Signatures of gluon saturation from structure function measurements

And connection to particle production in $p + A$ collisions

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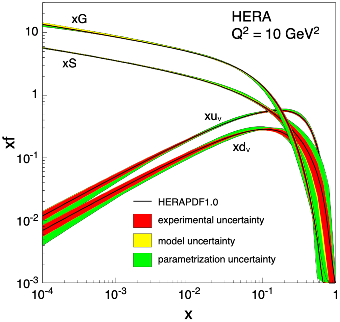
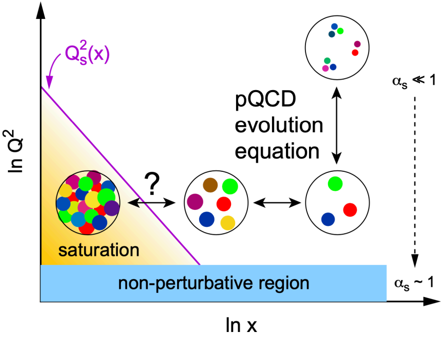
HERA total $\gamma^* + p$ cross section data: parton densities $\sim x^{-\lambda}$, eventually violates unitarity

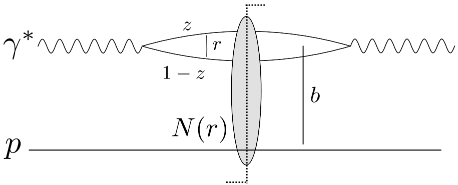


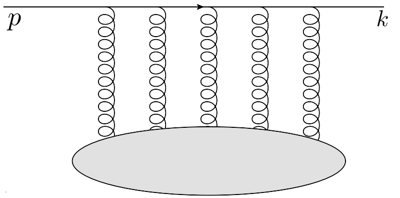


Non-linear QCD effects at small x (e.g. $gg \to g$) should tame this growth
$\Rightarrow$ Saturated state of gluonic matter at small x and moderate Q^2

- 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

DIS $\leftrightarrow$ forward particle production at the LHC





Inclusive cross section

Optical theorem:

$\sigma^{\gamma^* p} \sim \Psi^* \otimes \Psi \otimes N$

$\sim$ dipole N $\sim$ "gluon structure"

Hadron production in $p + A$

- Quark in amplitude
- Antiquark in c.c. amplitude

$\sigma^{p+A\to\pi^0+X} \sim$ dipole N

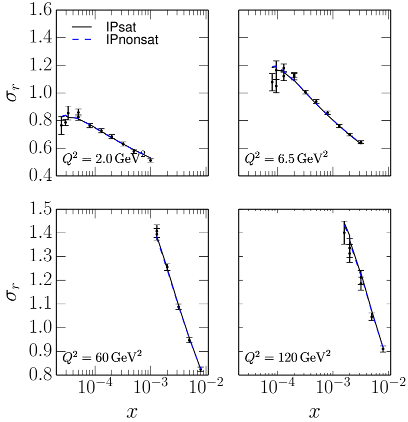
DIS (HERA, EIC) – LHC complementarity

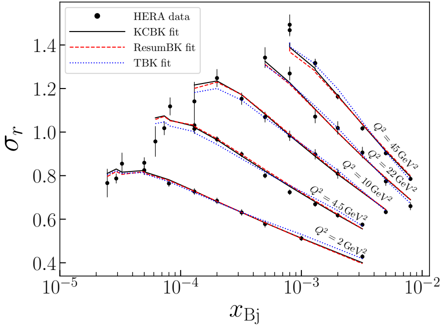
- DIS: precise and theoretically clean structure function measurements, pointlike probe
- FOCAL: Particle production at forward rapidity, much smaller x, complicated probe

Dipole $N = 1 - \frac{1}{N_c} \mathrm{tr}\, V(\mathbf{x}) V^\dagger(\mathbf{y})$ is a conventient d.o.f. at high energy

