Selected probes of gluon saturation at the EIC

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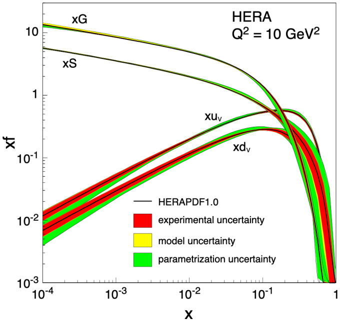
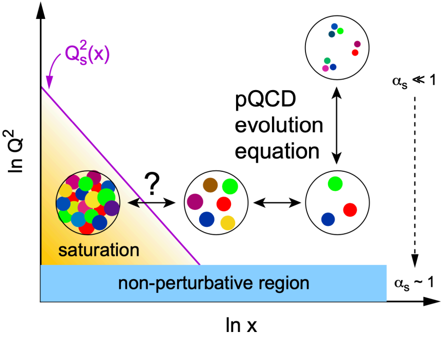
Lessons from HERA

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





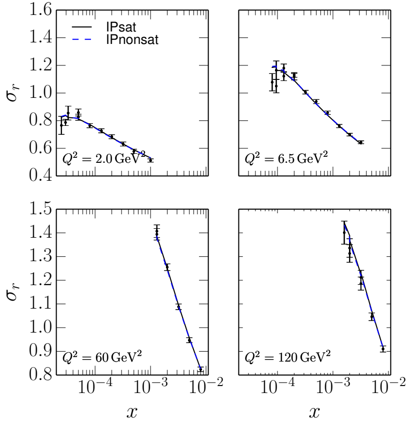
Non-linear QCD effects at small x (e.g. $gg \to g$) should tame this growth

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

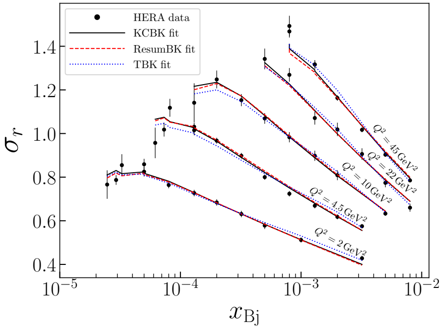
- Large densities $\sim A^{1/3}$ in nuclei
- Accessible also in p+A at the LHC (at smaller x), but γ^* a much cleaner probe

1. Structure functions

Looking for gluon saturation



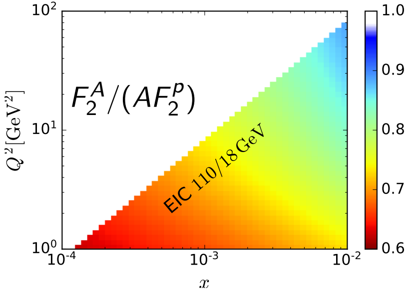
- Equally good description with and without non-linear dynamics H.M, P. Zurita, 1804.05311

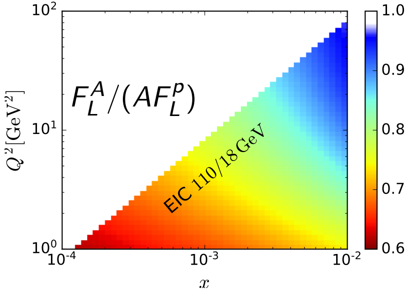


- CGC calculations entering NLO era
- Good agreement with HERA data
  Beuf, Hänninen, Lappi, H.M, 2007.01645

  Hänninen, H.M, Paatelainen, Penttala, 2211.03504

Non-linear QCD dynamics in inclusive cross section

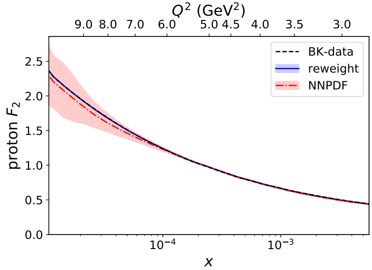


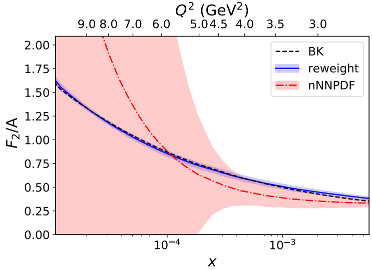


Based on Lappi, H.M, 1309.6963

- 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

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

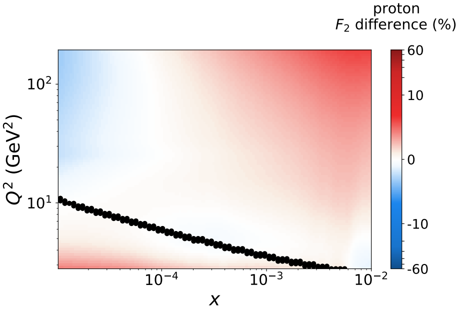
Remove the effect of the non-perturbative initial condition:

