/x$). NLO: $q \to qg$ ($1 \to 2$ kinematics)
- Same dipole amplitude appears, $\mathrm{d}\sigma/\mathrm{d}p_T^2 \sim xg(x,\mu^2) \int \mathrm{d}^2\mathbf{r} e^{i\mathbf{p}\cdot\mathbf{r}}(1 - N(\mathbf{r}, x))$
- DIS data: fit initial condition, x dependence of N perturbative (BK/JIMWLK)
  - $p \to A$: optical Glauber, no free parameters
- p_T shape of the nuclear suppression well described, less suppression than in the data (LO)