1. Inclusive DIS

Looking for gluon saturation



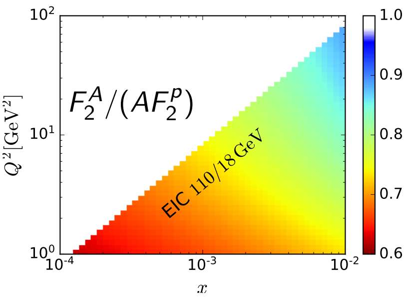


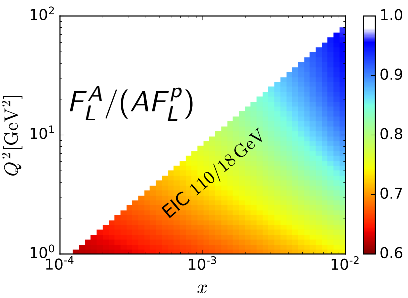
- Equally good description with and without non-linear dynamics H.M, P. Zurita, 1804.05311

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

Beuf, Hänninen, Lappi, H.M, 2007.01645

Non-linear QCD dynamics in inclusive cross section

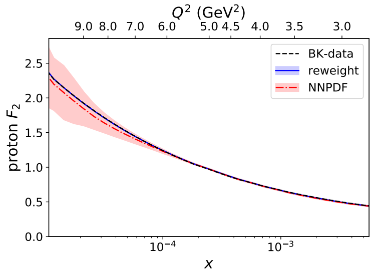


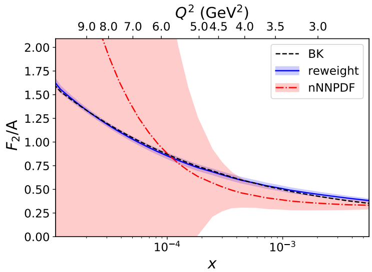


Based on Lappi, H.M, 1309.6963

- Significant nuclear suppression expected for F_2 and F_L
- F_L probes more directly dipole sizes $r \sim 1/Q \Rightarrow$ stronger Q^2 and x dependence
- F_2 sensitive to non-perurbatively large dipoles, so F_L and $F_{2,c}$ theoretically better
  Diffractive structure functions also very interesting!

Extracting genuine signals of saturation from QCD evolution





Both DGLAP (no saturation) and BK (saturation) based calculations can usually be fitted to one set of data

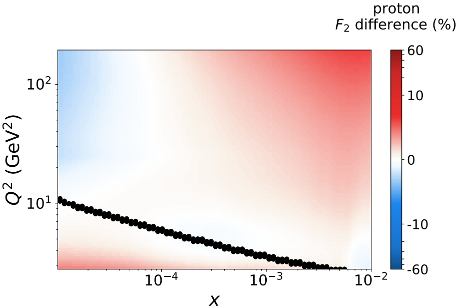
Remove the effect of the non-perturbative initial condition:

- 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

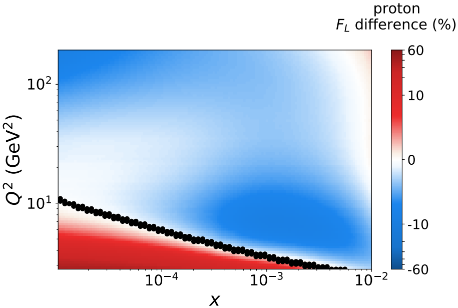
Details: NNPDF 3.1 for protons, nNNPDF2.0 for nuclei, 1000 MC replicas reweighted

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

Evolution dynamics I: protons



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

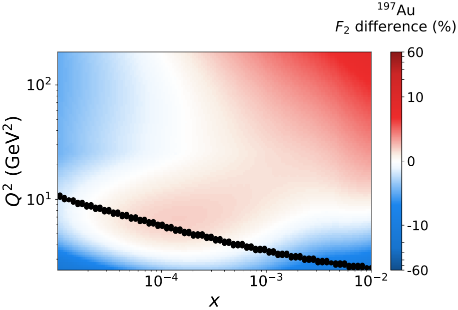


- Quantify differences in evolution when moving away from the matching line
  $\Rightarrow$ how precisely $F_{2,L}$ need to be measured to see signals of non-linear dynamics
- Only $\sim$ few percent differences in F_2 in the EIC energy range
- F_L more sensitive, differences up to $\sim 10\%$ at the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

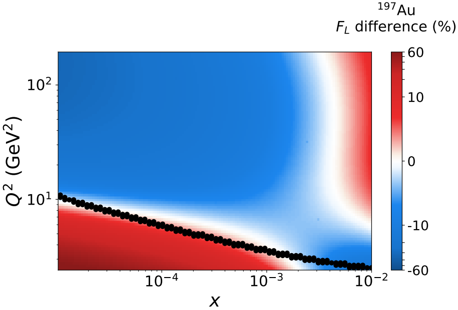
Interested in absolute values? See backup for 1d plots

