Color charge correlations in the proton and initial condition for the BK evolution

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Mostly based on A. Dumitru, H. Mäntysaari, R. Paatelainen,
`arXiv:2103.11682 [hep-ph]` and `2105.08503 [hep-ph]`

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Saturation and Diffraction at the LHC and the EIC / 2021

Motivation

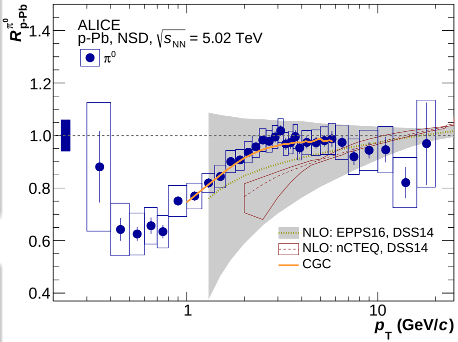
Recipe for successful small-x phenomenology

- Parametrize initial condition for the small-x (BK/JIMWLK) evolution
- Fit parameters describing non-perturbative structure at $x \sim 0.01$ to DIS data
- Compute e.g. particle production in pA, vector meson production at HERA, ...

A necessary ingredient

Dipole-proton scattering amplitude N at moderate x

- Evolution towards small-x perturbatively calculable
- This work: N form LCPT calculations consistently with high-x data $\Rightarrow x, \vec{r}, \vec{b}$ dependent IC for BK



ALICE, 1801.07051

Initial condition for the small-x evolution

Common approach

MV model (derived assuming a large nucleus)

$$\langle \rho^a(\vec{q}_1)\rho^b(\vec{q}_2)\rangle \sim g^2\mu\,\delta^{(2)}(\vec{q}_1+\vec{q}_2)$$

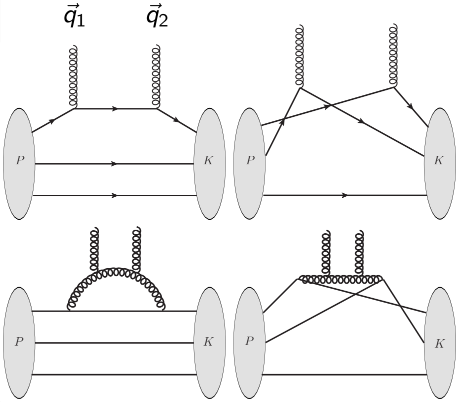
In coordinate space: correlator is local,
$\vec{b}$ dependence via $\mu \to \mu(\vec{b})$

This work: LCPT calculation

Dumitru, Skokov, Stebel, 2001.04516 and Dumitru, Miller, Venugopalan, 1808.02501

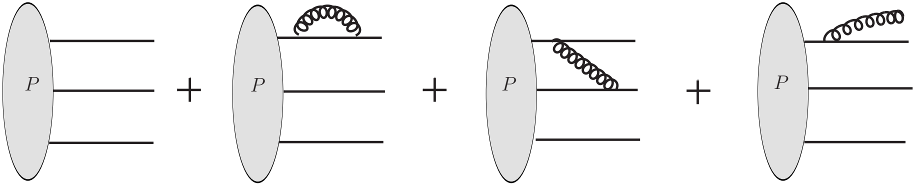
- Compute $\langle \rho^a(\vec{q}_1)\rho^b(\vec{q}_2)\rangle$ directly by attaching two gluons to the proton
- Extension to NLO: include gluon emission

  Dumitru, Paatelainen, 2010.11245



A. Dumitru, H.M, R. Paatelainen, 2103.11682

Proton state at moderate x



Leading order:

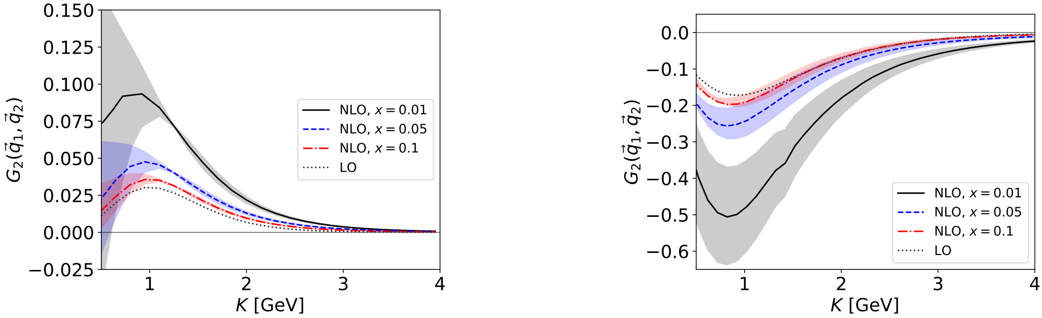
$$|P\rangle = \frac{1}{\sqrt{6}} \int \frac{dx_1 dx_2 dx_3}{\sqrt{x_1 x_2 x_3}} \delta(1 - x_1 - x_2 - x_3) \int \frac{d^2 k_1 d^2 k_2 d^2 k_3}{(16\pi^3)^3} 16\pi^3 \delta(\vec{k}_1 + \vec{k}_2 + \vec{k}_3) \times \psi(k_1, k_2, k_3) \sum_{i_1, i_2, i_3} \epsilon_{i_1 i_2 i_3} |p_1, i_1; p_2, i_2; p_3, i_3\rangle$$

- Universal valence quark wave function $\psi(k_1, k_2, k_3)$ Brodsky, Schlumpf, hep-ph/9402214
  Constrained by high-x data (e.g. radius, anomalous magnetic moment)
- Perturbative gluon emission included in Dumitru, Paatelainen, 2010.11245

Color charge correlator at NLO

The NLO calculation of 2010.11245 numerically implemented in 2103.11682

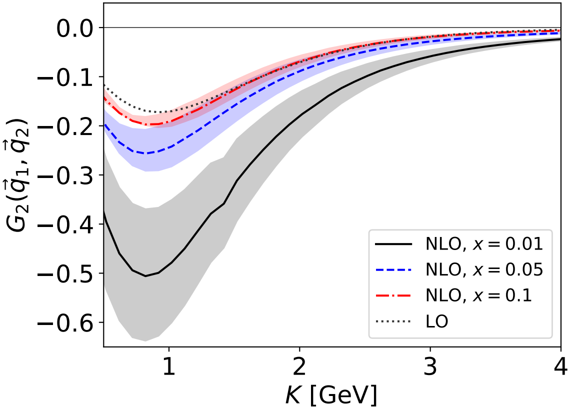
Momentum space: define $\langle \rho^a(\vec{q}_1)\rho^b(\vec{q}_2)\rangle = \delta^{ab} g^2 G_2(\vec{q}_1, \vec{q}_2)$

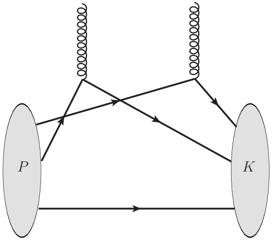


$\vec{q}_1 = \vec{q}_2 = (K/2, 0)$ (*parallel*) $\quad$ $\vec{q}_1 = (K/\sqrt{2}, 0), \vec{q}_2 = (0, K/\sqrt{2})$ (*perpend*)

- NLO (gluon emission) is small correction at $x = 0.1$ (gluon IR cut), important at $x = 0.01$
- Very different correlator depending on momentum configuration
- Bands: varying collinear regulator

