CGC today

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WHAT IS CGC?

A wonderful and simple idea: Gribov, Levin, Ryskin 1983.

In a dense system (hadron or nucleus) the average density of partons (or color fields) defines a natural transverse scale $Q_S^2 \propto \rho$.

"Gluon density" or "Momentum divide" or Saturation momentum: Q_S.

At resolution $\Delta x^2 < Q_S^{-2}$ the system is dilute partonic: gluon density at high momentum $\Phi(k) \propto 1/k^2$ (up to logarithmic corrections)

At low resolution $\Delta x^2 > Q_S^{-2}$ the system is saturated. There are much less gluons than perturbative expectation: at $k < Q_S$, $\Phi(k) \propto const$, or maybe even $\Phi(k) \propto k^2$.

Q_S - **typical "gluon density" in the wave function. Also "typical momentum" of gluons in the wave function. Also the only dimensional parameter that determines the bulk of physical properties of the nucleus.**

Q_S **dominates inclusive observables.**

Where to look for it?

Q_S is always there - even in a proton at rest, but $Q_S^2 \sim 0.04 Gev^2$ - nonperturbativey small and saturated regime is intractable.

Q_S grows with atomic number and with energy $Q_S^2 \propto A^{1/3} s^{\# \alpha_s}$

Naturally the best way to get into perturbative saturation regime ("CGC") $Q_S^2 \gg \Lambda_{QCD}^2$ is to probe heavy nucleus at high energy.

To minimize final state interactions the probe better be small (density of produced particles small), so the best place is p-A collisions.

CGC pheno.

Early CGC inspired phenomenology described qualitative features of various data:
A. Kharzeev-Levin-Nardi for multiplicity at RHIC and LHC {KLN, Phys.Rev. C71 (2005) 054903; Nucl.Phys. A747 (2005) 609-629}
The "simplest" observable roughly proportional to the saturation momentum:

$$\frac{dN}{dy} \propto \frac{1}{\alpha_S(Q_S^2)} S Q_S^2 \times ln \frac{Q_S^2(1)}{Q_S^2(2)}$$

Q_S depends on energy, rapidity and centrality

$$Q_S^2 = Q_0^2 N_{part} \left[x_0 \frac{W}{Q_0} e^{\pm y} \right]^{\lambda}; \qquad Q_0 = 0.6 \ Gev; \quad x_0 = 0.01; \quad \lambda = 0.205$$

Fits fairly well RHIC multiplicty data, and does a decent job for LHC as well.

B. Disappearance of Cronin enhancement in favour of suppression at forward rapidity at d-Au at RHIC. {Kharzeev, Kovchegov, Tuchin; Phys.Lett. B599 (2004) 23-31; Albacete et.al. Phys.Rev.Lett. 92 (2004) 082001}
At forward rapidity low x (strongly evolved) nucleus glue is probed. Saturation makes it grows slower with energy in A than in p - result suppression of R_{pA} at intermediate momenta $\sim Q_S$.

C. Decorrelation in forward di hadron production in d-Au. {Albacete, Marquet; Phys.Rev.Lett. 105 (2010) 162301}
Q_S is intrinsic transverse momentum, thus in production of di-hadrons it reduces back-to-back correlations. Most pronounced at forward rapidity, where the nucleus Q_S is largest.

Dipole: the main diagnostics tool.

A convenient observable that probes the saturation scale is the scattering amplitude of a color dipole. At high energy

$$s(\vec{x},\vec{y}) = Tr[S^\dagger(\vec{x})S(\vec{y})]$$

where $S(\vec{x})$ - the eikonal S-matrix of a quark at transverse coordinate $\vec{x}$. It probes the target color field at the position of the quark.

For $|\vec{x}-\vec{y}| \ll Q_S^{-1}$ color transparency:

$$s(\vec{x},\vec{y}) \approx 1 - |x-y|^2 Q_S^2$$

For $|\vec{x}-\vec{y}| > Q_S^{-1}$ black disk limit:

$$s(\vec{x},\vec{y}) \approx 0$$

.

