Testing the CGC in \( p+Pb \) collisions at the LHC
What the CGC is about: coherence effects in high energy QCD (small-x)

High gluon densities in the projectile/target

**Saturation**: gluon self-interactions tame the growth of gluon densities towards small-\( x \)

\[
\frac{\partial \phi(x, k_t)}{\partial \ln(x_0/x)} \approx K \otimes \phi(x, k_t) - \phi(x, k_t)^2
\]

radiation recombination

\( k_t \lesssim Q_s(x) \)

Breakdown of independent particle production

\[
A(k \lesssim Q_s) \sim \frac{1}{g} \quad gA \sim \mathcal{O}(1)
\]
What the CGC is about: coherence effects

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HIC phenomenology

- Nuclear shadowing, String fusion, percolation
- Resummation of multiple scatterings
- kt-broadening
- Energy dependent cutoff in event generators

\[ R_{g}^{Pb}(Q^2=1.69 \text{GeV}^2) \]

\[ x, Q_0^2(k_t) \sim k_t \sim Q_s(x) \]

\[ x, Q_s^2 \sim 100 \text{ GeV} \]

\[ x, Q_s^2 \sim 1000 \text{ GeV} \]

\[ x, Q_s^2 \sim 2500 \text{ GeV} \]

\[ x, Q_s^2 \sim 5000 \text{ GeV} \]

\[ x, Q_s^2 \sim 10000 \text{ GeV} \]

\[ x, Q_s^2 \sim 20000 \text{ GeV} \]

\[ x, Q_s^2 \sim 50000 \text{ GeV} \]

\[ x, Q_s^2 \sim 100000 \text{ GeV} \]

\[ x, Q_s^2 \sim 200000 \text{ GeV} \]

\[ x, Q_s^2 \sim 500000 \text{ GeV} \]

\[ x, Q_s^2 \sim 1000000 \text{ GeV} \]

\[ x, Q_s^2 \sim 2000000 \text{ GeV} \]

\[ x, Q_s^2 \sim 5000000 \text{ GeV} \]

\[ x, Q_s^2 \sim 10000000 \text{ GeV} \]

\[ x, Q_s^2 \sim 20000000 \text{ GeV} \]

\[ x, Q_s^2 \sim 50000000 \text{ GeV} \]

\[ x, Q_s^2 \sim 100000000 \text{ GeV} \]

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\[ x, Q_s^2 \sim 500000000 \text{ GeV} \]

\[ x, Q_s^2 \sim 1000000000 \text{ GeV} \]

\[ x, Q_s^2 \sim 2000000000 \text{ GeV} \]

\[ x, Q_s^2 \sim 5000000000 \text{ GeV} \]

\[ x, Q_s^2 \sim 10000000000 \text{ GeV} \]

\[ x, Q_s^2 \sim 20000000000 \text{ GeV} \]

\[ x, Q_s^2 \sim 50000000000 \text{ GeV} \]

\[ x, Q_s^2 \sim 100000000000 \text{ GeV} \]
Coherence effects are essential for the description of data in HIC collisions (RHIC, LHC).

Is the CGC effective theory (at its present degree of accuracy) the best suited framework to quantify those coherence phenomena in LHC HI collisions?

Pros and Cons:
- Derived from QCD within a controlled approximation -> Theory driven predictive power
- Systematic unified description of different observables/collision systems
- Limited degree of applicability: High-(x,Q2) effects not accounted for

François Gelis

Why small-x gluons matter

Color Glass Condensate

Factorization

Stages of AA collisions

Leading Order

Leading Logs

Glasma fields

Initial color fields

Link to the Lund model

Rapidity correlations

Matching to hydro

Glasma stress tensor

Glasma instabilities

Summary

Initial condition from CGC: Leading Logs

Consider now quantum corrections to the previous result, restricted to \( \Lambda^1 + 1 < k^+ < \Lambda^0 + 0 \):

\[
\delta T_{\mu \nu}^{NLO} = \left[ \ln \left( \frac{\Lambda^0 + 0}{\Lambda^1 + 1} \right) H_1 + \ln \left( \frac{\Lambda^1 - 1}{\Lambda^0 - 0} \right) H_2 \right] T_{\mu \nu}^{LO}.
\]

