The glasma initial state at LHC

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Outline

- Saturation scale from HERA, b–dependent fits
- MV model
  - Value of Q_s
  - Classical Yang-Mills calculation
- Beyond MV: using directly bCGC, IPsat dipole cross sections

Talk based on

- H. Kowalski, T. L. and R. Venugopalan, Phys. Rev. Lett. **100**, (2008) 022303, arXiv:0705.3047 [hep-ph].
- T. L., arXiv:0711.3039 [hep-ph].
- T. L., S. Srednyak, R. Venugopalan, in progress

Multiplicities at RHIC: assumptions

RHIC @ 130 GeV: $\frac{\mathrm{d}N_{\mathrm{tot}}}{\mathrm{d}\eta} \approx 1000$

RHIC @ 200 GeV: $\frac{\mathrm{d}N_{\mathrm{tot}}}{\mathrm{d}\eta} \approx 1150$

Assume either

Fast thermalization, ideal hydro, entropy conservation

or

parton-hadron duality

▼

$$N_{\mathrm{init}}(\mathrm{gluons}) \approx N_{\mathrm{final}}(\mathrm{hadrons})$$

Note: For $E_{T,\mathrm{init}}/E_{T,\mathrm{final}}$ these scenarios are widely different.

For LHC I'll use same identification $N_{\mathrm{init}} \approx N_{\mathrm{final}}$.

Glass and Glasma

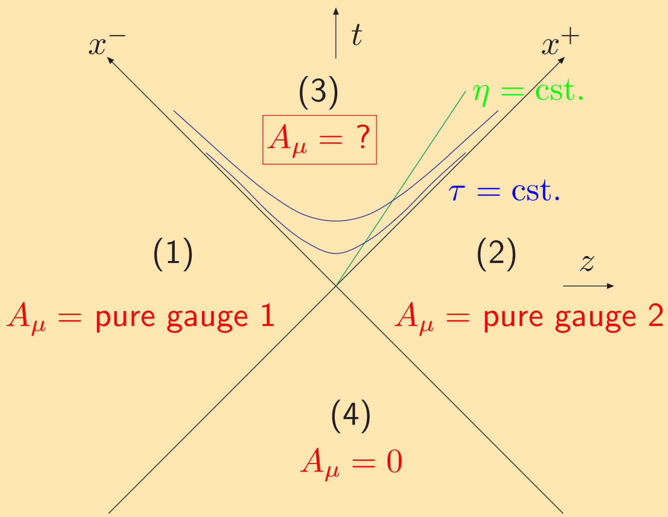
Gluon saturation: At large energies (small x) the hadron/nucleus wavefunction is characterized by saturation scale $Q_\mathrm{s} \gg \Lambda_\mathrm{QCD}$.

At $\mathbf{p}_T \sim Q_\mathrm{s}$: strong gluon fields $A_\mu \sim 1/g$ ▶ large occupation numbers $\sim 1/\alpha_\mathrm{s}$ ▶ classical field approximation.

CGC: The saturated wavefunction of one nucleus

Glasma:[1]

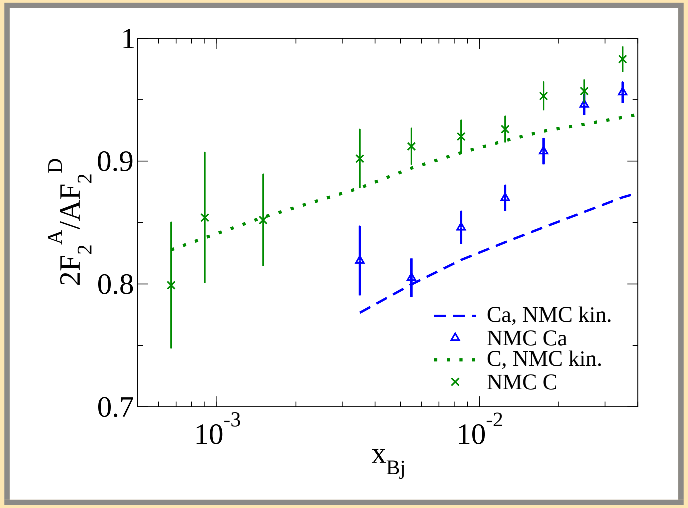
- The coherent, classical field configuration of two colliding sheets of CGC.
- Initial condition for heavy ion collision at $0 < \tau \lesssim 1/Q_\mathrm{s}$.