Q_S is the crossover scale between the "color transparency" and "black disk" behavior.

At transverse momenta $Q > Q_s$, the gluon field is weak and linear evolution prevails.

At momenta $Q < Q_s$ collective emission is important, gluon field saturates and grows much slower with energy.

Energy evolution of $s(x, y)$ is governed by the Balitsky-Kovchegov equation (to leading order in α_s) :

$$\frac{d}{dY}s(x,y) = -\frac{\bar{\alpha}_s}{\pi}\int d^2z \frac{(x-y)^2}{(x-z)^2(y-z)^2}\left[s(x,y) - s(x,z)s(y,z)\right]$$

This is the "mean field" approximation - the complete evolution is more complicated and is an infinite hierarchy of equations, coupling "dipoles" to "quadrupoles" etc. Those are the Dyson-Schwinger equations of the "QCD Reggeon Field Theory" - Balitsky hierarchy or JIMWLK equation. The dipole is very useful - in the large N_c limit it determines many physical observables.

Improving precision: NLO corrections.

Real quantitative predictions require a real quantitative approach.

For quantitative applications leading order BK is too crude: energy growth of Q_S is much too fast.

Running coupling improves things, and so the Rc BK was used quantitatively to describe low x DIS data, and subsequently single particle inclusive spectrum at LHC.

Still one really needs to develop consistent higher order pertubative calculations to make this approach a *bona fide* quantitative science.

Last 3-4 years this has been one of the (two) main directions of the CGC effort.

1. Increase the accuracy of predictions significantly - introducing NLO.

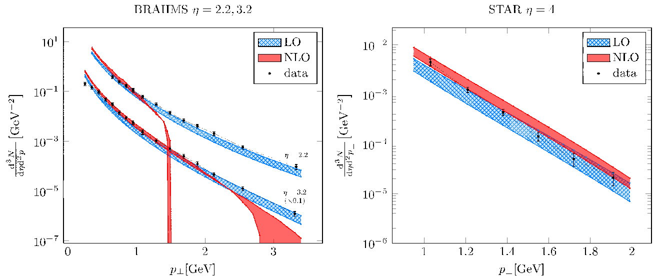
2. Meet the challenges of p-Pb data from LHC - initial state "quasi collectivity".

NLO1 - single inclusive production.

Dumitru, Hayashigaki, Jalilian-Marian - Nucl.Phys. A765 (2006) 464-482 (hybrid LO)

Altinoluk and A. K.; Phys.Rev. D83 (2011) 105004 (part of NLO); G.A. Chirilli, B.W. Xiao, F. Yuan; Phys.Rev. D86 (2012) 054005 (complete NLO)

Trouble: instability of NLO corrections: Stasto, Xiao and Zaslavsky; Phys.Rev.Lett. 112 (2014) 1, 012302

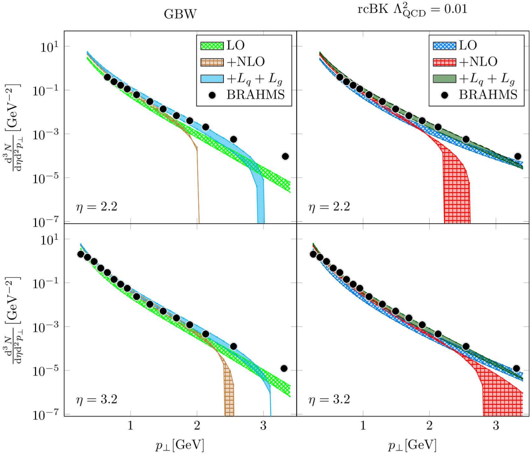


Recent progress: include the Ioffe time cutoff. Only low enough frequency modes are resolved by the target at given energy, and only those can produce particles.

