Properties of glasma color fields

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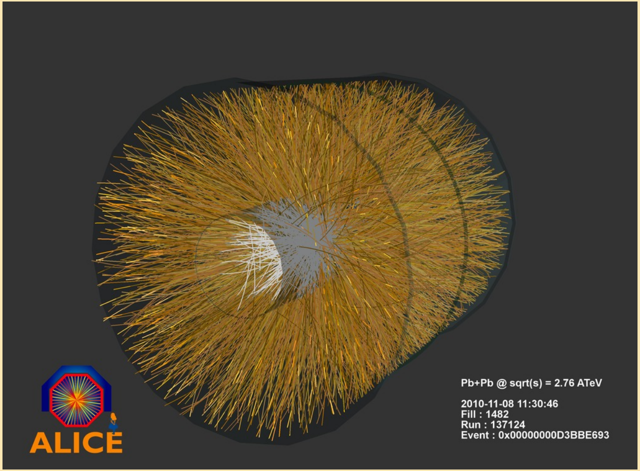
Outline

- Color Glass Condensate, saturation basics
- Glasma initial stage color field
- Glasma flux tubes and strings
- Non-flow particle correlations

Gluon saturation

A heavy ion event at the LHC

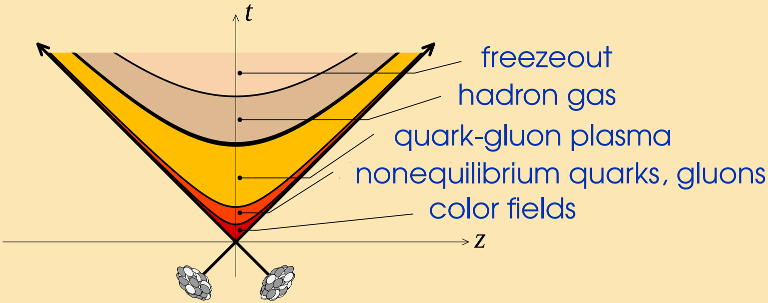


How does one understand what happened here?

Heavy ion collision in spacetime

The purpose in heavy ion collisions: to create QCD **matter**,
i.e. system that is large and lives long
compared to the microscopic scale

$$t \gg \frac{1}{T} \qquad L \gg \frac{1}{T} \qquad T > 200\text{MeV}$$



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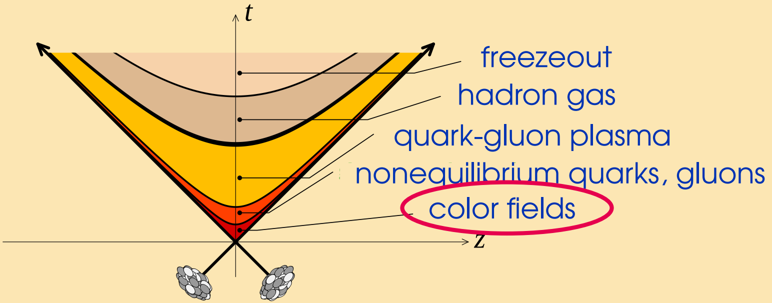

Concentrate here on the **earliest stage**

Gluon saturation, Glass and Glasma

Small x: the hadron/nucleus wavefunction is characterized by **saturation scale** $Q_s \gg \Lambda_{QCD}$.

Gluon saturation, Glass and Glasma

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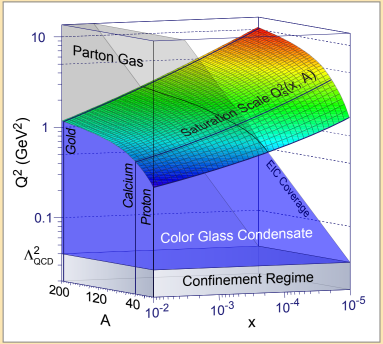
$\mathbf{p}_T \sim Q_s$: strong fields $A_\mu \sim 1/g$

- occupation numbers $\sim 1/\alpha_s$
- classical field approximation.
- small α_s, but nonperturbative



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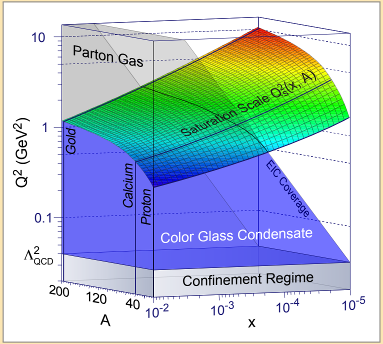

CGC: Effective theory for wavefunction of nucleus

- Large x = color charge ρ, **probability** distribution $W_y[\rho]$
- Small x = classical gluon field A_μ + quantum flucts.

