Ultra-forward particle production from CGC+Lund fragmentation

Phys. Rev. D 94, 054004

Pablo Guerrero Rodríguez\textsuperscript{a}

\textit{in collaboration with}

Javier L. Albacete\textsuperscript{a} and Yasushi Nara\textsuperscript{b}

\textsuperscript{a} CAFPE and Departamento de Física Teórica y del Cosmos, Universidad de Granada

\textsuperscript{b} Akita International University, Yuwa

‘LHC Working Group on Forward Physics and Diffraction’

March 23, 2018

Madrid
# Outline

1. **Introduction**
   - Forward production in the Color Glass Condensate: Hybrid formalism

2. **The Monte-Carlo event generator**
   - Perturbative parton production: implementation of DHJ formula
   - Multiple scattering: eikonal model
   - Hadronization: Lund fragmentation model

3. **Results:**
   - RHIC: d-Au @ 200 GeV
   - LHCf: p-p @ 7 TeV
   - LHCf: p-Pb @ 5.02 TeV
   - LHCf: nuclear modification factor $R_{p-Pb}$ @ 5.02 TeV

4. **Conclusions, future prospects**
1. Introduction
Forward particle production in the Color Glass Condensate

- The analysis of the very forward region of particle production in high-energy collisions gives us access to the wave functions of colliding objects in the extreme limits of phase space.

\[ x_p \approx \frac{p_t}{\sqrt{s}} e^{y_h} \]

\[ x_t \approx \frac{p_t}{\sqrt{s}} e^{-y_h} \]
Forward particle production in the Color Glass Condensate

- The analysis of the very forward region of particle production in high-energy collisions gives us access to the wave functions of colliding objects in the extreme limits of phase space.

\[ x_p \approx \frac{p_t}{\sqrt{s}} e^{y_h} \]

\[ x_t \approx \frac{p_t}{\sqrt{s}} e^{-y_h} \]

**Highly asymmetric collision!**

**Dilute** ensemble of fast valence quarks

**Dense** pack of ‘slow’ radiated gluons
Forward particle production in the Color Glass Condensate

- The analysis of the very forward region of particle production in high-energy collisions gives us access to the wave functions of colliding objects in the extreme limits of phase space.

\[ x_p \approx \frac{p_t}{\sqrt{s}} e^{y_h} \]

\[ x_t \approx \frac{p_t}{\sqrt{s}} e^{-y_h} \]

\[ \sqrt{s} = 7 \, \text{TeV} \]
\[ p_t \lesssim 1 \, \text{GeV} \]
\[ 8.8 \leq y \leq 9.0 \]

LHCf:

- Smallest x values observed yet

\[ x_p \sim 10^{-1} \div 1 \]
\[ x_t \sim 10^{-8} \div 10^{-9} \]
Forward particle production in the Color Glass Condensate

- Hybrid formalism: the CGC interpretation of dilute-dense interactions

\[
\frac{d\sigma}{dyd^2k_\perp} \sim \text{pdf}(x_p, \mu^2) \times \text{uGD}(x_t, k^2_\perp)
\]
Forward particle production in the Color Glass Condensate


\[
\frac{d\sigma}{dyd^2k_\perp} \sim \text{pdf}(x_p, \mu^2) \times \text{uGD}(x_t, k_{\perp}^2)
\]
Forward particle production in the Color Glass Condensate

- Hybrid formalism: the CGC interpretation of dilute-dense interactions

\[
\frac{d\sigma}{dyd^2k_\perp} \sim \text{pdf}(x_p, \mu^2) \times \text{uGD}(x_t, k^2_\perp)
\]
Forward particle production in the Color Glass Condensate


\[
\frac{d\sigma}{dyd^2k_\perp} \sim \text{pdf}(x_p, \mu^2) \times \text{uGD}(x_t, k_{\perp}^2)
\]

**Multiple scattering:**
All terms of order \( gA(x) \sim O(1) \) must be resummed.

Strong color field: \( A(x) \sim \frac{1}{g} \)
Forward particle production in the Color Glass Condensate

- Hybrid formalism: the CGC interpretation of dilute-dense interactions

\[
\frac{d\sigma}{dy d^2 k} \sim \text{pdf}(x_p, \mu^2) \times \text{uGD}(x_t, k^2_{\perp})
\]

Multiple scattering:
All terms of order \( gA(x) \sim O(1) \) must be resummed.