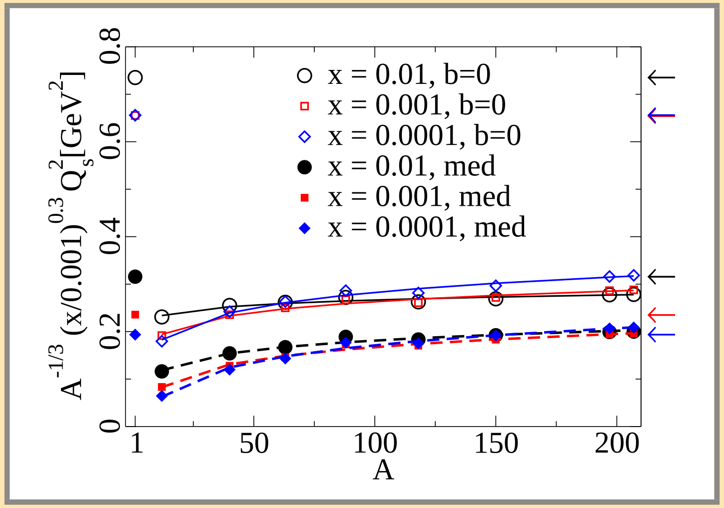


[1] T. Lappi and L. McLerran, *Nucl. Phys.* **A772** (2006) 200 [hep-ph/0602189].

Value of Q_s from DIS, from proton to nucleus

Kowalski, Teaney [2], Kowalski, T.L., Venugopalan [3]: DGLAP-improved parametrization of dipole cross section, fit to HERA data.





Result $Q_s(b_{\text{med}}) \approx 1.2\,\mathbf{GeV}$ at RHIC, $Q_s(b_{\text{med}}) \approx 1.6 \ldots 1.9\,\mathbf{GeV}$ at LHC.

Also get detailed geometrical "lumpy" picture of nucleus; ▶ noncentral collisions etc.

[2] H. Kowalski and D. Teaney, *Phys. Rev.* **D68** (2003) 114005 [hep-ph/0304189].

[3] H. Kowalski, T. Lappi and R. Venugopalan, *Phys. Rev. Lett.* **100** (2008) 022303 [arXiv:0705.3047 [hep-ph]].

Relating DIS to AA in the MV model, Q_{s} vs. $g^2\mu$

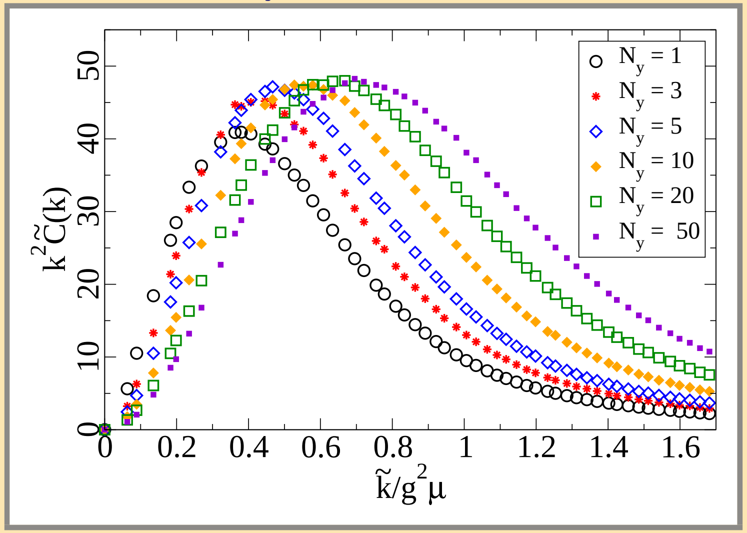
MV model, CYM has $g^2\mu$, DIS has Q_{s}, what is the relation[4]?