2-body contribution



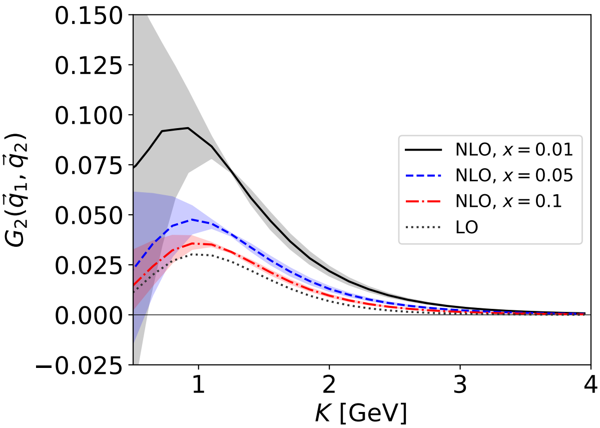


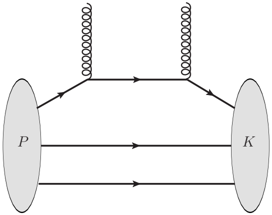
A. Dumitru, H.M, R. Paatelainen, 2103.11682

$\vec{q}_1 = \vec{q}_2 = (K/2, 0)$ (*parallel*)

- If all momentum is given to a one quark, $\langle P| - |K\rangle$ overlap is highly suppressed
- (Negative) "cat's ears" diagram dominates at LO, this conclusions still holds at NLO

1-body contribution





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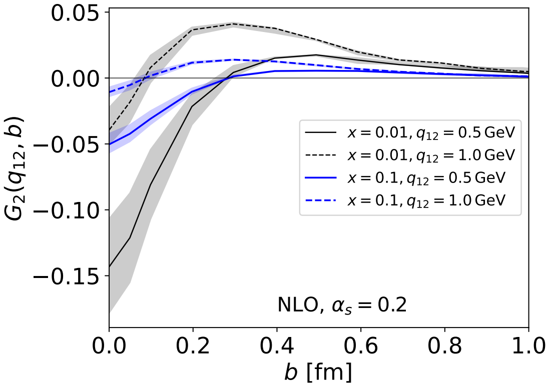
$\vec{q}_1 = (K/\sqrt{2}, 0), \vec{q}_2 = (0, K/\sqrt{2})$ (*perpend*)

- Now much smaller penalty when attaching to only one quark
- (Positive) "handbag" diagram dominates at LO, this conclusions still holds at NLO

Mixed space

Study impact parameter dependence, define $\vec{q}_{12} = \vec{q}_1 - \vec{q}_2$ and

$$G_2(\vec{q}_{12}, \vec{b}) = \int \frac{\mathrm{d}^2 \vec{K}}{(2\pi)^2} e^{-i\vec{b}\cdot\vec{K}} G_2\left(\frac{\vec{q}_{12} - \vec{K}}{2}, -\frac{\vec{q}_{12} + \vec{K}}{2} \right).$$

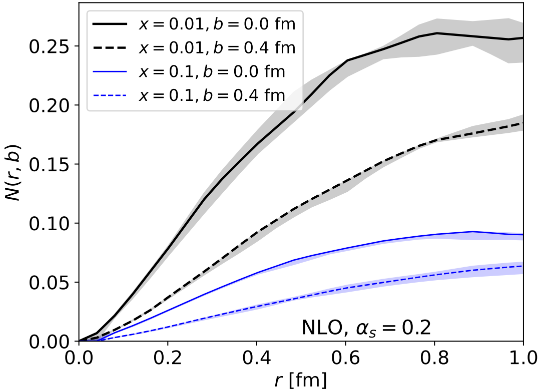


- Repulsive correlations at small b
- Attractive correlations at larger b
- Compare to b-dep MV models where $\sim T_p(\vec{b})$ $\sim$ our result at large b
- Increasing $|\vec{q}_{12}|$: "handbag" diag more important, less repulsive correlations