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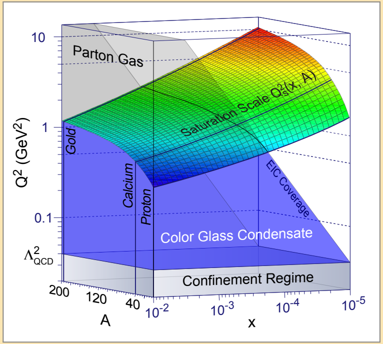

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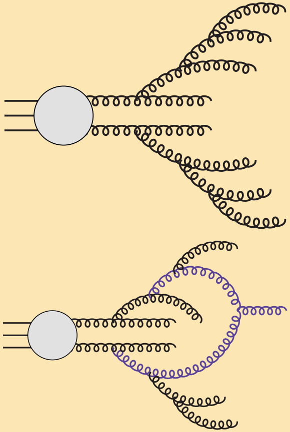
Glasma: field configuration of two colliding sheets of CGC. (Here $y \sim \ln \sqrt{s}$)

Gluon saturation in IMF: nonlinear interactions

Saturation when phase space density of gluons large

- Number of gluons $xG(x, Q^2)$
- Size of one gluon $\sim 1/Q^2$
- Transverse space available πR_p^2
- Coupling α_s



Estimate in terms of gluon numbers

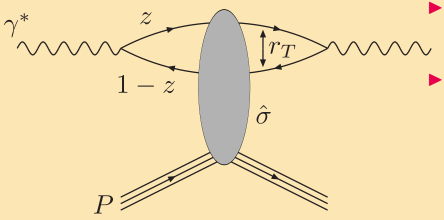
Nonlinearities important when

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

Solve for $Q^2 = Q_s^2$; "saturation scale"

(LHC kinematics: $Q_s \approx 1 .. 2\text{GeV}$)

Gluon saturation in dipole picture: unitarity



- Scattering amplitude: unitarity limit $\mathcal{N} \leq 1$
(probability < 1)
- Two gluon exchange:

$$\mathcal{N}(r) \sim \alpha_s \frac{r^2 xG(x, Q^2 \sim 1/r^2)}{\pi R_p^2}$$

2-gluon exchange wrong when $Q^2 \sim \frac{1}{r^2} \lesssim Q_s^2 \sim \frac{\alpha_s xG(x, Q_s^2)}{\pi R_p^2}$

Gluon saturation in target rest frame

- Degree of freedom is scattering amplitude (not number of partons)
- Saturation appears as unitarity constraint
$\Longrightarrow$ Built into formalism; does not look dynamical.

Wilson line

Classical color field described as Wilson line

$$V(\mathbf{x}_T) = P \exp \left\{ ig \int \mathrm{d}x^- A^+_{\mathrm{cov}}(\mathbf{x}_T, x^-) \right\} \quad \in \quad \mathrm{SU}(3)$$

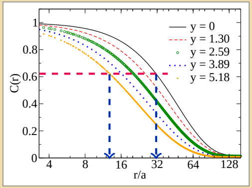
Relation to color charge ρ : $\quad {\nabla_T}^2 A^+_{\mathrm{cov}}(\mathbf{x}_T, x^-) = -g\rho(\mathbf{x}_T, x^-)$

Physical interpretation: **Eikonal propagation of parton through target color field**

Q_s is characteristic momentum/distance scale

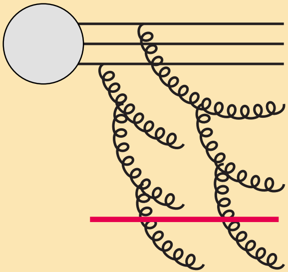
Precise definition used here:

$$C(\mathbf{x}_T) \;=\; \frac{1}{N_c} \left\langle \mathrm{Tr}\, V^\dagger(\mathbf{0}_T) V(\mathbf{x}_T) \right\rangle \;=\; e^{-\frac{1}{2}} \iff \mathbf{x}_T^2 \;=\; \frac{2}{Q_s^2}$$



CGC color field is ISR

- In partonic picture: gluon field is cascade of ISR
- Gluons have k_T, but ordered in k^+, not k_T
- EFT cutoff: color charge/field
- Many color charges: conservation only on average



Quantitative calculations:

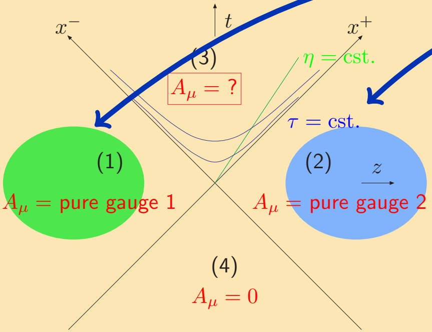
- Do not count gluons
- In stead: d.o.f is eikonal amplitude
- Unitarity constraint, not Λ_{QCD}, cuts off $\int_0 \frac{dk_T}{k_T}$
  $\Longrightarrow$ typical $k_T \sim Q_s$

Now: initial stage of heavy ion collision in this picture

Glasma fields

How to obtain intitial glasma fields

Now let **two** dense color field systems collide



Need LC gauge fields $A^i_{(1,2)} = \frac{i}{g} V_{(1,2)}(\mathbf{x}_T)\partial_i V^\dagger_{(1,2)}(\mathbf{x}_T)$

$V(\mathbf{x}_T)$ = Wilson line for nuclei (1) and (2)