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

Evolution dynamics II: nuclei



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



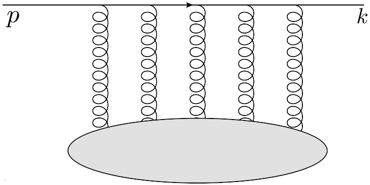
- Larger effects in nuclei, as $Q_s^2 \sim A^{1/3} \Rightarrow$ stronger non-linear phenomena
- F_2 is needed in $\sim 10\%$ precision in EIC kinematics, for $F_L \sim 15\%$ accuracy is enough
- Much larger differences in LHeC/FCC-he energy range

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

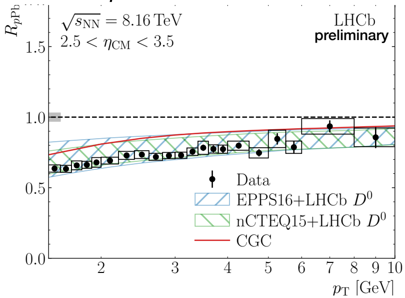
2. Connection to inclusive particle production

See also next talk by Jamal

Inclusive hadron production at forward rapidity



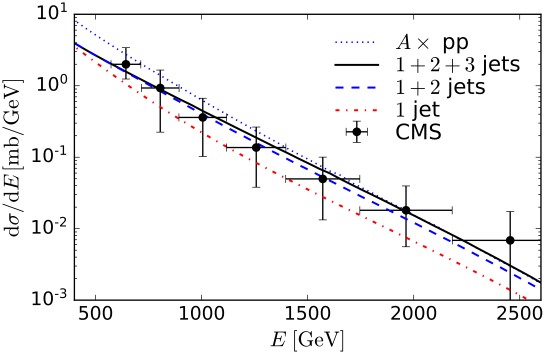
$p + A \to \pi^0 + X$



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)

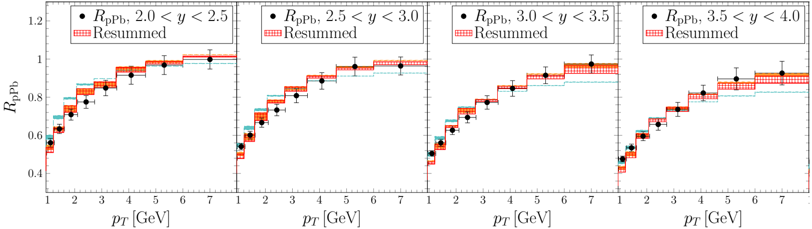
Saturation and forward jets



Paukkunen, H.M, 1910.13116. CMS-CASTOR data: 1812.01691

- CMS has a forward calorimeter CASTOR at $5.2 < \eta < 6.6$
- Access very small x, but can only see total jet energy
- LO CGC calculation with possibility to simultaneously produce > 1 jets
- Good description of the data, and significant suppression seen at low E
- Suppression compatible with CGC calculation

CGC is approaching precision level



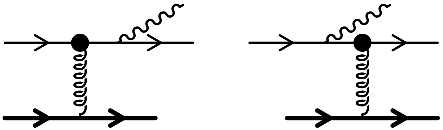
- Recent progress towards precision level: NLO single inclusive hadron production

  Chirilli, Xiao, Yuan, 1112.1061, later e.g. Stasto, Xiao, Zaslavsky, 1307.4057; Ducloué, Iancu, Lappi, Mueller, Soyez, Triantafyllopoulos, Zhu, 1712.07480

- NLO $h^{\pm}$ production with LO small-x evolution: excellent agreement with LHCb data

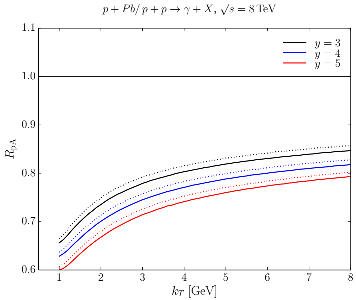
  Shi, Wang, Wei, Xiao, 2112.06975

- All necessary ingredients available for full NLO accuracy consistently with NLO DIS