Altinoluk et.al. Phys.Rev. D91 (2015) 9, 094016;

Things have improved quite a bit, but there is still a problem at higher p_T.

Watanabe et.al. Phys.Rev. D92 (2015) 034026



NLO2 - evolution.

NLO is not just fixed order corrections, it is also corrections to evolution.
Corrections to the BK equation:

$$\frac{d}{dY}s(x,y) = -\frac{\bar{\alpha}_s}{\pi}\int d^2z \frac{(x-y)^2}{(x-z)^2(y-z)^2}\left[s(x,y) - s(x,z)s(y,z)\right] + \alpha_s^2\Delta$$

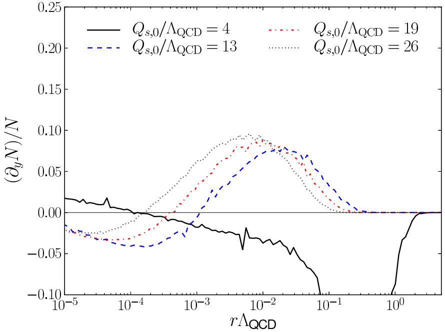
Balitsky, Chirilli; Phys.Rev. D77 (2008) 014019

Corrections to Balitsky hierarchy, or JIMWLK equations have also been calculated:

Balitsky-Chirilli; Phys.Rev. D88 (2013) 111501

Kovner, Lublinsky, Mulian; Phys.Rev. D89 (2014) 6, 061704; JHEP 1408 (2014) 114

Just like with BFKL - NLO corrections are large and negative.



From Lappi, Mantysaari Phys.Rev. D91 (2015) 7, 074016

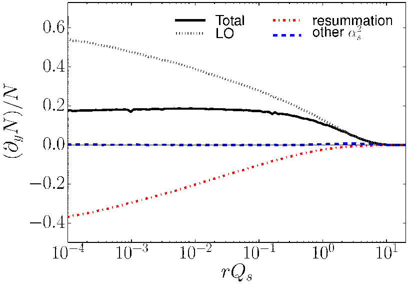
Large transverse logarithms are not dealt properly with. **Physics:** slow modes (at small p_T) are included into LO evolution, whereis when evolve in energy they have to be resummed in the initial condition and excluded from evolution. NLO “oversubtracts” their contribution. Very much like NLO in single inclusive!

Resummation needed!

Resummations have long history

Sabio Vera; Nucl.Phys. B722 (2005) 65-80; Motyka and Stasto; Phys.Rev. D79 (2009) 085016; Beauf; Phys.Rev. D89 (2014) 7, 074039; Iancu et.al. Phys.Lett. B744 (2015) 293-302

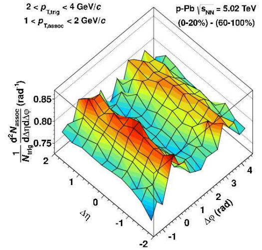
The latest suggestion (Iancu et.al. same as in Sabio Vera, 2005) - suppress emissions of gluons at distances $\ln |z - x/|x - y| \sim 1/\alpha_s$.



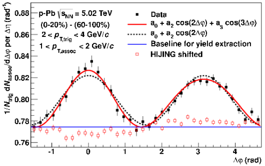
From Lappi, Mantysaari arXiv:1601.06598

Quasi collectivity?

Ridge correlations in p-p (CMS) and p-A.



Striking: the ridge is almost backward-forward symmetric.



Ridge in CGC.