To the coordinate space: dipole scattering amplitude

When $N \ll 1$ can derive: Dumitru et al, 1808.02501

$$N(\vec r, \vec b) = -g^4 C_F \int \frac{\mathrm{d}^2\vec K \mathrm{d}^2 \vec q}{(2\pi)^4} \frac{\cos\left(\vec b \cdot \vec K\right)}{(\vec q - \frac{1}{2}\vec K)^2 \, (\vec q + \frac{1}{2}\vec K)^2} \times \left(\cos(\vec r \cdot \vec q) - \cos\left(\frac{\vec r \cdot \vec K}{2}\right)\right) G_2\left(\vec q - \frac{1}{2}\vec K, -\vec q - \frac{1}{2}\vec K\right).$$



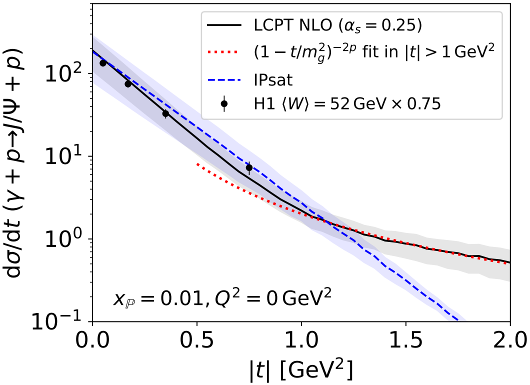
A. Dumitru, H.M, R. Paatelainen, 2103.11682

Direct calculation: find dipole-target scattering amplitude (with b dependence!) = IC for BK

Reminders: all input from high-x proton valence WF. x is the gluon long. momentum cutoff.

Proton shape

- In exclusive scattering $\sqrt{-t}$ is Fourier conjugate to b
- Coherent J/ψ spectra $\leftrightarrow$ density profile
- Compare to IPsat where $Q_s^2 \sim e^{-b^2/(2B)}$
- LCPT at small t: close to Gaussian
- Large $t \leftrightarrow$ small b: powerlaw, large differences in the region where $\langle \rho\rho \rangle \sim \; T_p$ does not hold
- Scaled H1 data at lower $x_{\mathbb{P}} \approx 0.0035$ is shown for comparison



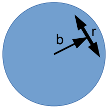
A. Dumitru, H.M, R. Paatelainen, 2105.08503 [hep-ph]

Bands: wave function uncertainty J. Penttala et al, 2006.02830

H1 data: 1304.5162

More differential imaging: angular dependence

Does the dipole prefer to scatter parallel or perpendicular to the impact parameter?



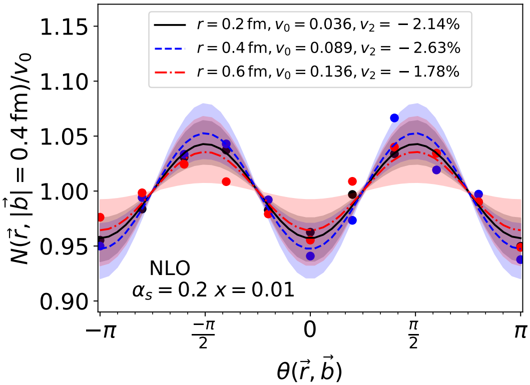
Parametrize:

$N(\vec{r}, \vec{b}) = N_0(|\vec{r}|, |\vec{b}|)[1 + 2v_2 \cos(2\theta(r, b))]$

Typically in CGC models:

$\langle\rho\rho\rangle \sim T_p(b) \Rightarrow v_2 > 0$ Iancu, Rezaeian, 1702.03943

- We find $v_2 < 0$ from LCPT calculation
- Weak dependence on $|\vec{r}|$



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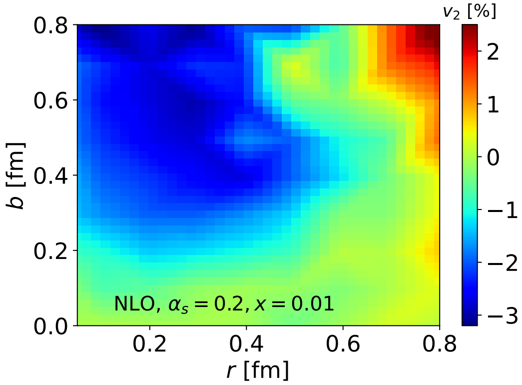
Dipole-v_2: LCPT vs MV

Parametrize: $N(\vec{r},\vec{b}) = N_0(|\vec{r}|,|\vec{b}|)[1 + 2v_2\cos(\theta(r,b))]$.