- Resummation to all orders + eikonal approximation: Wilson line \( U(z_{\perp}) \)

Strong color field: \( A(x) \sim \frac{1}{g} \)
Forward particle production in the Color Glass Condensate

- Hybrid formalism: the CGC interpretation of dilute-dense interactions

\[
\frac{d\sigma}{dyd^2k_\perp} \sim \text{pdf}(x_p, \mu^2) \times uGD(x_t, k_t^2)
\]

**Multiple scattering:**
All terms of order \( gA(x) \sim O(1) \)
must be resummed.

- Resummation to all orders + eikonal approximation: Wilson line \( U(z_\perp) \)
- Unintegrated gluon distribution:

\[
uGD(x_0, k_t) = \text{FT} \left[ 1 - \frac{1}{N_c} \left\langle \text{tr}(UU^\dagger) \right\rangle_{x_0} \right]
\]

Dipole scattering amplitude

Strong color field: \( A(x) \sim \frac{1}{g} \)
Forward particle production in the Color Glass Condensate

- Hybrid formalism: the CGC interpretation of dilute-dense interactions

\[
\frac{d\sigma}{dyd^2k_{\perp}} \sim \text{pdf}(x_p, \mu^2) \times uGD(x_t, k_{\perp}^2)
\]

Non-linear small-x evolution:

BK-JIMWLK equations:

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

- Radiation
- Recombination

BK: evolution of 2-point function
JIMWLK: (coupled) evolution of all n-point functions
Forward particle production in the Color Glass Condensate

- Hybrid formalism: the CGC interpretation of dilute-dense interactions

\[ \frac{d\sigma}{dy d^2 k_\perp} \sim \text{pdf}(x_p, \mu^2) \times \text{uGD}(x_t, k_{t}^2) \]

Non-linear small-x evolution:
BK-JIMWLK equations:

\[ \frac{\partial \text{uGD}(x, k_t)}{\partial \ln(x_0/x)} \sim \mathcal{K} \otimes \text{uGD} - \text{uGD}^2 \]

\( Q_s^2(x) \) : Signals when radiation and recombination terms become parametrically of the same order
Forward particle production in the Color Glass Condensate

- Hybrid formalism: the CGC interpretation of dilute-dense interactions
  \[ \frac{d\sigma}{dyd^2k_\perp} \sim \text{pdf}(x_p, \mu^2) \times uGD(x_t, k_t^2) \]

- Non-linear small-x evolution:
  BK-JIMWLK equations:
  \[ \frac{\partial uGD(x, k_t)}{\partial \ln(x_0/x)} \sim K \otimes uGD - uGD^2 \]
  \[ Q_s^2(x) : \text{Signals when radiation and recombination terms become parametrically of the same order} \]

- LHCf: \((p-p)\)
  \[ Q_s \gtrsim 1 \text{ GeV} \]
2. The Monte-Carlo event generator
Perturbative parton production: implementation of DHJ formula


\[
\frac{d\sigma^{h_1h_2 \rightarrow (q/g)X}}{dyd^2k_t} = \frac{K}{(2\pi)^2} \frac{\sigma_0}{2} x_p f(q/g)/h_1(x_p, \mu^2) N(F/A), h_2(x_t, k_t^2)
\]
Perturbative parton production: implementation of DHJ formula


\[
\frac{d\sigma^{h_1 h_2 \rightarrow (q/g) X}}{dyd^2 k_t} = \frac{K}{(2\pi)^2} \frac{\sigma_0}{2} x_p f(q/g) / h_1 (x_p, \mu^2) N(F/A, h_2 (x_t, k_t^2)}
\]

- Proton PDF: CTEQ6 LO set (J. Pumplin et. al., JHEP 07 (2002) 012)

- Default factorization scale:

**LHCf:** \( \mu = \max\{k_t, Q_s\} \)

**RHIC (forward):** \( Q_s < 1 \) GeV \( \Rightarrow \mu = 1 \) GeV

(LHCf data description insensitive to cutoff)
Perturbative parton production: implementation of DHJ formula


\[
\frac{d\sigma^{h_1 h_2 \rightarrow (q/g) X}}{dy d^2 k_t} = \frac{K}{(2\pi)^2} \frac{\sigma_0}{2} x_p f(q/g)/h_1(x_p, \mu^2) N_{(F/A), h_2} (x_t, k_t^2)
\]

- uGD's: Fourier transforms of dipole scattering amplitudes.

\[
N_{F(A)}(x, k_t) = \int d^2 r e^{-i k_t \cdot r} \left[ 1 - N_{F(A)}(x, r) \right].
\]

- Small-x evolution: We take parametrization of \(N_{F(A)}(x, r)\) from the AAMQS fits to data on the structure functions measured in e+p scattering at HERA:

rc-BK evolution

Perturbative parton production: implementation of DHJ formula


\[
\frac{d\sigma^{h_1 h_2 \rightarrow (q/g) X}}{dy d^2 k_t} = \frac{K}{(2\pi)^2} \frac{\sigma_0}{2} x_p f_{(q/g)}/h_1(x_p, \mu^2) N_{(F/A), h_2}(x_t, k^2_t)
\]

rc-BK evolution

- Initial conditions for evolution:

\[
N_F(x_0, r) = 1 - \exp \left[ -\frac{(r^2 Q^2 s_0)^\gamma}{4} \log \left( \frac{1}{\Lambda r} + e \right) \right]
\]

\[
x_0 = 10^{-2} \quad \gamma = 1.101 \quad Q^2 s_0 = 0.157 \text{ GeV}^2
\]
Perturbative parton production: implementation of DHJ formula


\[
\frac{d\sigma^{h_1 h_2 \rightarrow (q/g) X}}{dy d^2 k_t} = \frac{K}{(2\pi)^2} \frac{\sigma_0}{2} x_p f(q/g) / h_1(x_p, \mu^2) N_{(F/A), h_2}(x_t, k_t^2)
\]

**rc-BK evolution**

- Initial conditions for evolution:

\[
N_F(x_0, r) = 1 - \exp \left[ -\frac{(r^2 Q_{s0}^2)^\gamma}{4} \log \left( \frac{1}{\Lambda r} + e \right) \right]
\]

\[x_0 = 10^{-2} \quad \gamma = 1.101 \quad Q_{s0}^2 = 0.157 \text{ GeV}^2\]

- uGD's for nuclear target:

\[
Q_{s0, nucleus}^2 = A^{1/3} Q_{s0, proton}^2
\]

**Oomph factor**
Perturbative parton production: implementation of DHJ formula


\[
\frac{d\sigma_{h_1 h_2 \rightarrow (q/g) X}}{dy d^2 k_t} = \frac{K}{(2\pi)^2} \frac{\sigma_0}{2} x_p f(q/g) / h_1(x_p, \mu^2) N(F/A), h_2(x_t, k_t^2)
\]

- Implicit integration in impact parameter \( \vec{b} \): \( \sigma_0 / 2 \)

Free fit parameter of AAMQS fits:

\[
\frac{\sigma_0}{2} = 16.5 \text{ mb}
\]

Perturbative parton production: implementation of DHJ formula


\[
\frac{d\sigma^{h_1 h_2 \rightarrow (q/g)X}}{dy d^2 k_t} = \frac{K}{(2\pi)^2} \frac{\sigma_0}{2} x_p f(q/g) / h_1 \left(x_p, \mu^2\right) N_{(F/A), h_2} \left(x_t, k_t^2\right)
\]

- Implicit integration in impact parameter $\vec{b}$: $\sigma_0 / 2$

  Free fit parameter of AAMQS fits:

  \[
  \frac{\sigma_0}{2} = 16.5 \text{ mb}
  \]

- $K$-factor: not the result of any calculation. May account for:
  - Higher order corrections
  - Non-perturbative effects
  - (...)
Multiple scattering: eikonal model