(FG, Lappi, Venugopalan (2008))

small-x d.o.f (dynamical)  valence d.o.f (static)

fields \( \Lambda_i^+ \)  sources \( P^+ \)  

LHC  RHIC  SPS
**CGC Theory Status: Entering the NLO era**

**Evolution Equations:**
\[
\frac{\partial \phi(x, k)}{\partial \ln(1/x)} = \mathcal{K} \otimes \phi(x, k) - \phi^2(x, k) \quad \frac{\partial W[\rho]}{\partial Y} = \ldots
\]

- Running coupling kernel in BK evolution for the 2-point function
  - Full NLO kernel for BK-JIMWLK [Balitsky Chirilli]
- Analytic [Iancu & Triantafyllopoulos'] and numerical [Dumitru et al] solutions of full B-JIMWLK hierarchy for n-point functions
- ... 

**Production processes**
\[
\frac{dN_{AB \rightarrow X}}{d^3 p_1 \ldots} [\phi(x, k); W_Y[\rho]]
\]

- Running coupling and full NLO corrections to kt-factorization [Kovchegov, Horowitz, Balitsky, Chirilli]
- Inelastic terms in the hybrid formalism [Altinoluk and Kovner]
- Hadron-hadron, hadron-photon* correlations [Heikki's talk, Jalilian Marjan's talk]
- Factorization of multiparticle production processes at NLO [Gelis et al]
- DIS NLO photon impact factors [Chirilli]
- ...

**Used in phenomenological works?**
- Yes
- No
- A bit :)

G. Beuf's Talk
Empiric information needed to constrain:
- Non-perturbative parameters: initial conditions for BK-JIMWLK evolution, impact parameter dependence
- K-factors to account for higher order corrections (effectively also for missing high-(x,Q2) contributions, energy-conservation corrections etc)

**proton**
- Abundant high quality data at small-x
- Good simultaneous description of e+p and p+p data
- Global rcBK fits to constrain gluon distribution

**nuclei**
- Few data at small-x
- LHC Pb+Pb data and RHIC dAu forward data troublesome (more later)
The baseline: proton collisions

1. Global fits to e+p data at small-x

![Graph](Image)

$\phi \left[ k_t, x_0 = 10^{-2}, Q_{s0}^2, \gamma, \ldots \right]$  

$\frac{\partial \phi(x, k_t)}{\partial \ln(x_0/x)} \approx K \otimes \phi(x, k_t) - \phi(x, k_t)^2$

initial conditions  

rcBK evolution  

e+p x-section

<table>
<thead>
<tr>
<th>Set</th>
<th>$Q_{s0, \text{proton}}^2$ (GeV$^2$)</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>h</td>
<td>0.168</td>
<td>1.119</td>
</tr>
<tr>
<td>h'</td>
<td>0.157</td>
<td>1.101</td>
</tr>
</tbody>
</table>

2. Extract NP fit parameters (initial conditions for evolution)

$\sim \frac{1}{k_t^2 \gamma}$  

$\gamma > 1$

$Y=6$

$Y=1.5$

$10^2$  

$10$ $k_t$ (GeV/c)

$\sigma^P [\phi(k_t, x)]$
The baseline: proton collisions

1. Global fits to e+p data at small-x

2. Extract NP fit parameters (initial conditions for evolution)

3. Run consistency and stability checks

JLA, Armesto, Milhano, Quiroga, Salgado

JLA, Milhano, Quiroga, Rojo
The baseline: proton collisions

1. Global fits to e+p data at small-x

\[
\frac{dN^g}{d\eta d^2p_t} \sim K \alpha_s(Q_r^2) \phi(x_1, k_t) \otimes \phi(x_2, k_t - p_t) \otimes FF(Q_f^2)
\]