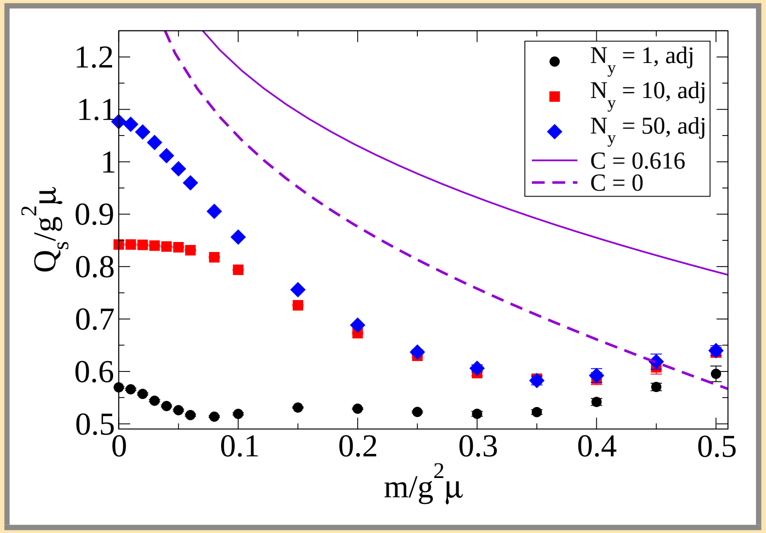
Compute the Wilson line correlator ▶ correlation length $\sim 1/Q_{\mathrm{s}}$ vs. $g^2\mu$.

Result, consistently with numerical CYM calculations, is $Q_{\mathrm{s}} \approx 0.6 g^2\mu$.

$[N_y = 1$; no longitudinal structure. Analytical results $N_y \to \infty$.$]$

See also discussion by K. Fukushima [5]





[4] T. Lappi, arXiv:0711.3039 [hep-ph].

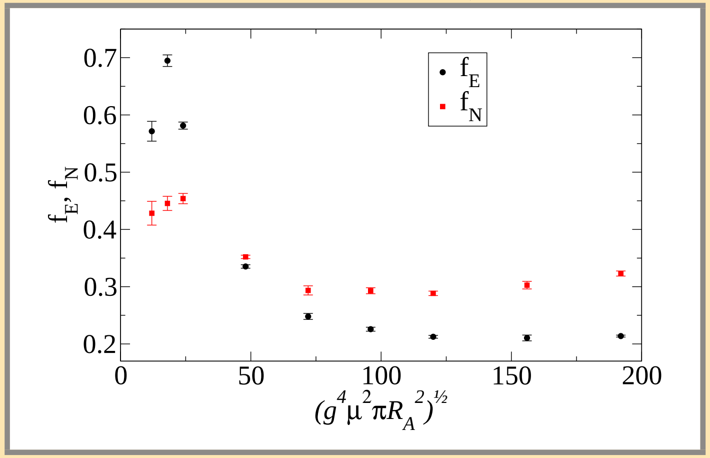
[5] K. Fukushima, arXiv:0711.2364 [hep-ph].

MV numerical results: energy, gluon multiplicity

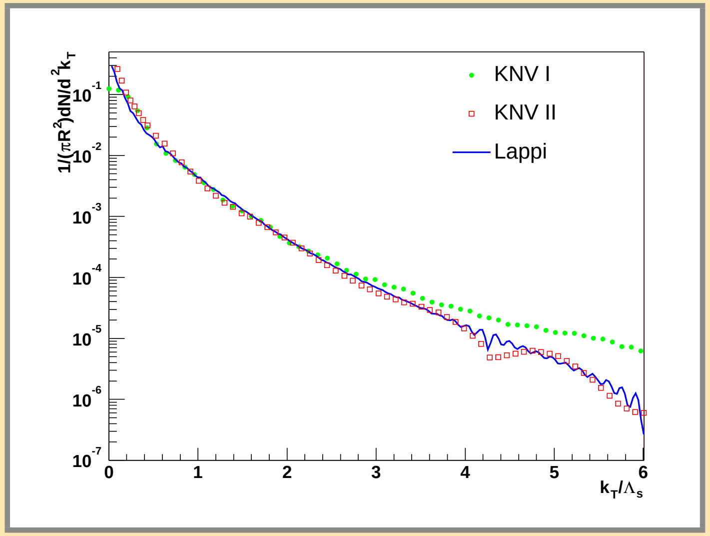
$$\frac{\mathrm{d}E}{\mathrm{d}\eta} = f_E \frac{(g^2\mu)^3 \pi R_A^2}{g^2}$$

$$\frac{\mathrm{d}N}{\mathrm{d}\eta} = f_N \frac{(g^2\mu)^2 \pi R_A^2}{g^2}$$

For strong fields $f_{E,N}$ are $\sim$ cst.



$\mathrm{d}N/\mathrm{d}^2\mathbf{k}_T$ has tail $\sim \frac{1}{\mathbf{k}_T{}^4}$, **IR-finite**.