- Our approach:
  Monte-Carlo implementation of

  Hybrid formalism + Multiple parton scattering
Multiple scattering: eikonal model

- Number of **independent** hard scatterings according to Poisson probability distribution of mean $n$, where:

$$n(b, s) = T_{pp}(b) \sigma_{DHJ}(s)$$
Multiple scattering: eikonal model

- Number of **independent** hard scatterings according to Poisson probability distribution of mean $n$, where:

$$n(b, s) = T_{pp}(b)\sigma_{DHJ}(s)$$

- $b$ randomly generated between 0 and $b_{max}$:

$$b_{max} = \sqrt{\frac{\sigma_{nd}}{\pi}}$$

- Spatial overlap: convolution of two Gaussians.

$$T_{pp}(b) = \frac{1}{4\pi B} \exp\left(-\frac{b^2}{4B}\right)$$
Multiple scattering: eikonal model

- Number of **independent** hard scatterings according to Poisson probability distribution of mean $n$, where:

$$n(b, s) = T_{pp}(b)\sigma_{DHJ}(s)$$

- $b$ randomly generated between 0 and $b_{max}$:

$$b_{max} = \sqrt{\frac{\sigma_{nd}}{\pi}}$$

- For a nuclear target of mass number $A$:

$$T_{pA}(b) = \frac{1}{\pi R_p^2 (A^{2/3} + 1)} \exp\left(\frac{-b^2}{R_p^2 (A^{2/3} + 1)}\right)$$

$$R_A^2 = R_p^2 A^{2/3}$$
Hadronization: Lund fragmentation model

- Simple but powerful picture of hadron production based on the breaking of strings between partons:

- Probability of string breaking by quark pair with $m_\perp^2 = m_q^2 + p_\perp q^2$:

\[
\text{Prob}(m_q^2, p_\perp q^2) \propto \exp \left( \frac{-\pi m_q^2}{\kappa} \right) \exp \left( \frac{-\pi p_\perp q^2}{\kappa} \right)
\]

As implemented in: PYTHIA 8
Hadronization: Lund fragmentation model

- Simple but powerful picture of hadron production based on the breaking of strings between partons:

- Probability of string breaking by quark pair with \( m^2_{\perp} = m^2_q + p^2_{\perp q} \):

\[
\text{Prob}(m^2_q, p^2_{\perp q}) \propto \exp\left(-\frac{\pi m^2_q}{\kappa}\right) \exp\left(-\frac{\pi p^2_{\perp q}}{\kappa}\right)
\]

- Lund fragmentation function:

\[
f(z) \propto \frac{1}{z} (1 - z)^a \exp\left(-\frac{b \left(m^2_h + p^2_{\perp h}\right)}{z}\right)
\]

As implemented in: PYTHIA 8
3. Results
RHIC: d-Au @ 200 GeV

- Forward spectra observed at RHIC allows for a description in terms of CGC:

\[ \sqrt{s} = 200 \text{ GeV} \]

\[ 1 < p_t < 2 \text{ GeV} \]

\[ 3.2 < y < 3.4 \]

\[ x_p \sim 10^{-1} \]

\[ x_t \sim 10^{-4} \]
Forward particle production in the Color Glass Condensate

• Previous approaches:

\[
\frac{d\sigma^{hadrons}}{d^2 k_{\perp} dy} = \frac{d\sigma^{partons}}{d^2 k_{\perp} dy} \otimes D_{h/p}
\]

RHIC: d-Au @ 200 GeV

- Our approach:
  Monte-Carlo implementation of

  Hybrid formalism + Lund string fragmentation

As implemented in: PYTHIA 8
• Increment of evolution rapidity with respect to RHIC: \( \Delta Y \sim \ln \left( \frac{x_0}{x} \right) \sim 14 \)
• Only difference with respect to RHIC set: dynamical evolution of uGD’s according to rcBK equation.
- Similar situation that in the proton-proton case.
- Plenty of room for improvement in the proton-nucleus implementation.
- Low momentum region well described.
LHCf: nuclear modification factor $R_{p-Pb} @ 5.02$ TeV

- Approximate constant flat suppression of: $0.15 \approx 1/\langle N_{coll} \rangle$
LHCf: nuclear modification factor $R^{\pi^0}_{p-Pb} @ 5.02$ TeV

$R^{\pi^0}_{p-Pb} \equiv \frac{1}{\langle N_{coll} \rangle} \frac{dN_{pPb\rightarrow\pi^0 X}/dyd^2p_t}{dN_{pp\rightarrow\pi^0 X}/dyd^2p_t}$

- Approximate constant flat suppression of: $0.15 \approx 1/\langle N_{coll} \rangle$

This behavior can be understood as a direct consequence of the behavior of the ratios of the uGD’s:
4. Conclusions, future prospects
Conclusions, future prospects

- We achieve a good description of single inclusive spectra of charged particles and neutral pions at RHIC and the LHC respectively, and nuclear modification factors for proton-lead collisions at the LHC.