4. Apply gained knowledge in the study of other systems (theory driven extrapolation)

JLA, Dumitru, Fujii, Nara

2. Extract NP fit parameters (initial conditions for evolution)

\[
\sim \frac{1}{k_t^{2\gamma}} \quad \gamma > 1
\]

\[
\text{Set} \quad Q^2_{2\text{proton}} \quad (\text{GeV}^2) \quad \gamma
\]

\[
\begin{array}{c|cc}
\text{MV} & 0.2 & 1.119 \\
\text{h} & 0.168 & 1.119 \\
\end{array}
\]

3. Proton-proton collisions at 1.96 TeV

\[
\text{FF}(Q)
\]

5. Proton-proton collisions at 7 TeV

\[
\text{CMS data } |\eta|<2.4
\]

\[
\text{MV DSS-L} \\
\text{MV DSS-NLO, calc(y=y*0.9)} \\
\text{g1.119 DSS-NLO} \\
\text{g1.101 DSS-NLO} \\
\text{MV KKP} \\
\text{g1.119 KKP} \\
\text{g1.101 KKP}
\]
Modeling the impact parameter dependence

\[ \phi^{\text{Pb}}(x_0, k_t, B) = \phi^p(x_0, k_t; \{Q_{s0,Pb}^2 \to Q_{s0,Pb}^2(B)\}; \gamma) \rightarrow \phi^{\text{Pb}}(x, k_t, B) = \text{rcBK}[\phi^{\text{Pb}}(x_0, k_t, B)] \]

A) Most “natural” option: 
\[ Q_{s0,Pb}^2(B) = T_A(B) Q_{s0,p}^2 \quad \gamma^{\text{Pb}} = \gamma^P (> 1) \]

PROBLEM: yields \( R_{\text{pPb}} > 1 \) at high transverse momentum

B) Possible solution 
\[ Q_{s0,Pb}^2(B) = T_A(B)^{1/\gamma} Q_{s0,p}^2 \quad \text{and/or} \quad \gamma^{\text{Pb}} = 1(\text{MV}) + \frac{\#}{A^2/3} \]

hybrid formalism: 
\[ \frac{dN^g}{dy_h d^2k_t} \approx xq(x_1, k_{\perp}) \otimes \phi_A(x_2, k_t) \]

RHIC data does not constrain much the i.c. for BK evolution. K-factor needed at most forward rapidity

pp @ 200 GeV (only elastic term)

dAu @ 200 GeV (only elastic term)
Effect of NLO corrections

The effect of NLO corrections to the hybrid formalism can be very large!!!. Full NLO analyses needed

\[
\frac{dN^{pA\rightarrow hX}_{\eta d^2k}}{d\eta d^2k} = K^h \left( \frac{dN_{h}}{d\eta d^2k} \right)_{el} + \left( \frac{dN_{h}}{d\eta d^2k} \right)_{inel} \]

\[
\left( \frac{dN_{h}}{d\eta d^2k} \right)_{el} = \frac{1}{(2\pi)^2} \int_{x_F}^{1} \frac{dz}{z^2} \left[ \sum_{q} x_1 f_{g/p}(x_1, Q^2) \tilde{N}_F \left( x_2, \frac{p_t}{z} \right) D_{h/q}(z, Q^2) 
+ x_1 f_{g/p}(x_1, Q^2) \tilde{N}_A \left( x_2, \frac{p_t}{z} \right) D_{h/g}(z, Q^2) \right].
\]

\[
\left( \frac{dN_{h}}{d\eta d^2k} \right)_{inel} = \frac{\alpha_s(Q)}{2\pi^2} \int_{x_F}^{1} \frac{dz}{z^2} \frac{z^4}{k^4} \int^{Q} \frac{d^2q}{(2\pi)^2} q^2 \tilde{N}_F(x_2, q) x_1 \int_{x_1}^{1} \frac{d\xi}{\xi} \sum_{i,j=q,g} w_{i/j}(\xi) P_{i/j}(\xi) f_J(\frac{x_1}{\xi}, Q^2) D_{h/j}(z, Q^2)
\]

pp @ 200 GeV (g=1.119 i.c)

dAu @ 200 GeV (g=1.119 i.c)
- In the CGC, multiplicities rise proportional to the (local) saturation scale

\[ \frac{dN_{\text{gluons}}}{d\eta \, d^2b} \bigg|_{\eta=0} \propto Q_s^2(\sqrt{s}, b) \sim \sqrt{s}^{0.3} N_{\text{part}} \]