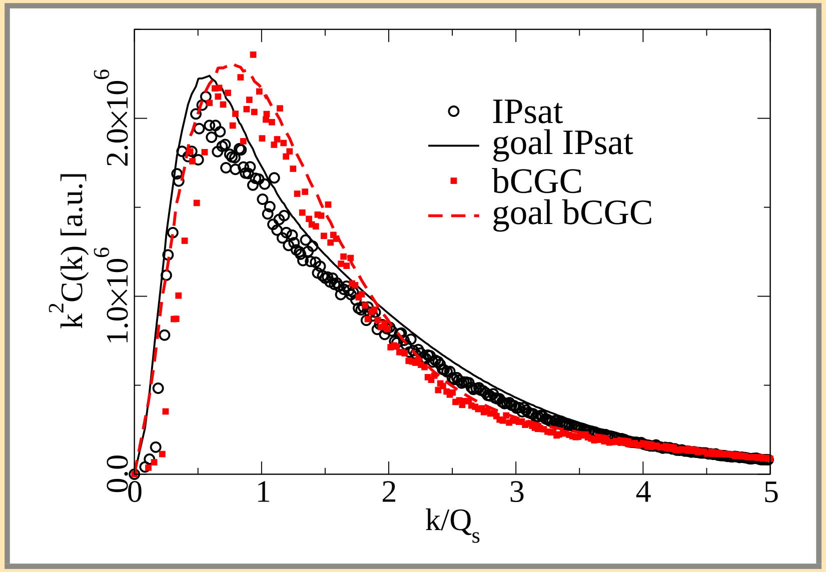
Result: $\frac{\mathrm{d}N}{\mathrm{d}\eta} \approx 0.9 \frac{Q_s^2 \pi R_A^2}{g^2}$

≈ 1100 for $Q_s = 1.2\mathrm{GeV}$.

[6] A. Krasnitz, Y. Nara and R. Venugopalan, *Phys. Rev. Lett.* **87** (2001) 192302 [hep-ph/0108092].
[7] T. Lappi, *Phys. Rev.* **C67** (2003) 054903 [hep-ph/0303076].

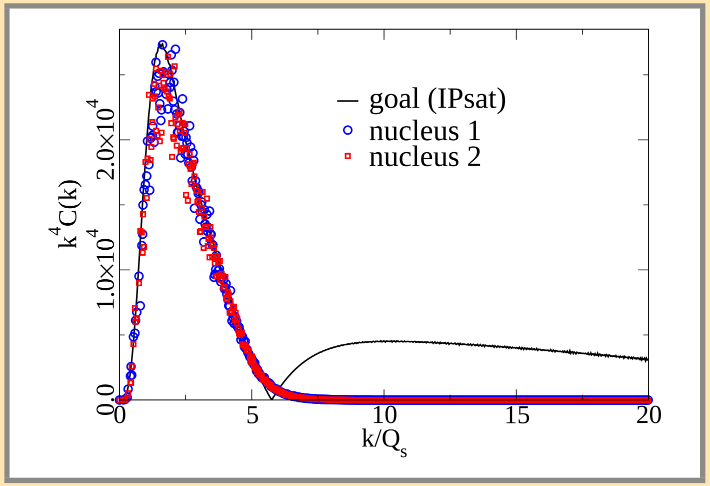
Beyond MV: constructing Wilson lines

For given $\frac{d\sigma_{\text{dip.}}}{d^2\mathbf{b}_T}(x,\mathbf{r}_T,\mathbf{b}_T)$ (use here IPsat and bCGC from Kowalski, Motyka, Watt [8]) construct corresponding



$$U(\mathbf{x}_T) = \mathrm{P}e^{ig\int \mathrm{d}x^- A^+(x^-,\mathbf{x}_T)}$$
$$= \prod_{x^-}\left(1+igA^+(x^-,\mathbf{x}_T)\,\mathrm{d}x^-\right),$$

A^+ at different x^- independent. (**“Nonlocal Gaussian”**)



Problem with these *HERA-tested and b-dependent* parametrizations: Not positive definite at large $\mathbf{k}_T$. ▶

[8] H. Kowalski, L. Motyka and G. Watt, *Phys. Rev.* **D74** (2006) 074016 [hep-ph/0606272].