$\tau = 0$: match using $[D_\mu, F^{\mu\nu}] = J^\nu$:

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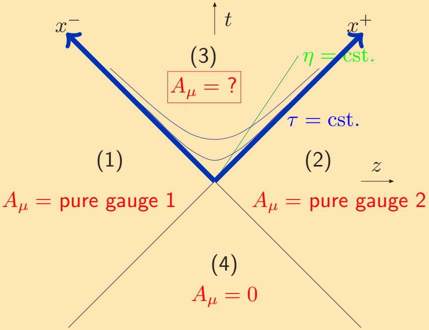

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$$\begin{aligned} A^i\Big|_{\tau=0} &= A^i_{(1)} + A^i_{(2)} \\ A^\eta\big|_{\tau=0} &= \frac{ig}{2}[A^i_{(1)}, A^i_{(2)}] \\ A^\tau &= 0 \text{ gauge choice} \end{aligned}$$

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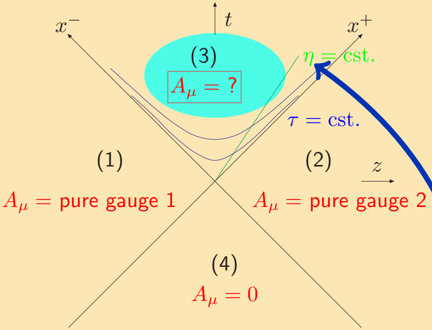

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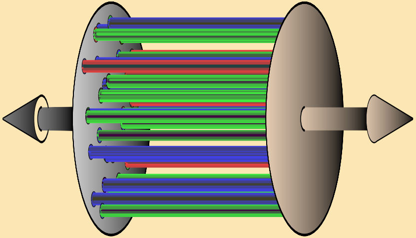
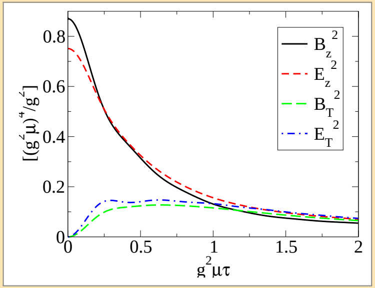
$\tau > \mathbf{0}$ Numerical **CYM** or approximations

This is the **glasma** field $\Longrightarrow$ Then average over initial Wilson lines.

Initial glasma fields

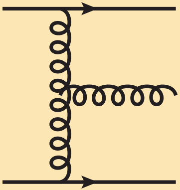




- Initial condition is longitudinal E and B field,
  at $\tau \sim 1/Q_s$ evolves to $E_z^2 \sim B_z^2 \sim 2E_x^2 \sim 2B_x^2 \sim 2E_y^2 \sim 2B_y^2$
- Depend on transverse coordinate
  with correlation length $1/Q_s \Longrightarrow$ gluon correlations
- Fix gauge, Fourier-decompose: Gluons with $p_T \sim Q_s$
- Configuration naturally has Chern-Simons charge $N_{CS} \sim \varepsilon^{\mu\nu\alpha\beta} F^a_{\mu\nu} F^a_{\alpha\beta} \sim E \cdot B$

Dilute limit, polarization, coherence

- $V(\mathbf{x}_T) \approx 1 - i\frac{1}{\boldsymbol{\nabla}_T{}^2}\rho(\mathbf{x}_T)$
- Gluon spectrum reduces to Bertsch-Gunion $\Longrightarrow$

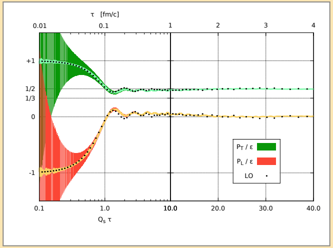


How to understand longitudinal fields at $\tau = 0$?

- $\exists$ 2 linear polarization states for gluon with $\mathbf{k}_T$:
  - $E_\perp(\perp \mathbf{k}_T)$ & B_z
  - $B_\perp(\perp \mathbf{k}_T)$ & E_z
- Both polarizations produced
- Boost invariant energy

$$\frac{\mathrm{d}E}{\mathrm{d}\eta} = \frac{1}{\tau}\operatorname{Tr} E^i E^i + \frac{\tau}{2}\operatorname{Tr} F_{ij}F_{ij} + \tau \operatorname{Tr} E^\eta E^\eta + \frac{1}{\tau}[D_i, A_\eta][D_i, A_\eta]$$

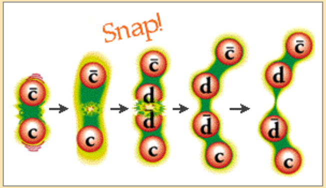
- Only phase consistent with finite energy @ $\tau = 0$:
  1 polarization in purely B_z and other in purely E_z
- Then decohere with τ



(Epelbaum, Gelis, `arXiv:1307.2214`: quantum fluctuations change the picture)

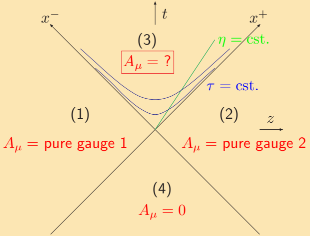
Glasma flux tubes and strings

Color flux tubes and strings: where is the energy?