LCPT calculation



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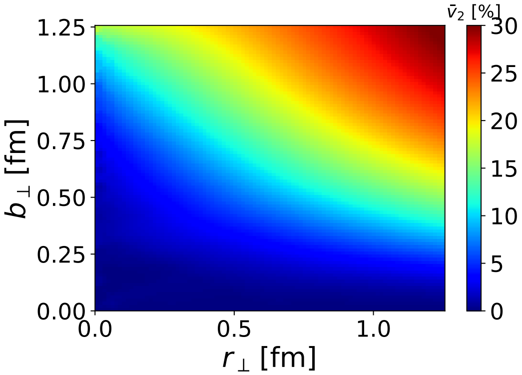
MV model with $\langle\rho\rho\rangle \sim T_p(\vec{b})$

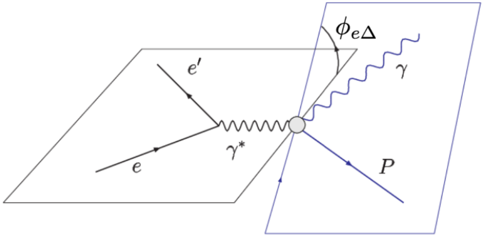


H.M, K. Roy, F. Salazar, B. Schenke, 2011.02464

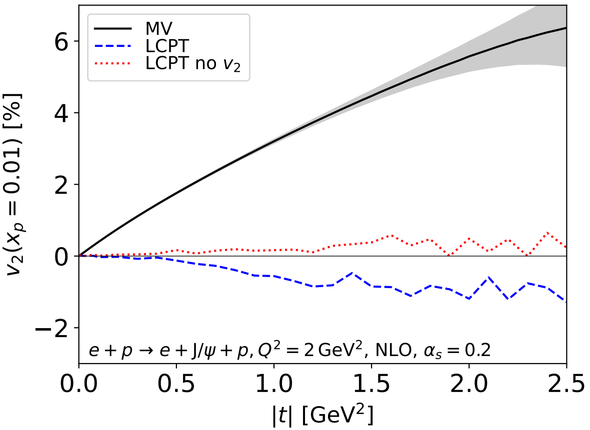
Different sign and r, b systematics between LCPT and MV model calculations!

Accessing angular dependence of the dipole amplitude

See Farid's talk: study
$e + p \to J/\psi + e + p$
Angular dependence in dipole contributes especially to v_2 in
$d\sigma \sim v_0[1 + 2v_1 \cos\phi_{e\Delta} + 2v_2 \cos 2\phi_{e\Delta}]$



CLAS collaboration



Dumitru, H.M, Paatelainen, Roy, Salazar, Schenke, 2105.10144

- Negative v_2 in the LCPT dipole renders the v_2 in J/ψ production negative.
- Note: also kinematical contribution that gives $v_2 > 0$ if dipole does not depend on angles

Conclusions

- Starting point: proton valence quark Fock state
  $+$ petrubative calculation of one gluon emission A. Dumitru, R. Paatelainen, 2010.11245
- Evaluated color charge correlator $\langle \rho\rho \rangle$ in coordinate and momentum spaces
- Observe significant deviations from "b-dep MV" results (where $\langle \rho\rho \rangle \sim T_p$) especially close to the center of the proton
- The obtained dipole $N(\vec{r}, \vec{b}, x)$ can be used as an initial condition for BK evolution
- Angular dependence of N is very different than in MV model, here find $v_2 < 0$ (=dipole prefers to scatter perpendicular to the impact parameter)