Overall, different CGC works predict we’ll know the answer very soon!!
Nuclear ugd’s and nuclear modification factors

Setting up the evolution

\[ \phi_{Pb}(x_0, k_t, B) = \phi_P(x_0, k_t; \{Q_{s0,p}^2 \rightarrow Q_{s0,Pb}^2(B)\}; \gamma) \rightarrow \phi_{Pb}(x, k_t, B) = rcBK[\phi_{Pb}(x_0, k_t, B)] \]

A) Most “natural” option:  
\[ Q_{s0,Pb}^2(B) = T_A(B) Q_{s0,p}^2 \quad \gamma_{Pb} = \gamma_P(> 1) \]

**PROBLEM:** yields \( R_{pPb} > 1 \) at high transverse momentum

B) Possible solution  
\[ Q_{s0,Pb}^2(B) = T_A(B)^{1/\gamma} Q_{s0,p}^2 \quad \text{and/or} \quad \gamma_{Pb} = 1(MV) + \frac{\#}{A^2/3} \]

**Graphs:**

- **A)** Most “natural” option: 
  - \( R_{pPb}(\eta=0) \)
  - rcBK-MC kt-factorization
  - EPS09 nPDF
  - IP-Sat (Tribedy & Venugopalan)
  - rcBK (Tribedy & Venugopalan)

- **B)** Possible solution:
  - \( R_{pPb}(\eta=0) \)
  - rcBK-MC kt-factorization
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Nuclear ugd’s and nuclear modification factors

Setting up the evolution

$$\phi^{\text{Pb}}(x_0, k_t, B) = \phi^{p}(x_0, k_t; \{Q^2_{s0,p} \rightarrow Q^2_{s0,Pb}(B)\}; \gamma) \rightarrow \phi^{\text{Pb}}(x, k_t, B) = rcBK[\phi^{\text{Pb}}(x_0, k_t, B)]$$

A) Most “natural” option:  

$$Q^2_{s0,Pb}(B) = T_A(B) Q^2_{s0,p} \quad \gamma^{\text{Pb}} = \gamma^{p}(> 1)$$

**PROBLEM:** yields R_{pPb} > 1 at high transverse momentum

B) Possible solution  

$$Q^2_{s0,Pb}(B) = T_A(B)^{1/\gamma} Q^2_{s0,p} \quad \text{and/or} \quad \gamma^{\text{Pb}} = 1(MV) + \frac{\#}{A^2/3}$$

The yields themselves carry very valuable information!
Moving forward

Yet another issue: Where to switch from $kt$-factorization to hybrid formalism? $x_{1(2)} \sim \frac{m_t}{\sqrt{s}} \exp(\pm y_h)$

Midrapidity: $kt$-factorization:

$$\frac{dN_g}{d\eta d^2p_t} \sim \phi^P(x_1) \otimes \phi^{Pb}(x_2)$$

Forward rapidity: hybrid formalism

$$\frac{dN}{d\eta d^2p_t} \sim pdf^P(x_1) \otimes \phi^{Pb}(x_2)$$
Moving forward: Testing the non-linear evolution

For $R_{pPb}(\eta=0)$:
- rcBK-MC kt-factorization
- EPS09 nPDF
- IP-Sat (Tribedy & Venugopalan)
- rcBK (Tribedy & Venugopalan)

For $R_{pPb}(\eta=2)$:
- rcBK-MC, kt-factorization
- rcBK-MC, hybrid LO
- rcBK-MC, hyb LO+inel. term $\alpha=0.1$
- rcBK-MC, hybrid LO
- rcBK-MC, Npart $>10$
- EPS09 nPDF

For $R_{pPb}(\eta=4)$:
- rcBK-MC, min bias
- rcBK-MC, Npart $>10$
- rcBK-MC, LO+inelastic term $\alpha=0.1$
- EPS09 nPDF

For $R_{pPb}(\eta=6)$:
- rcBK-MC, min bias
- rcBK-MC, Npart $>10$
- rcBK-MC, LO+inelastic term $\alpha=0.1$
- EPS09 nPDF

$p_t$ (GeV/c) vs. $R_{pPb}$ for various $\eta$ values.
Forward di-hadron angular correlations

At small-x, the transverse momentum transfer is controlled by the saturation scale. **CGC description**: A quark (gluon) emits a gluon. The pair scatters independently off the target.