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

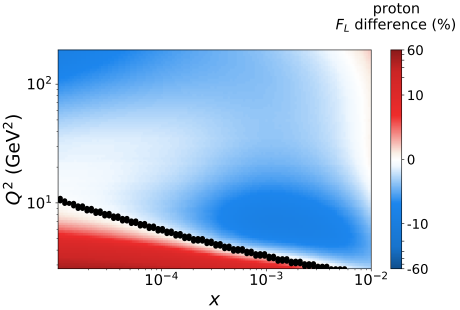
Details: NNPDF 3.1 for protons, nNNPDF2.0 for nuclei, 1000 MC replicas reweighted

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

Evolution dynamics I: protons



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

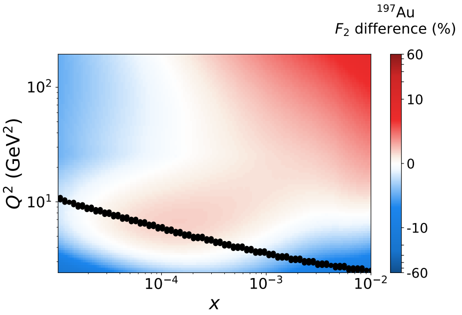


- Quantify differences in evolution when moving away from the matching line
  $\Rightarrow$ how precisely $F_{2,L}$ need to be measured to see signals of non-linear dynamics
- Only $\sim$ few percent differences in F_2 in the EIC energy range
- F_L more sensitive, differences up to $\sim 10\%$ at the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

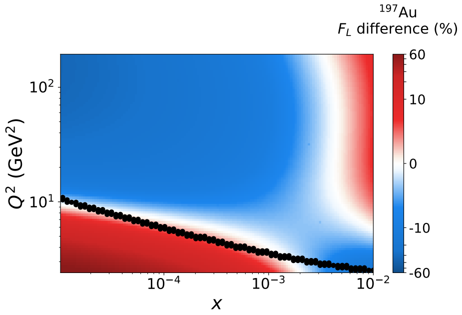
Interested in absolute values? See backup for 1d plots

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

Evolution dynamics II: nuclei



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

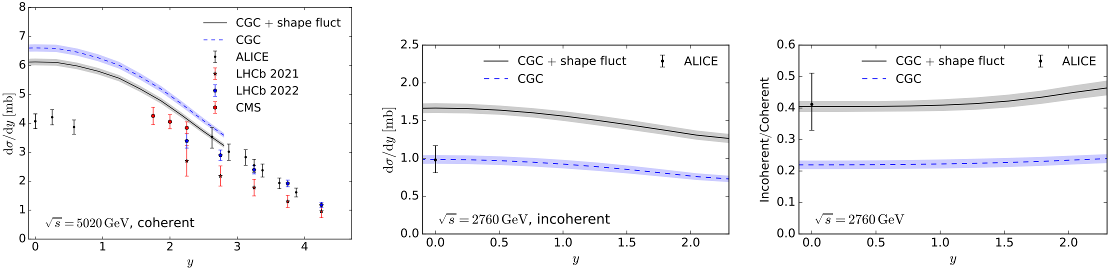


- Larger effects in nuclei, as $Q_s^2 \sim A^{1/3} \Rightarrow$ stronger non-linear phenomena
- F_2 is needed in $\sim 10\%$ precision in EIC kinematics, for $F_L \sim 15\%$ accuracy is enough