"2-component" picture partons + strings

- $t = 0$ Longitudinal (jet axis) momentum of receding partons
- Longitudinal motion: shift to potential energy of (homogenous?) color electric field
- String breaking: release to kinetic energy of newly created partons



Glasma fields: 1-scale problem

- Total $\sqrt{s} = \infty$, carried by beams
- Count energy /unit rapidity (spacetime rapidity η)
- **Fields** boost invariant $\Longrightarrow$ no longitudinal (beam direction) momentum
- Energy carried by k_T of gluons

Color flux tubes and strings: transverse coordinate

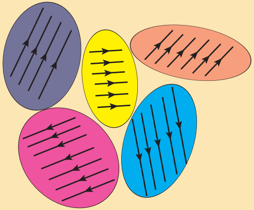
For strings, I have only questions:

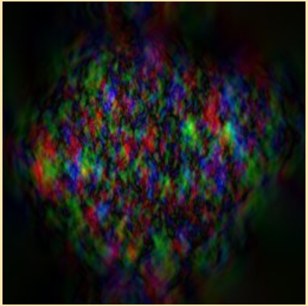
- What is “thickness” of string?
- Does a string have both momentum and position? Uncertainty relation? 2-scale argument?

Classical-Yang-Mills

- Fields in coordinate space:

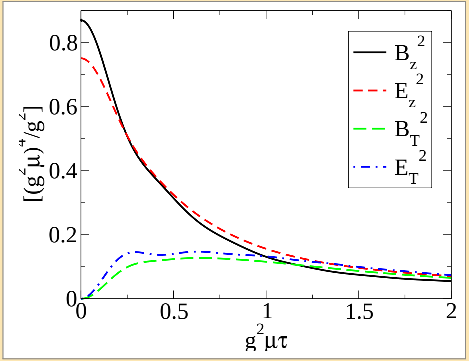
  $\Longrightarrow$ k_T by Fourier-transform
- Heisenberg uncertainty relation satisfied
- For very small scale substructure (hot spots in proton), becomes limiting factor!

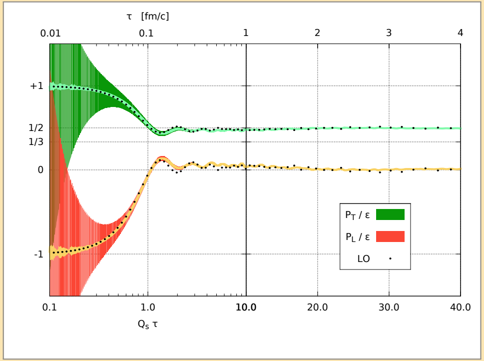




Color flux tubes and strings: time and rapidity

- Volume of one unit $\Delta\eta$ grows as $\sim \tau$
- String with constant tension: $\frac{dE}{d\eta} \sim \tau \ldots$ until string breaks
- Boost-invariant fields redshifted $\Longrightarrow$ after coherence lost $\frac{dE}{d\eta} \sim$ cst



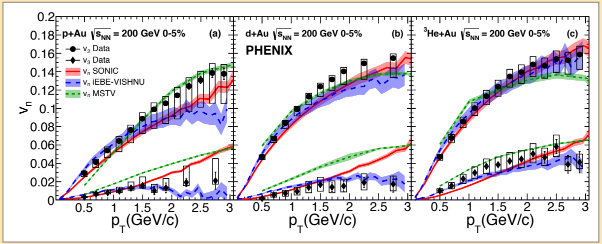


Azimuthal particle correlations

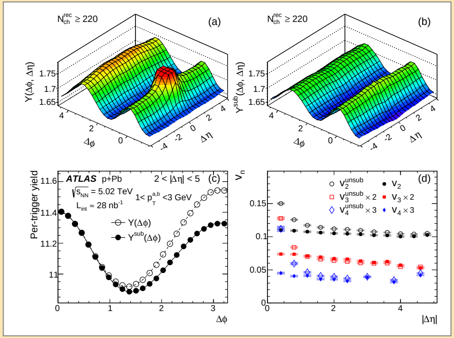
Azimuthal correlations, v_n's

Experimental observation

- Azimuthal anisotropy in particle production
- In AA, (high N_{ch}) pA & pp, LHC and RHIC



PHENIX, Nature Phys. **15** (2019) no.3, 214



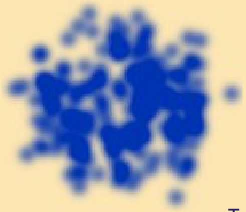
Show as yield/trigger or as v_n:
ATLAS, Phys. Rev. C **90** (2014) 4, 044906

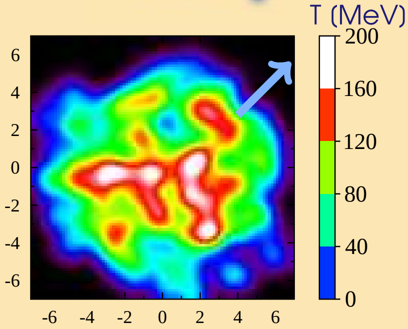
What is the origin of the effect?