Multiplicity at RHIC and LHC

One final parameter: what is x in $Q_\mathrm{s}(x)$? Denote $x = c_x Q_\mathrm{s}(x)/\sqrt{s}$

Version 1 Take $c_x = 1$, i.e. solve x from $x = Q_\mathrm{s}(x)/\sqrt{s}$

- RHIC

200 GeV	c_x	x	$Q_\mathrm{s}\,[\mathrm{GeV}]$	$\mathrm{d}N_g/\,\mathrm{d}\eta$
IPsat	1.00	5.56×10^{-3}	1.1	1000
bCGC	1.00	5.05×10^{-3}	1.0	850

Version 2 Choose c_x so that $x = c_x Q_\mathrm{s}(x)/\sqrt{s}$ gives $\mathrm{d}N_g/\,\mathrm{d}\eta = 1150$ at RHIC 200 GeV.

- LHC

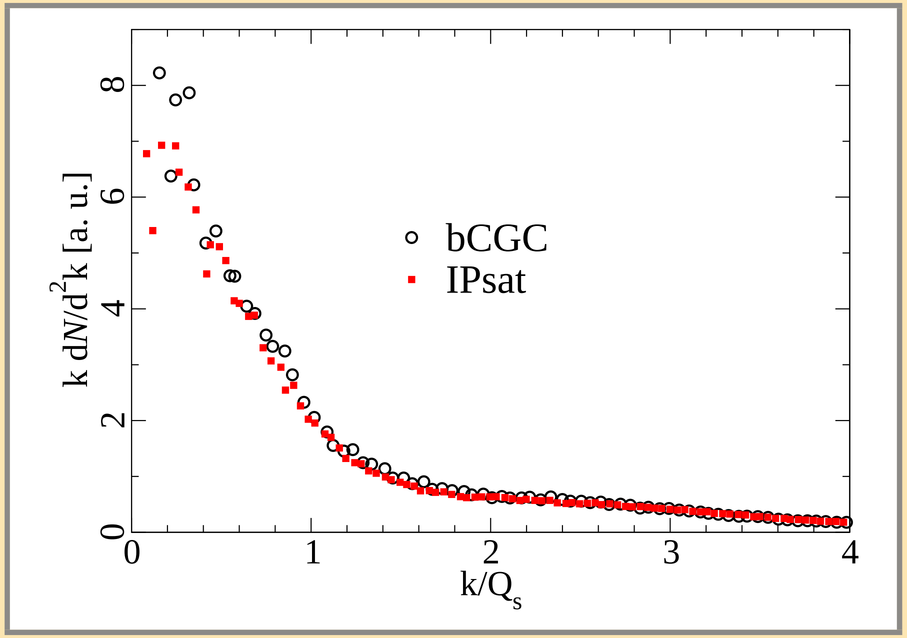
5500 GeV	c_x	x	$Q_\mathrm{s}\,[\mathrm{GeV}]$	$\mathrm{d}N_g/\,\mathrm{d}\eta$
IPsat	0.58	1.98×10^{-4}	1.9	2900
bCGC	0.24	0.67×10^{-4}	1.6	2200

Gluon spectrum

Used dipole model parametrizations don't give $1/\mathbf{k}_T{}^4$ tail in momentum space (unlike MV) ▶ softer spectrum.