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

2. Exclusive vector meson production

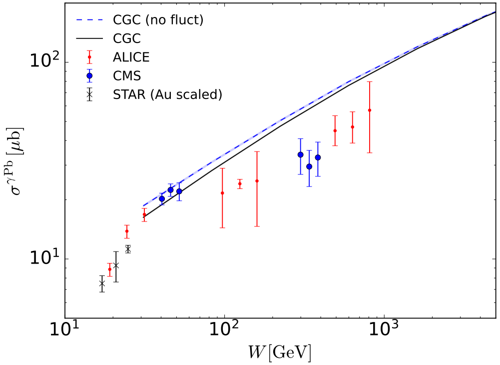
Coherent and incoherent J/ψ production



- Normalization $\approx$constrained by HERA J/ψ data: not enough suppression around $y \sim 0$
  - Note: Forward y dominated by largish $x_{\mathbb{P}} \sim 0.01$, $y = 0$ corresponds to $x_{\mathbb{P}} \approx 6 \cdot 10^{-4}$
- Nucleon substructure fluctuations: slightly larger suppression (dense hot spots), much larger incoherent cross section
- Cross section ratio (where some model uncertainties cancel) prefers substructure

H.M, Salazar, Schenke, 2207.03712

Photoproduction cross section: $\gamma + \mathrm{Pb} \to \mathrm{J}/\psi + \mathrm{Pb}$

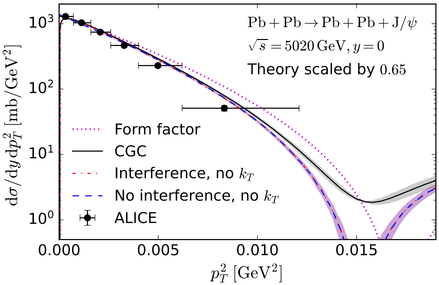


Theory curves start at $x_{\mathbb{P}} = 0.01$

H.M, Salazar, Schenke, in progress

- Recent data from DIS23/HP23:
  - Measure J/Ψ production in UPCs
  - Divide data in different forward neutron multiplicity channels
  - Different # of neutrons
    $\to$ different Pb-Pb distance
    $\to$ different photon flux
    $\Rightarrow$ extract $\gamma-$Pb cross section!
- Advantage: access to large-W contribution which contributes only very little at forward rapidities to $\mathrm{d}\sigma/\mathrm{d}y$
- Challenge: describe the large suppression at large W & energy dependence

Nuclear geometry from J/ψ spectra

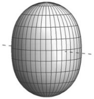
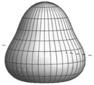
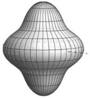


H.M, Salazar, Schenke, 2207.03712

$x_{\mathbb{P}} \approx 0.0006$

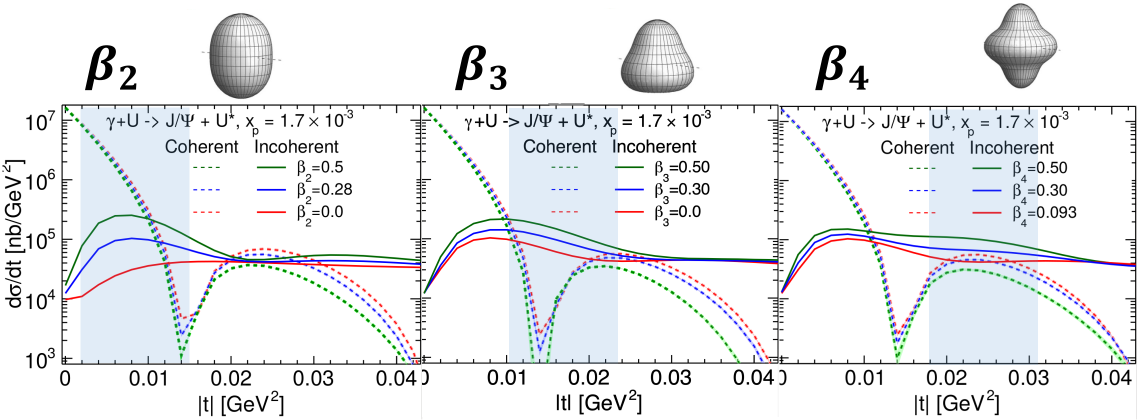
- Coherent J/ψ production at low p_T^2
- Normalization fixed by HERA data, ALICE data overestimated
  - Theory scaled down to compare p_T^2 spectra
- *Form factor* = Linearized calculation
- Saturation modifies the density profile $\rightarrow$ black disc $\Rightarrow$ steeper p_T^2 profile as in seen in the data
- Non-zero photon k_T washes out the dip
  Also small interference effect at $p_T^2 \approx 0$
- EIC: in principle can remove the photon k_T by measuring the outgoing electron