- Collective flow?
- Initial state gluon correlations?

Azimuthal correlations from flow

In large systems (nucleus-nucleus) this dominates





- Spatial substructure of nuclei
  $\Longrightarrow$ Temperature/pressure gradients
- Interactions/collectivity:
  $\Longrightarrow$ Anisotropic force
  → anisotropy in momentum

Large system (AA):

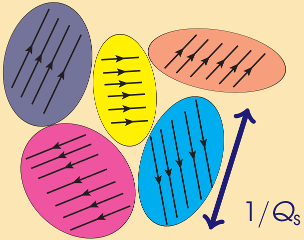
- Nucleons in nuclei, "MC Glauber" dominates
- Lifetime long $\Longrightarrow$ response hydrodynamic

Proton-proton, proton-nucleus systems:

- Subnucleon scale important
- Lifetime shorter $\Longrightarrow$ Pre-equilibrium flow, viscosity & other "semi-hydro" features much more important

Domains in the target color field

Physical origin for initial state particle correlations



How is color field seen by individual quark?

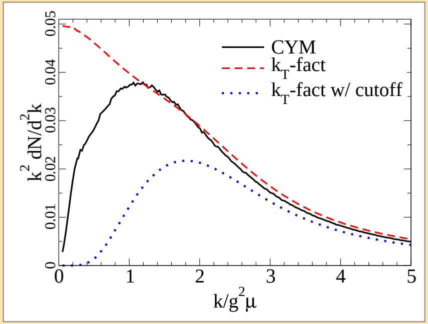
- Momentum transfer from target E-field
- "Domains" of size $\sim 1/Q_s$
  (Note actual calculation has Wilson lines, with correlation length, not explicit domains)
- Several probe particles inside domain: multiparticle azimuthal correlations.

- $\sim Q_s^2 S_\perp$ domains ($S_\perp$ = size of interaction area, πR_A^2, πR_p^2)
- $\sim {N_c}^2$ colors
- Relative correlation $\sim \frac{1}{{N_c}^2 Q_s^2 S_\perp}$ $\Longrightarrow$ stronger in small systems
- Manifestation in momentum & coordinate space $\Longrightarrow$ relevant for both flow & non-flow

Conclusions

- Gluon saturation & CGC: a weak-coupling & nonperturbative picture in the "BFKL" kinematic regime
- Classical color fields
  - Natural way to include gluon saturation
  - Measurable in dilute-dense processes like DIS
  - Can calculate dense-dense collision
- My personal opinion: glasma fields best thought of as perturbative gluons
  - Understand time dependence
  - High k_T-spectrum perturbative, k_T-factorization
  - But IR is regulated at $k_T \sim Q_s$

    $\Longrightarrow$ requires nonperturbative calculation — can be done with CYM



Glasma at $\tau = 0$

Energy density and Chern-Simons charge at $\tau = 0$

At exactly $\tau = 0$ can do a lot of things analytically
(changing notation $\alpha^i \equiv A^i_{(1)}$, $\beta^i \equiv A^i_{(2)}$)

$$\begin{aligned} \langle \varepsilon(\mathbf{x}_T) \rangle &= (-ig)^2 \left(\delta^{ij}\delta^{kl} + \varepsilon^{ij}\varepsilon^{kl} \right) \left\langle \mathrm{Tr} \left([\alpha^i_{\mathbf{x}_T}, \beta^j_{\mathbf{x}_T}][\alpha^k_{\mathbf{x}_T}, \beta^l_{\mathbf{x}_T}] \right) \right\rangle \quad (\sim \vec{E}^2 + \vec{B}^2 \underset{\tau=0}{=} E_z^2 + B_z^2) \\ \langle \dot{\nu}(\mathbf{x}_T) \rangle &= (-ig)^2 \quad \delta^{ij}\varepsilon^{kl} \quad \left\langle \mathrm{Tr} \left([\alpha^i_{\mathbf{x}_T}, \beta^j_{\mathbf{x}_T}][\alpha^k_{\mathbf{x}_T}, \beta^l_{\mathbf{x}_T}] \right) \right\rangle \quad (\sim \vec{E} \cdot \vec{B} = E^z \cdot B^z) \end{aligned}$$

Here $\dot{\nu}$ related to axial charge per unit area $\left.\frac{dN_5}{d^2\mathbf{x}_T\, d\eta}\right|_{\tau \lesssim 1/Q_s} \approx \frac{\tau^2}{2} \frac{g^2 N_f}{2\pi^2} \dot{\nu}(\mathbf{x}_T, \tau = 0^+)$