Several initial state mechanisms for particle angular collimation at large rapidity separation:

"Glasma graphs" Dumitru, Gelis, Jalilian-Marian, Lappi: Phys.Lett. B697 (2011) 21; A.k.a. Bose enhancement - Altinoluk et.al. Phys.Lett. B751 (2015) 448-452

Local anisotropy - "Domains" of color field A.K., M. Lublinsky : Phys.Rev. D83 (2011) 034017

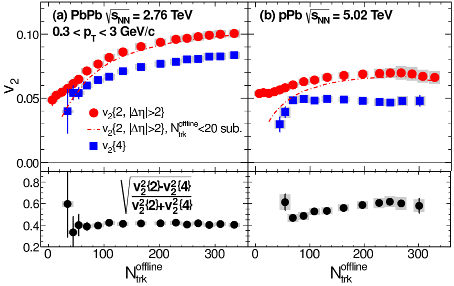
Density variation E. Levin a A. Rezaeian: Phys.Rev. D84 (2011) 034031

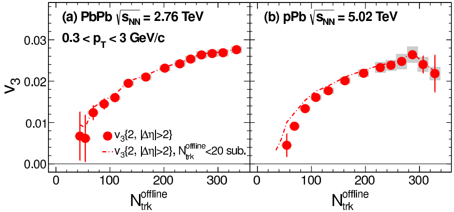
Diagrammatic analysis: Kovchegov and Wertepny; Nucl.Phys. A906 (2013) 50-83

CGC based "Glasma Graphs" give pretty good description of data Dusling and Venugopalan Phys.Rev.Lett. 108 (2012) 262001, Phys.Rev. D87 (2013) 5, 054014.

But things got more interesting.

The correlations point to collective, or at least quasi collective behavior.





The flow coefficients measure correlations between the emitted particles, and are believed to encode collectivity of the final state. For double inclusive spectrum

$$\frac{d^2N}{d^2p_1 d^2p_2} = 1 + \sum_{n=1}^{\infty} 2V_n(\mathbf{p_1}, \mathbf{p_2}) \cos(n\Delta\phi)$$

$$v_n^2 = \frac{V_n(p_T, p_T^{ref})}{\sqrt{V_n(p_T^{ref}, p_T^{ref})}}; \quad n = 2, 3$$

Analogously for v_2^4 - from four particle inclusive spectrum.
In particular hydro codes seem to describe the data on v_n.
But it is disconcerting: the produced system has a small spatial extent, and the momenta involved in the correlations are quite big $\sim 8Gev$, so that hydro is certainly suspect.

An interesting question: does the v_n data necessarily requires strong final state interactions? Is it possible that nontrivial initial state correlations mimic collectivity (quasi collectivity)?

Color field domains?

There is an ongoing effort to understand whether initial state correlations can lead to significant v_2^n.

The main focus: local anisotropy, or "color field domain" mechanism.

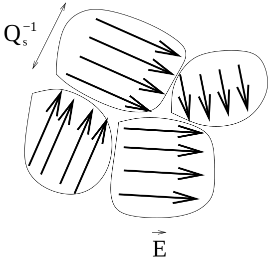


Figure: Cartoon of a typical field configuration in a saturated target.

Dumitru, McLerran, Skokov; Phys.Lett. B743 (2015) 134-137 - Bose enhancement ("Gasma graphs") alone cannot give v_2^4. **Including "local anizotropy" effects can give the right order of magnitude effect.**

Kovner and Lublinsky; Phys.Rev. D84 (2011) 094011 - at high energy local anisotropy has to be subleading in $1/N_c$

Dumitru, Skokov; Phys.Rev. D91 (2015) 7, 074006; McLerran, Skokov; Nucl.Phys. A947 (2016) 142-154; Lappi et.al. ; JHEP 1601 (2016) 061 - subleading $1/N_c$ maybe quite enough. Explore various model/physics aspects of the effect. There is still a lot to be understood.

WHERE DOES v_3 COME FROM? The outstanding question is v_3. Gluons are real and so they scatter with equal probability in the direction of the color field, and in the opposite direction. This leads to absense of odd harmonics.
Gluons are very resistant to producing v_3 in the leading dense approximation. But we still do not understand everything, so the last word has not been spoken yet. And the work continues.