Quark passes through the target + emits γ

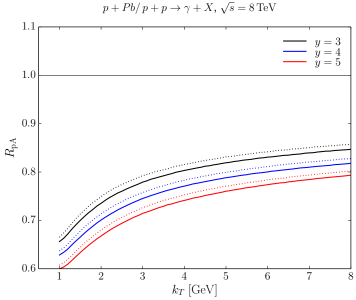
Gelis, Jalilian-Marian hep-ph/0205037



Ducloue, Lappi, H.M, 1710.02206

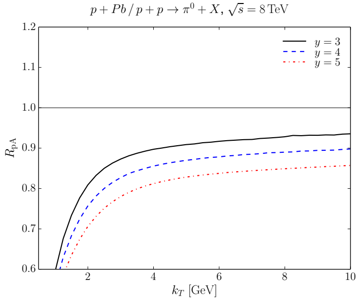
- Again same ingredients: collinear large-x quark in amplitude + c.c. amplitude $\Rightarrow$ dipole
- Need to impose an isolation cut $\sqrt{(y_\gamma - y_q)^2 + (\phi_\gamma - \phi_q)^2} > R$
- Weak dependence on cone size (solid $R = 0.4$, dotted $R = 0.1$)
- Significant suppression at large k_T at LHC energies (RHIC: $R_{pA} \approx 1$ for $k_T \gtrsim 3\mathrm{GeV}$)

Photons vs hadrons



Ducloue, Lappi, H.M, 1710.02206

- $1 \to 2$ kinematics
- Can have large photon p_T with target gluon $k_T \sim Q_s$



Ducloue, Lappi, H.M, 1710.02206

- $1 \to 1$ kinematics
- Large pion $p_T \Leftrightarrow$ target gluon $k_T \gg Q_s$

More suppression for photons, but expect NLO single inclusive to be more similar to photons

- NLO small-x evolution may also have a significant role, open question...

Conclusions

Inclusive DIS

- Significant nuclear effects expected in the EIC energy range
- Determine initial condition for small-x evolution
- When looking for genuine saturation effects:
  important to minimize the effect of the fitted non-perturbative initial condition

Forward particle production at the LHC

- Significant nuclear effects already seen by LHCb
- Simultaneous description of structure functions and hadron production crucial in order to see signals of non-linear dynamics

Precision level (NLO) CGC phenomenology: almost there

Backups

Gluon saturation and the Color Glass Condensate

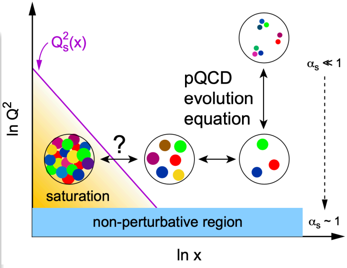
- Very high occupation number $xg(x, Q^2)$, apparent size $1/Q^2$

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

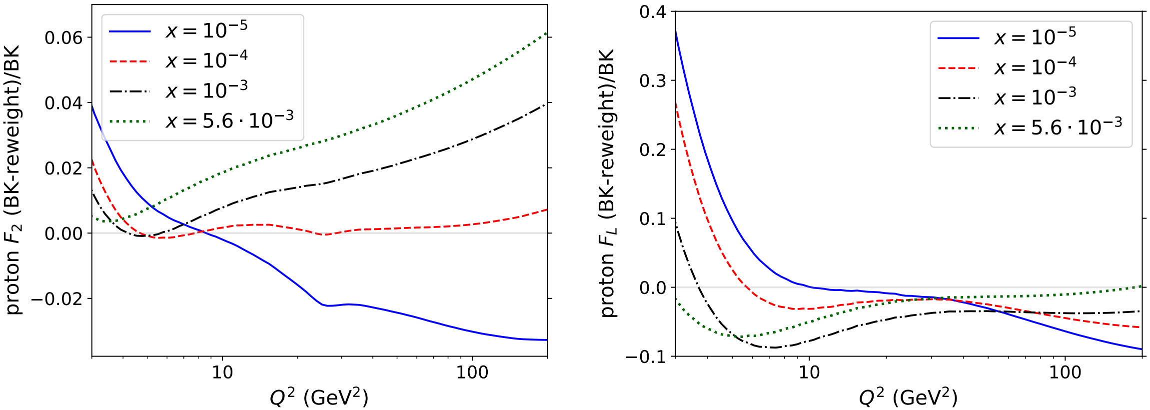
- DIS or particle production in $p+A$: scale Q^2 or $p_T^2 \sim Q_s^2$: probe transition to saturated region