Nuclei independent $\Longrightarrow$ for $\langle \cdot \rangle$ factorize out **Weizsäcker-Williams gluon distribution**

$$\left\langle \mathrm{Tr} \left([\alpha^i_{\mathbf{x}_T}, \beta^j_{\mathbf{x}_T}][\alpha^k_{\mathbf{x}_T}, \beta^l_{\mathbf{x}_T}] \right) \right\rangle = \frac{1}{2} i f^{abc} i f^{a'b'c} \left\langle \alpha^{i,a}_{\mathbf{x}_T} \alpha^{k,a'}_{\mathbf{x}_T} \right\rangle \left\langle \beta^{j,b}_{\mathbf{x}_T} \beta^{l,b'}_{\mathbf{x}_T} \right\rangle , \quad \boxed{W^{ik}(\mathbf{x}_T, \mathbf{y}_T) \equiv \frac{\left\langle \alpha^{i,a}_{\mathbf{x}_T} \alpha^{k,a}_{\mathbf{x}_T} \right\rangle}{{N_c}^2 - 1}}$$

Distributions in Gaussian approximation

In Gaussian approximation WW-distribution from **dipole** $D_{\mathbf{x}_T\mathbf{y}_T} = \frac{1}{N_c}\left\langle \operatorname{Tr}\left(V_{\mathbf{x}_T} V^\dagger_{\mathbf{y}_T}\right)\right\rangle$

$$W^{ik}(\mathbf{x}_T, \mathbf{y}_T) = \frac{1}{2}\delta^{ij} G(r) + \frac{1}{2}\left(\delta^{ij} - 2\frac{\mathbf{r}_T{}^i \mathbf{r}_T{}^j}{r^2}\right) h(r) = \frac{1}{g^2 N_c}\left(\frac{\partial^i_{\mathbf{x}_T}\partial^k_{\mathbf{y}_T}\ln(D_{\mathbf{x}_T\mathbf{y}_T})}{\ln(D_{\mathbf{x}_T\mathbf{y}_T})}\right)\left(\left(D_{\mathbf{x}_T\mathbf{y}_T}\right)^{\frac{C_A}{C_F}} - 1\right)$$

$$\textbf{Unpolarized} \quad G(r) = \frac{1}{g^2 N_c}\frac{1-\left(D(r)\right)^{C_A/C_F}}{\ln\left(D(r)\right)}\left(\partial_r^2 + \frac{1}{r}\partial_r\right)\ln\left(D(r)\right)$$

$$\textbf{Linearly polarized} \quad h(r) = \frac{1}{g^2 N_c}\frac{1-\left(D(r)\right)^{C_A/C_F}}{\ln\left(D(r)\right)}\left(\partial_r^2 - \frac{1}{r}\partial_r\right)\ln\left(D(r)\right)$$

$\langle\varepsilon\rangle$ only depends on $G(r=0)$; correlations on both $G(r)$ and $h(r)$

- GBW parametrization $G(r) = \frac{1-e^{-(C_A/C_F)Q_s^2 r^2/4}}{g^2 N_c r^2/4}$ & $h(r) = 0$
- MV model: $\ln D(r) \sim -r^2 \ln r \implies G(r=0)$ diverges, need to regulate

Glasma graph approximation

For correlations need 8-point functions

$$\langle \alpha^{i,a}_{\mathbf{x}_T} \alpha^{k,c}_{\mathbf{x}_T} \alpha^{i',a'}_{\mathbf{y}_T} \alpha^{k',c'}_{\mathbf{y}_T} \rangle, \qquad \alpha^{i}_{\mathbf{x}_T} = \frac{i}{g} V(\mathbf{x}_T) \partial_i V(\mathbf{x}_T)$$

(This is why higher cumulants difficult)

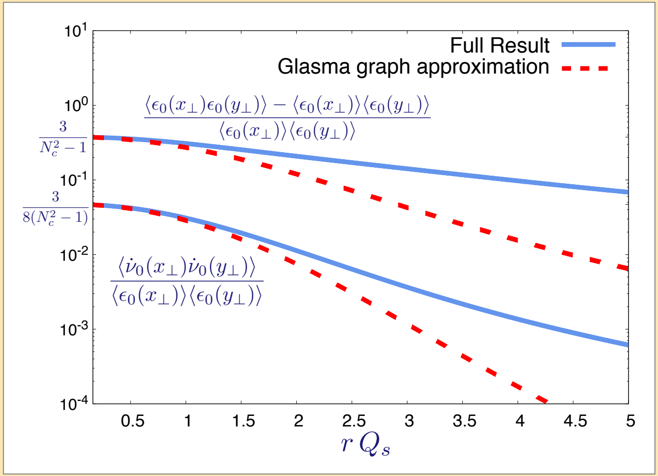
- T. L. and S. Schlichting, Phys. Rev. D **97** (2018) no.3, 034034 : used short distance "Glasma graph" approximation, factorize