- Underestimate energy, does not match perturbative expectation

+ Numerics converges very well in continuum limit

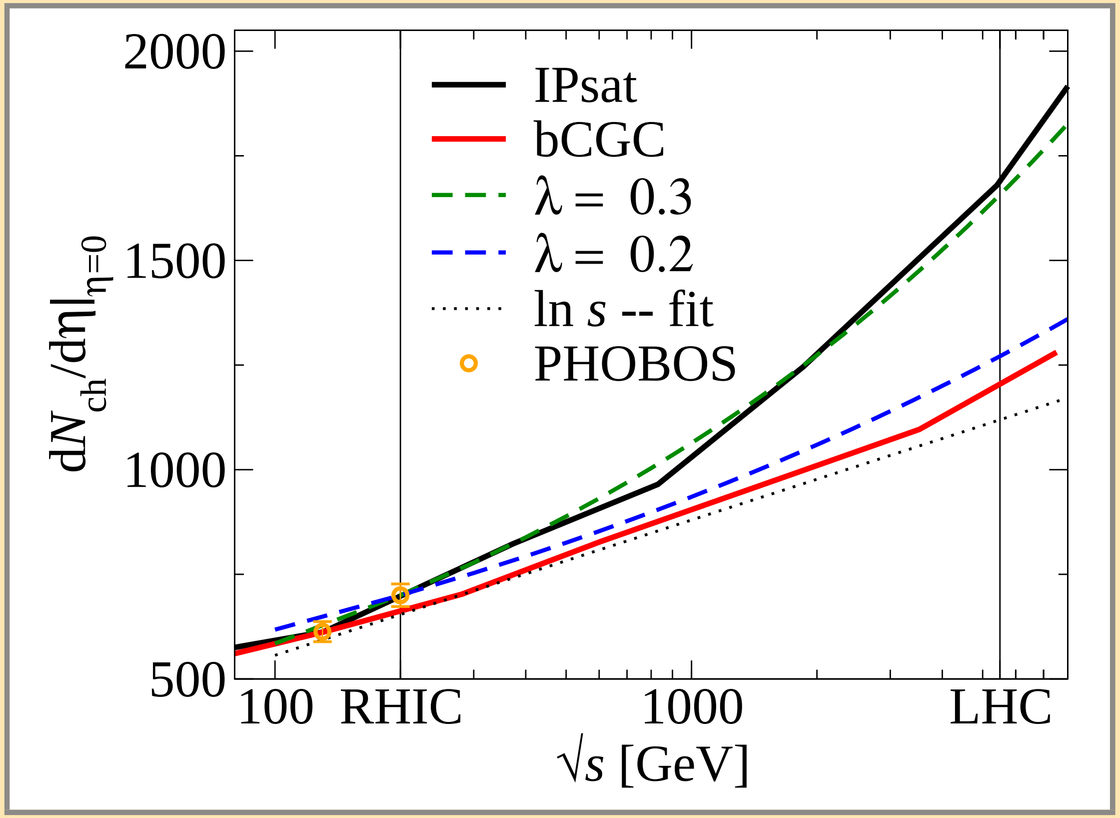


MV model result was $\langle p_T \rangle \approx Q_\mathrm{s}$, now

$$\langle p_T \rangle \approx 0.6 Q_\mathrm{s}\ (\mathrm{RHIC})\ \ldots 0.7 Q_\mathrm{s}\ (\mathrm{LHC})$$

$\sqrt{s}$ dependence

IPsat: both Q_s and multiplicity close to $\lambda = 0.3$–behavior **purely from DGLAP**



bCGC: The b-dependent fit leads to a smaller λ than GBW ▶ slower increase with energy.

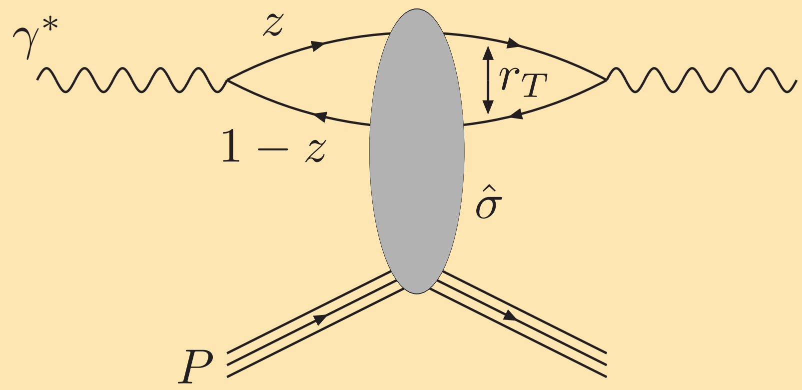
Conclusions

- Towards a consistent quantitative calculation of the glasma initial state
- Predictions for LHC from on HERA-tested dipole cross sections
- Extend to noncentral collisions, more realistic “lumpy” nuclear geometry: work in progress.

Backups

Relation to DIS

DIS at high energy/small x: dipole cross section, which can be calculated from the classical field:



$$\hat{\sigma}(\mathbf{r}_T) = \int \mathrm{d}^2\mathbf{b}_T \frac{1}{N_\mathrm{c}} \mathrm{Tr} \left\langle 1 - U^\dagger\left(\mathbf{b}_T + \frac{\mathbf{r}_T}{2}\right) U\left(\mathbf{b}_T - \frac{\mathbf{r}_T}{2}\right)\right\rangle$$

$$U(\mathbf{x}_T) = P\exp\left\{ig\int \mathrm{d}x^- A^+_{\mathrm{cov}}(\mathbf{x}_T, x^-)\right\}$$

This same Wilson line gives the (LC gauge) pure gauge field in the $\tau = 0$ initial condition for the two nucleus problem.

$$A^i_{(\text{one nucleus})} = \frac{i}{g} U(\mathbf{x}_T)\partial_i U^\dagger(\mathbf{x}_T)$$