  This adds evidence to the idea that the main properties of forward data are dominated by the saturation effects encoded in the unintegrated gluon distribution of the target.
Conclusions, future prospects

• We achieve a good description of single inclusive spectra of charged particles and neutral pions at RHIC and the LHC respectively, and nuclear modification factors for proton-lead collisions at the LHC.

  This adds evidence to the idea that the main properties of forward data are dominated by the saturation effects encoded in the unintegrated gluon distribution of the target.

• Our approach allows for a description of spectra at the smaller values of transverse momentum.

  Opens the door for a calculation of particle multiplicities and other soft observables.
Conclusions, future prospects

- We achieve a good description of single inclusive spectra of charged particles and neutral pions at RHIC and the LHC respectively, and nuclear modification factors for proton-lead collisions at the LHC.

This adds evidence to the idea that the **main properties of forward data are dominated by the saturation effects** encoded in the unintegrated gluon distribution of the target

- Our approach allows for a **description of spectra at the smaller values of transverse momentum**

  Opens the door for a calculation of particle **multiplicities** and other soft observables

- Forward particle production is of key importance in the development of air showers

  **Theoretically controlled extrapolation of our results to the scale of ultra-high energy cosmic rays**, thus serving as starting point for future works on this topic
Conclusions, future prospects

- We achieve a good description of single inclusive spectra of charged particles and neutral pions at RHIC and the LHC respectively, and nuclear modification factors for proton-lead collisions at the LHC. This adds evidence to the idea that the main properties of forward data are dominated by the saturation effects encoded in the unintegrated gluon distribution of the target.

- Our approach allows for a description of spectra at the smaller values of transverse momentum. Opens the door for a calculation of particle multiplicities and other soft observables.

- Forward particle production is of key importance in the development of air showers. Theoretically controlled extrapolation of our results to the scale of ultra-high energy cosmic rays, thus serving as starting point for future works on this topic.

- There is still a lot of room for improvement! (NLO corrections, proper Monte-carlo implementation of proton-nucleus, etc.)
* Back-up
Perturbative parton production: implementation of DHJ formula

- **Degree of accuracy of our approach:**
  - DHJ formula \(\rightarrow\) leading logarithmic (LL)
  - Scale dependence of PDF’s \(\rightarrow\) LO DGLAP evolution
  - Scale dependence of UGD’s \(\rightarrow\) rc-BK evolution

- **State-of-the-art degree of accuracy:**
  - DHJ formula \(\rightarrow\) NLO\(^1,2\)
  - Scale dependence of PDF’s \(\rightarrow\) DGLAP NNLO\(^3\)
  - Scale dependence of UGD’s \(\rightarrow\) BK NLO\(^4,5\)

---

• LO BK equation resumming $\alpha_s \ln(1/x)$ contributions to all orders:

$$\frac{\partial \mathcal{N}(r, Y)}{\partial Y} = \int dr_1 K^{\text{LO}}(r, r_1, r_2)$$

$$\times [\mathcal{N}(r_1, Y) + \mathcal{N}(r_2, Y) - \mathcal{N}(r, Y) - \mathcal{N}(r_1, Y) \mathcal{N}(r_2, Y)]$$

**LO Evolution Kernel:**

$$K^{\text{LO}}(r, r_1, r_2) = \frac{N_c \alpha_s}{2\pi^2} \frac{r^2}{r_1^2 r_2^2}$$
**BACK-UP: BK equation with running coupling**

- **LO BK equation resumming** $\alpha_s \ln (1/x)$ **contributions to all orders:**

  \[
  \frac{\partial N(r, Y)}{\partial Y} = \int dr_1 K^{\text{LO}}(r, r_1, r_2) \times \left[ N(r_1, Y) + N(r_2, Y) - N(r, Y) - N(r_1, Y)N(r_2, Y) \right]
  \]