Accessing deformed structure of the uranium at the EIC

$\boldsymbol{\beta_2}$  $\boldsymbol{\beta_3}$  $\boldsymbol{\beta_4}$ 

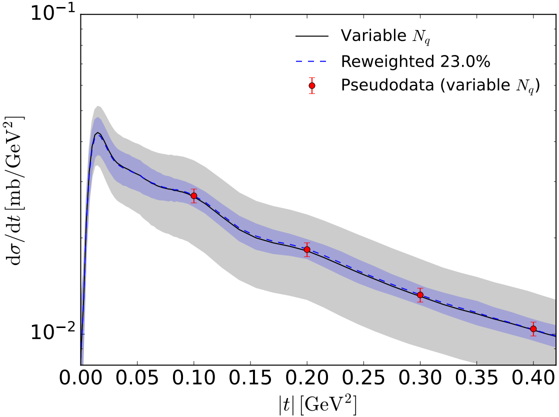
- Unlike Au/Pb: large deformations in uranium, effectively included in Woods-Saxon: $R(\theta) = R_0[1 + \beta_2 Y_2^0(\theta) + \beta_3 Y_3^0(\theta) + \beta_4 Y_4^0(\theta)]$
- Constrained by low-energy data probing charge distribution
- What about small-x gluons, similar deformations?
- Probe using exclusive vector meson production at the EIC
- Input to simulations of e.g. U+U collisions at RHIC

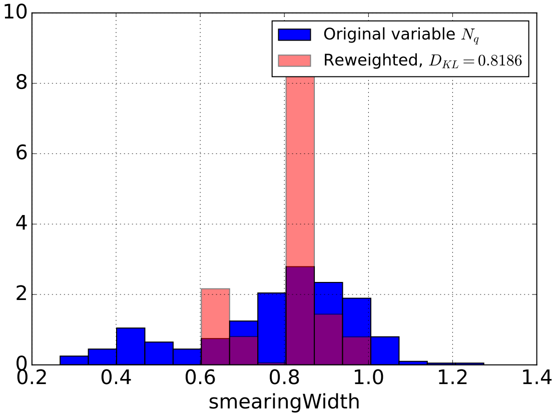
Accessing deformed structure of the uranium at the EIC



- Incoherent cross section in different $|t|$ ranges sensitive to different β_i
  Large deformations ⇒ large density fluctuations in 2d after a random 3d rotation
  Different deformations take place at different length scales ⇒ different t
- Also a small effect on coherent cross section at large $|t| \sim$ short(er) distance structure

Constraining nucleon substructure: $\gamma + \mathrm{Au} \to \mathrm{J}/\psi + \mathrm{Au}$





- Bayesian inference of fluctuating geometry (2202.01998): HERA data does not fix all parameters exactly
- Incoherent J/ψ production $\gamma + \mathrm{Au}$: additional constraints
- How accurately that can be measured? Here impact studied assuming 5% uncertainty

Backups

Gluon saturation and the Color Glass Condensate

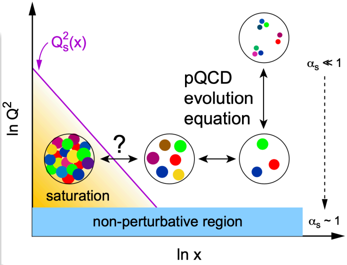
- Very high occupation number $xg(x, Q^2)$, apparent size $1/Q^2$

Non-linear dynamics important when

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

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

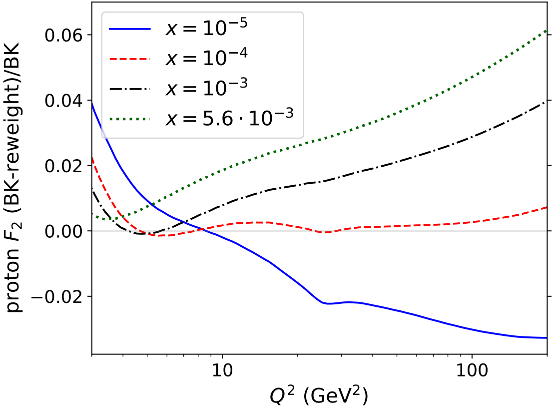
- DIS or particle production in $p + A$: scale Q^2 or $p_T^2 \sim Q_s^2$: probe transition to saturated region