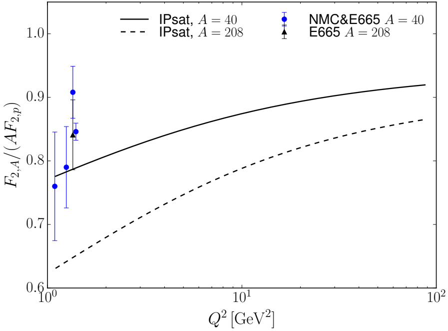
Color Glass Condensate

- 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



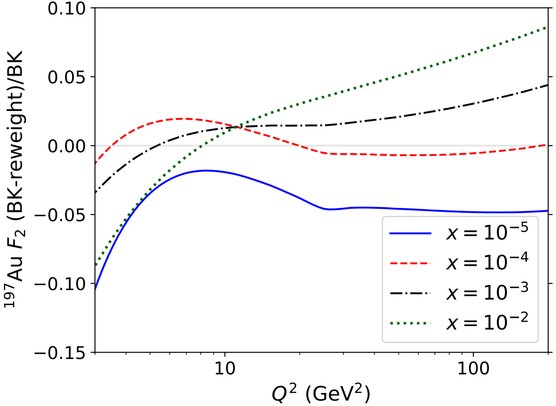
Nuclear suppression in structure functions before the EIC

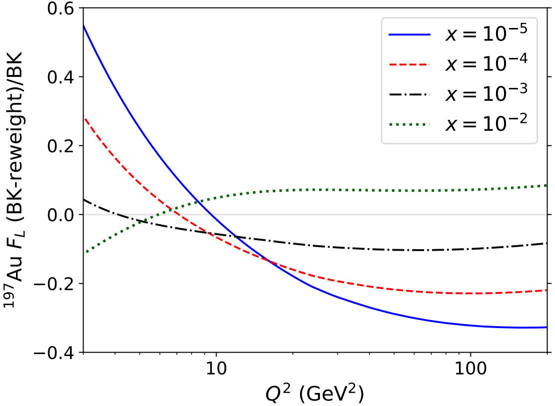


Here $x \sim 0.01$ H.M, Zurita, 1804.05311

- Before the EIC: very limited nuclear structure function data available at small-x
- Roughly consistent with saturation model calculations
- x, Q^2, A systematics from the EIC important
- Another important observable: *diffractive* structure functions, never measured for nuclei (would require a separate talk)

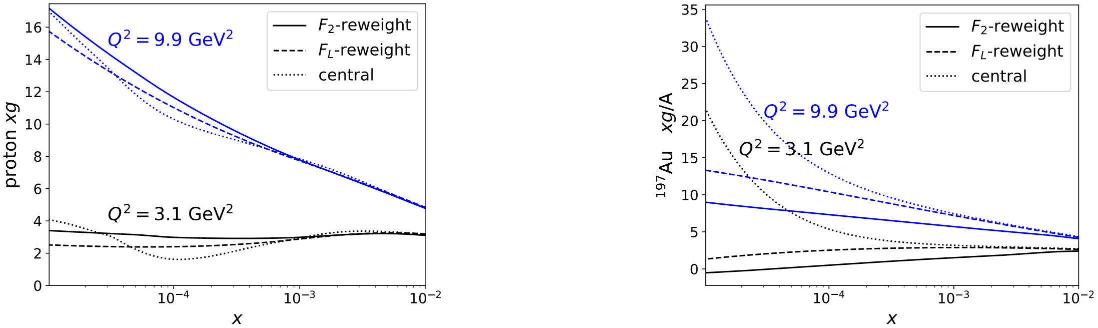
Relative differences: nuclear F_2 and F_L





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

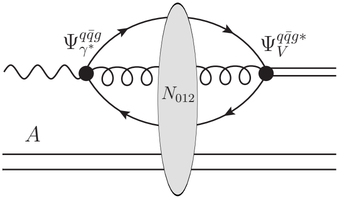
Theory developments: towards NLO

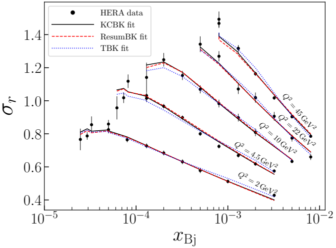
Most of the CGC phenomenology so far: LO (resumming $\alpha_s \ln 1/x$)

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

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