$$\left\langle \alpha^{i,a}_{\mathbf{x}_T} \alpha^{k,c}_{\mathbf{x}_T} \alpha^{i',a'}_{\mathbf{y}_T} \alpha^{k',c'}_{\mathbf{y}_T} \right\rangle = \overbrace{\left\langle \alpha^{i,a}_{\mathbf{x}_T} \alpha^{k,c}_{\mathbf{x}_T} \right\rangle \left\langle \alpha^{i',a'}_{\mathbf{y}_T} \alpha^{k',c'}_{\mathbf{y}_T} \right\rangle}^{\text{disconnected}} \qquad [r = |\mathbf{x}_T - \mathbf{y}_T|]$$
$$+ \underbrace{\left\langle \alpha^{i,a}_{\mathbf{x}_T} \alpha^{i',a'}_{\mathbf{y}_T} \right\rangle \left\langle \alpha^{k,c}_{\mathbf{x}_T} \alpha^{k',c'}_{\mathbf{y}_T} \right\rangle + \left\langle \alpha^{i,a}_{\mathbf{x}_T} \alpha^{k',c'}_{\mathbf{y}_T} \right\rangle \left\langle \alpha^{k,c}_{\mathbf{x}_T} \alpha^{i',a'}_{\mathbf{y}_T} \right\rangle}_{\text{connected}}$$

- Full more complicated result obtained by J. L. Albacete, P. Guerrero-Rodríguez and C. Marquet, JHEP **1901** (2019) 073, P. Guerrero-Rodríguez, arXiv:1903.11602 (hep-ph).

Correlation functions

- Glasma graph correct for short distance
- Full result has larger longer-distance correlation (softer power law)



P. Guerrero-Rodríguez, arXiv:1903.11602 (hep-ph).

Time evolution

Time evolution

Analytical expression for Glasma fields at $\tau = 0^+$. How to go beyond?

- **C**lassical **Y**ang **M**ills on the lattice:
  Widely used (e.g. IPglasma), subject for another talk ...
- Series in τ ?
  G. Chen, R. J. Fries, J. I. Kapusta and Y. Li, Phys. Rev. C **92** (2015), 064912 ;

  M. E. Carrington, A. Czajka and S. Mrowczynski, (arXiv:2012.03042 (hep-ph)).

  Problem: $\varepsilon(\tau = 0)$ in the MV model is UV-divergent; although fine for $\tau > 0$

  (On the lattice regulate by lattice spacing)
- Boost invariant free field evolution:

$$E^\eta(\tau, k_\perp) = E_0^\eta(k_\perp) J_0(k\tau) \qquad E^i(\tau, k_\perp) = -i\epsilon^{ij}\frac{k^j}{k} B_0^\eta(k_\perp) J_1(k\tau)$$

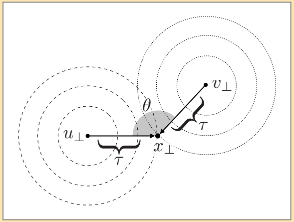
$$B^\eta(\tau, k_\perp) = B_0^\eta(k_\perp) J_0(k\tau) \qquad B^i(\tau, k_\perp) = -i\epsilon^{ij}\frac{k^j}{k} E_0^\eta(k_\perp) J_1(k\tau).$$

P. Guerrero-Rodríguez and T.L., (arXiv:2102.09993 (hep-ph)).
See also J. P. Blaizot, T.L. and Y. Mehtar-Tani, Nucl. Phys. A **846** (2010), 63-82;
H. Fujii, K. Fukushima and Y. Hidaka, Phys. Rev. C **79** (2009), 024909

Free field time evolution

$$\langle \varepsilon(\tau, \mathbf{x}_T) \rangle = \frac{g^2}{2} (\delta^{ij}\delta^{kl} + \epsilon^{ij}\epsilon^{kl}) f^{abn} f^{cdn} \int_{\mathbf{p}_T, \mathbf{k}_T, \mathbf{u}_T, \mathbf{v}_T} \langle \alpha^{i,a}_{\mathbf{u}_T} \alpha^{k,c}_{\mathbf{v}_T} \rangle_1 \langle \alpha^{j,b}_{\mathbf{u}_T} \alpha^{l,d}_{\mathbf{v}_T} \rangle_2$$

$$\times\ e^{i\mathbf{p}_T \cdot (\mathbf{x}_T - \mathbf{u}_T)} e^{i\mathbf{k}_T \cdot (\mathbf{x}_T - \mathbf{v}_T)} \left(J_0(p\tau) J_0(k\tau) - \frac{\mathbf{p}_T \cdot \mathbf{k}_T}{p_T k_T} J_1(p\tau) J_1(k\tau) \right)$$

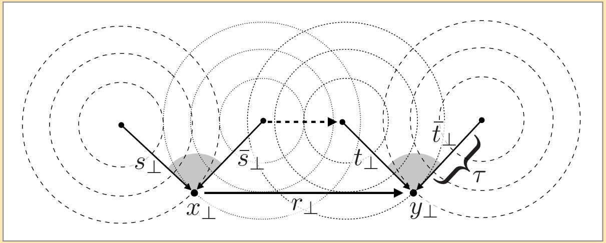


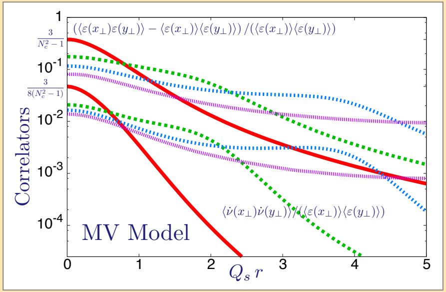
$$\langle \varepsilon(\tau, \mathbf{x}_T) \rangle \;=\; [\cdots] \int_{\mathbf{u}_T, \mathbf{v}_T} [\cdots] \frac{\delta(|\mathbf{x}_T - \mathbf{u}_T| - \tau)}{2\pi\tau} \frac{\delta(|\mathbf{x}_T - \mathbf{v}_T| - \tau)}{2\pi\tau} (1 + \cos(\theta_{\mathbf{x}_T - \mathbf{u}_T} - \theta_{\mathbf{x}_T - \mathbf{v}_T})).$$