Angular decorrelation happens if \( Q_s^{\text{Pb}}(x_A) \sim (k_1, k_2) \)

\[
x_p = \frac{|k_1| e^{y_1} + |k_2| e^{y_2}}{\sqrt{s}}
\]

\[
x_A = \frac{|k_1| e^{-y_1} + |k_2| e^{-y_2}}{\sqrt{s}}
\]

Ergo, decorrelation should be stronger with
- Increasing rapidity of the pair
- Increasing collision centrality
- Decreasing hadron momentum

\[
CP(\Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta \phi}
\]
Forward di-hadron angular correlations in RHIC dAu data

\[ J_{dA} = I_{dA} \times R_{dA} = \frac{1}{\langle N_{coll} \rangle} \frac{\sigma_{dA}^{\text{pair}}}{\sigma_{pp}^{\text{pair}}} \]

PHENIX data

Observed decorrelation IS stronger with

- Increasing rapidity of the pair
- Increasing collision centrality
- Decreasing hadron momentum
Uncertainties in current CGC phenomenological works:

- Need for a better description of n-point functions: [H Mantysaari & T. Lappi]
- Better determination of the pedestal: K-factors in single inclusive production?
- Role of double parton scattering?

- Alternative descriptions including resummation of multiple scatterings, nuclear shadowing and cold nuclear matter energy loss seem possible... [Kang et al]
di-hadron angular correlations at the LHC

• Analogous decorrelation phenomena should be seen at the LHC
• The increase in collision energy implies that they should be visible at
  * Lower rapidities of the produced pair
  * Higher transverse momentum
• All previously mentioned details are been taken care of. Stay tuned!!!
hadron-photon\* correlations in pPb collisions at the LHC

- hadron-dilepton pair

\[ Y_\gamma = Y_\pi = 4 \]

\[ M = 4 \text{ GeV} \]

- hadron-photon

\[ Y_\gamma = Y_\pi = \frac{1}{4} \]

\[ M = 8 \text{ GeV} \]

These processes are theoretically cleaner:
Only knowledge of 2-point needed!!
Important steps have been taken in promoting GCG to an useful quantitative tool
- Continuos progress on the theoretical side
- Phenomenological effort to systematically describe data from different systems (e+p, e+A, p+p, d+Au, Aa+Au and Pb+Pb) in an unified framework

Most solid CGC predictions for the upcoming p+Pb run:
- Suppression of nuclear modification factors at moderate pt already at mid-rapidity
- Stronger suppression at more forward rapidities (evolution)
- Suppression of di-hadron and photon-hadron angular correlations

Current predictions carry some uncertainty due to lack of data to constrain NP aspects of nuclear UGD. This problem can be largely fixed through the measurement of simple observables (i.e. single inclusive spectra) in p+Pb collisions

Phenomenological implementation of recent theoretical progress needed

Merci!!
If these data are confirmed... ALL initial state models are in trouble!!

Initial state - Jet probes -
- Jets are reconstructed in d+Au up to 40 GeV/c
$R_{pPb}^{ch}(\eta=0)$

- rcBK-MC, Min. bias
- rcBK-MC, Npart > 10
- rcBK-MC, Npart < 5

$c_{me}= 5 \text{ TeV}$

$Q_s^2(b) \sim T_A(b)$

$R_{pPb}^{ch}(\eta=2)$

- rcBK-MC, Min. bias
- rcBK-MC, Npart > 10
- rcBK-MC, Npart < 5

$c_{me}= 5 \text{ TeV}$

$Q_s^2(b) \sim T_A(b)$