  **LO Evolution Kernel:**

  \[
  K^{\text{LO}}(r, r_1, r_2) = \frac{N_c \alpha_s}{2\pi^2} \frac{r^2}{r_1^2 r_2^2}
  \]

- **Considering** $\alpha_s N_f$ **corrections:**

  - Running coupling: chains of quark loops
  - Emission of $q\bar{q}$ pair (instead of a gluon)

  \[
  \frac{\partial N(r, Y)}{\partial Y} = R[N] - S[N]
  \]

  Running coupling term: gathers all the $\alpha_s N_f$ factors that complete the $\beta$-function.

\[\text{(According to some separation scheme)}\]
BACK-UP: BK equation with running coupling

- LO BK equation resumming \( \alpha_s \ln(1/x) \) contributions to all orders:

\[
\frac{\partial N(r, Y)}{\partial Y} = \int dr_1 K^{\text{LO}}(r, r_1, r_2) \times [N(r_1, Y) + N(r_2, Y) - N(r, Y) - N(r_1, Y)N(r_2, Y)]
\]

**Small-x gluon emission**

**LO Evolution Kernel:**

\[
K^{\text{LO}}(r, r_1, r_2) = \frac{N_c \alpha_s}{2\pi^2} \frac{r^2}{r_1^2 r_2^2}
\]

(According to some separation scheme)

- Considering \( \alpha_s N_f \) corrections:

Running coupling: chains of quark loops

Emission of \( q\bar{q} \) pair (instead of a gluon)

\[
\frac{\partial N(r, Y)}{\partial Y} = \mathcal{R}[N] - S[N]
\]

Running coupling term: gathers all the \( \alpha_s N_f \) factors that complete the \( \beta \)-function

- Numerical evaluation of subtraction term \( S[N] \) demands very large computing time.

  "We only consider the running term \( \mathcal{R}[N] \) (prescription proposed by Balitsky\(^1\))"

**Running coupling Kernel:**

\[
K^{\text{Bal}}(r, r_1, r_2) = \frac{N_c \alpha_s(r^2)}{2\pi^2} \left[ \frac{r^2}{r_1^2 r_2^2} + \frac{1}{r_1^2} \left( \frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1 \right) + \frac{1}{r_2^2} \left( \frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1 \right) \right]
\]

---


---

Pablo Guerrero Rodríguez (UGR)  
UF production from CGC+Lund  
March 23, 2017  
47/42
• Dipole models are simple formulations for the description of Deep Inelastic Scattering processes (such as those observed in e-p collisions at HERA).

• We describe the effect of the small-x gluon field over the projectile as the multiple gluon exchange with a virtual quark-antiquark dipole.
Dipole models are simple formulations for the description of Deep Inelastic Scattering processes (such as those observed in e-p collisions at HERA).

We describe the effect of the small-x gluon field over the projectile as the multiple gluon exchange with a virtual quark-antiquark dipole.

Multiple gluon scattering in the eikonal approximation: definition of WILSON LINES:

\[ U(x_\perp) = \mathcal{P} \exp \left[ ig \int dx^- A^+(x^-, x_\perp) \right] \]
BACK-UP: Dipole models, Wilson lines

\[ U(x_\perp) = \mathcal{P} \exp \left[ ig \int dx^- A^+(x^-, x_\perp) \right] \]

- Dipole scattering amplitudes: two-point correlators of Wilson Lines:
\[ \mathcal{N}(\mathbf{r}, \mathbf{b}, x) = 1 - \frac{1}{N_c} \langle \text{tr}\{ U(x_{1\perp}) U^\dagger(x_{2\perp}) \} \rangle_x \]

- Unintegrated gluon distributions (uGD’s) defined as the Fourier transform of dipole scattering amplitude. We take the uGD’s as universal objects that represent the effect of gluon-saturated target over hadronic projectiles.
**BACK-UP: Dipole models, Wilson lines**

\[
U(x_\perp) = \mathcal{P} \exp \left[ i g \int dx^- A^+(x^-, x_\perp) \right]
\]

- Dipole scattering amplitudes: two-point correlators of Wilson Lines:

\[
\mathcal{N}(r, b, x) = 1 - \frac{1}{N_c} \langle \text{tr} \{ U(x_1\perp) U^\dagger(x_2\perp) \} \rangle_x
\]

- Unintegrated gluon distributions (uGD’s) defined as the Fourier transform of dipole scattering amplitude. We take the uGD’s as universal objects that represent the effect of gluon-saturated target over hadronic projectiles.