Interpretation: interfering spherical expansing waves from $\mathbf{u}_T, \mathbf{v}_T$ to $\mathbf{x}_T$

Free field time evolution

For energy density correlator this structure generalizes:
Correlators of charges at $\tau = 0 \implies$ correlators at $\tau > 0$



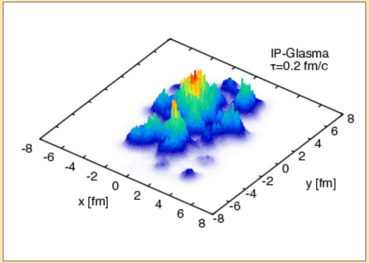


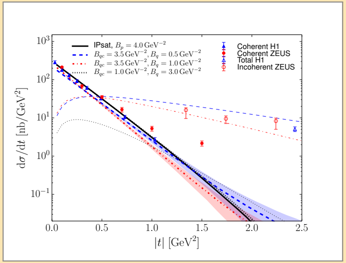
Explicit equation in paper.

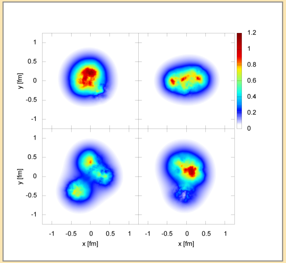
(Tehcnical note: glasma graph approximation, WW distributions, work to do still . . .)

Subnucleon structure

Subnucleon scales: IPglasma



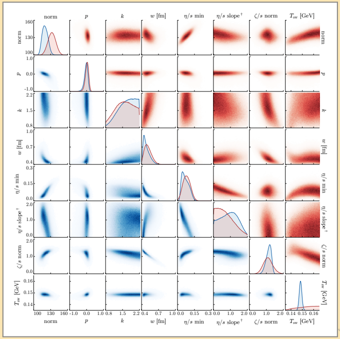




Hydro description of pA data: subnucleon structure

- Color field fluctuations
- Hot spots inside nucleon

Bayesian fits of HI data: same conclusion $\Longrightarrow$



Subnucleon scales: hotspot model

S. Demirci, T.L. and S. Schlichting, (arXiv:2101.03791 (hep-ph)) :

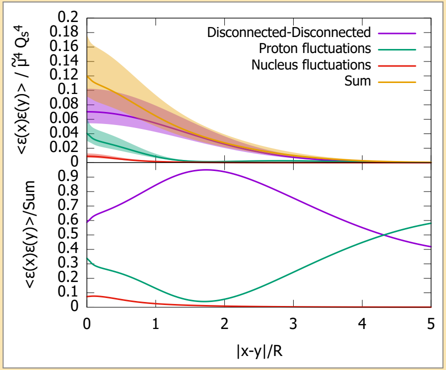
Analytically tractable dilute-dense model with proton hotspots

Parameters:

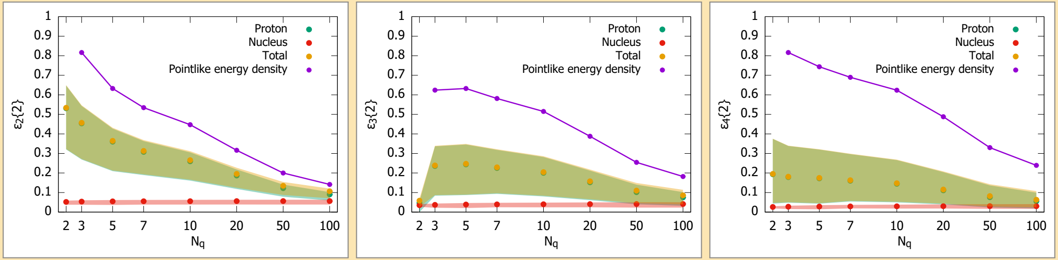
- Proton radius R
- Hot spot radius r
- Hot spot number N_q
- IR cutoff for color fields m

$\Longrightarrow$ Energy density correlator

$$\langle \varepsilon(\mathbf{x}_T)\varepsilon(\mathbf{y}_T)\rangle - \langle \varepsilon(\mathbf{x}_T)\rangle \langle \varepsilon(\mathbf{y}_T)\rangle$$



Hotspot model eccentricities



- For reasonable parameter values **hot spots dominate eccentricity**
- Future: constrain from coherent and incoherent exclusive DIS J/Ψ data