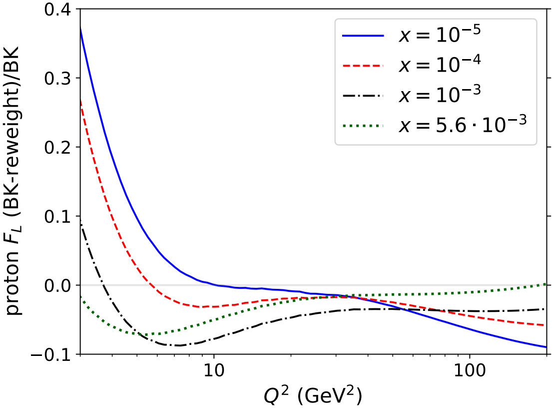


Color Glass Condensate

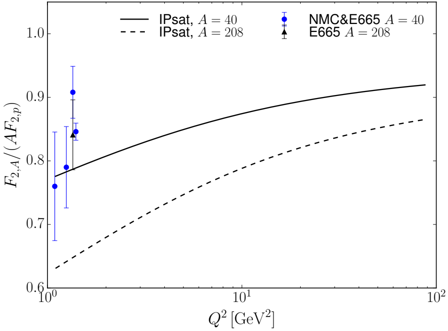
- Effective theory of QCD in the high energy limit
- Large x: static color charge ρ, small x: classical gluon field A_μ
- Unitarity built in, relevant d.o.f. is dipole-target amplitude $N \leq 1$

Relative differences: proton F_2 and F_L





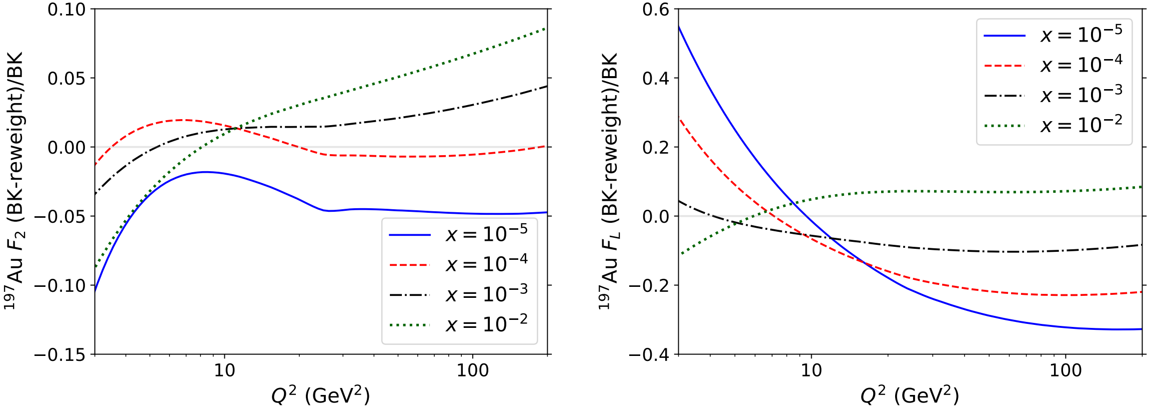
Nuclear suppression in structure functions before the EIC



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

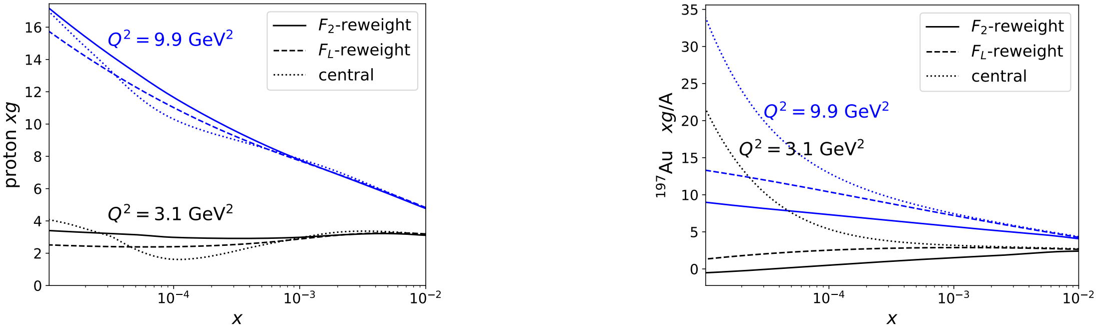
- Before the EIC: very limited nuclear structure function data available at small-x
- Roughly consistent with saturation model calculations
- x, Q^2, A systematics from the EIC important
- Another important observable: *diffractive* structure functions, never measured for nuclei (would require a separate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

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

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