- Phenomenological models \(\rightarrow\) **modelization of dipole scattering amplitude**

  For example: GBW model\(^1\)

\[
\mathcal{N}(r, b, x) = \theta(b_0 - b)(1 - \exp(-r^2Q_s^2/4))
\]
Dipole scattering amplitudes: two-point correlators of Wilson Lines:

\[ U(x_{\perp}) = \mathcal{P} \exp \left[ ig \int d^{-1}x A^+(x^-, x_{\perp}) \right] \]

- Dipole scattering amplitudes: two-point correlators of Wilson Lines:

\[ \mathcal{N}(r, b, x) = 1 - \frac{1}{N_c} \langle \text{tr} \{ U(x_{1\perp}) U^\dagger(x_{2\perp}) \} \rangle x \]

- Unintegrated gluon distributions (uGD’s) defined as the Fourier transform of dipole scattering amplitude. We take the uGD’s as universal objects that represent the effect of gluon-saturated target over hadronic projectiles.

- Phenomenological models → modelization of dipole scattering amplitude

For example: GBW model\(^1\)

\[ \mathcal{N}(r, b, x) = \theta(b_0 - b)(1 - \exp(-r^2 Q_s^2/4)) \]

- Small-x evolution encoded in BK equation

**Theoretically controlled tool for extrapolation!**

---

BACK-UP: Model of baryon production in Lund formalism

- **Diquark model**: diquarks in color antitriplets are (effectively) fundamental objects of the theory → diquark-antidiquarks fluctuations are an additional string breaking mechanism.

- **Popcorn model**: Quarks are the only fundamental objects. This model allows for the generation of intermediate mesons.

1. \( \bar{q} \ q \ q \ q \)
2. \( \bar{q} \ q \ q \ q \ q \ q \)
3. \( \bar{q} \ q \ q \ q \ \bar{q}' q' \ q \ q \)

Intermediate meson
**BACK-UP: Model of baryon production in Lund formalism**

- **Diquark model:** diquarks in color antitriplets are (effectively) fundamental objects of the theory. Diquark-antidiquarks fluctuations are an additional string breaking mechanism.

- **Popcorn model:** Quarks are the only fundamental objects. This model allows for the generation of intermediate mesons.

1. **Diquark model**
   - Diquark model: diquarks in color antitriplets are (effectively) fundamental objects of the theory. Diquark-antidiquarks fluctuations are an additional string breaking mechanism.

2. **Popcorn model**
   - Popcorn model: Quarks are the only fundamental objects. This model allows for the generation of intermediate mesons.

3. **Intermediate meson**
   - Intermediate meson

**Diagram:**
- Advanced popcorn ON
- Advanced popcorn OFF
- LHCf π₀ production data: 9.4<y<9.6
- K=1
- Softer neutral pion spectra

**Legend:**
- LHCf π₀ production data: 9.4<y<9.6
- K=1
- Softer neutral pion spectra
Good agreement with data in the whole $p_t$ range with $K = 1$ (except for data measured at STAR).

CGC + Lund approach allows to reach $p_t$ values as low as detected experimentally, $p_t \sim 0.2 \text{ GeV}$
Multiplicities in p-p collisions: TOTEM data (sneak peek)

- Good reproduction of charged hadron multiplicity for high rapidities
Feynman scaling: LHCf (preliminary) data (sneak peek)

- Model reproduces Feynman scaling
Feynman scaling: LHCf (preliminary) data (sneak peek)

- Model reproduces Feynman scaling
Nucleus-nucleus collisions: early results (sneak peek)
• CGC + Lund approach allows to reach $p_t$ values as low as detected experimentally, $p_t \sim 0.2$ GeV.
• Little sensibility to number of participants,
• BRAHMS data well described with $K = 1$.
• STAR data well described with $K = 0.4$ (also observed in previous analysis of data).