Particle multiplicities from CGC with local rcBK evolution in high-energy hadronic collisions at RHIC/LHC

H. Fujii\textsuperscript{1}, K. Itakura\textsuperscript{2}, Y. Kitadono\textsuperscript{2}, Y. Nara\textsuperscript{3}

(\textsuperscript{1}U Tokyo, \textsuperscript{2}KEK, \textsuperscript{3}Akita Int’l U)

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Particle productions at collider energies

- dominated by small-$x$ dof in hadrons
- BK evolution eqn for CGC sums $(\alpha_s \ln(1/x))^n$ and incorporates nonlinear effects
  $\Rightarrow$ saturation scale, $Q_s^2(x)$

- Successful phenomenology based on CGC picture in last decade
  - DIS at HERA (GBW, IIM, ...)
  - HIC at RHIC (KLN, ...)

- Recent highlight: running coupling (rc) BK eqn
  consistent with $Q_s^2(x) \sim 1/x^\lambda \sim 1/x^{0.3}$

- Applications of rcBK:
  - Global analysis of DIS  AAMQS, previous talk
  - Hadronic collisions, pp, pA and AA  Albacete, Albacete-Marquet, Albacete-Dumitru

**This work (in progress)**

To develop MC-DHJ formalism with the rcBK,
aiming at forward physics in pA (AA) at RHIC and LHC, cosmic ray reactions
rcBK eqn in Balitsky’s prescription:

\[
\frac{\partial N(r, y)}{\partial y} = \int d^2 r_1 K^{\text{run}}(r, r_1, r_2) \left[ N(r_1, y) + N(r_2, y) - N(r, y) - N(r_1, y)N(r_2, y) \right]
\]

- has the same structure as LO eqn with modified kernel:

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

where one-loop \( \alpha_s(r) = 1/[b_0 \ln(4C^2/r^2)] \) is cut off at \( \alpha_{\text{cut}} = 1.0 \)
- The initial condition at \( x = x_0 \) is assumed

\[
N(r, y_0) = 1 - \exp \left[ -\frac{r^2 Q_{s0}^2}{4} \gamma \ln \left( \frac{1}{\Lambda r} + e \right) \right]
\]
Framework II: hadronic collisions

\[ \frac{d\sigma^{A+B\to g}}{dy d^2p_T d^2X} \sim K \frac{\alpha_s}{p_T^2} \phi(k_1, x_1, b) \otimes \phi(k_2, x_2, X - b) \]

- is proved for pp, pA at LO, but is a working assumption for AA
- \( \phi(k, x) \propto k^2 \) F.T. \( \mathcal{N}_G(r, x) \) is the unintegrated gluon dist in the hadron.
- \( \mathcal{N}_G = 2\mathcal{N} - \mathcal{N}^2 \), with \( \mathcal{N} \) constrained by DIS
- \( \mathcal{N} \) in a nucleus requires a modeling for a nucleus
MC modeling for a nucleus:

- The simplest will be a homogeneous disk
  no impact parameter dependence
  an additional parameter $Q_{s0A}^2$ needed

- Random nucleons w/ Woods-Saxon dist.
  fluctuating density $\Rightarrow b$-dependence
  $Q_{s0A}^2 = Q_{s0p}^2 \times N$ w/o additional parameter

Drescher-Nara
MC-KT model

- **MC-KT/rcBK** = $k_T$ factorization formalism with $\phi$ obtained from rcBK evolution locally on transverse plane of a Monte-Carlo-generated nucleus
- applied at LHC

HF, K. Itakura, Y. Kitadono, Y. Nara  Particle multiplicity from CGC
Framework III: forward particle production

For pA or "Large-\(x\) – small-\(x\)" reactions: Dumitru-Hayashigaki-Jalilian-Marian (DHJ)

**DHJ factorization form**

\[
\frac{dN}{dy_h d^2p_T} = \frac{K}{(2\pi)^2} \sum_i \int_1^{x_F} \frac{dz}{z^2} \frac{d^2}{dz} \frac{1}{x_1} f_{i/p}(x_1, p_T^2) \bar{N} \left( \frac{p_T}{z}, x_2 \right) D_{h/i}(z, p_T^2),
\]

where the PDF \(f_{i/p}\) describes the large-\(x\), \(N\) the small-\(x\), and the FF \(D_{h/i}\) describes high-\(p_T\) fragmentation.

applied successfully to pA collisions, with rcBK solution for a homogeneous nucleus characterised by an effective scale \(Q_{sA}^2\) Albacete-Marquet
## Framework III': forward particle production

### State-of-the-art models w/ rcBK
- **AAMQS**: ep @ HERA ... rcBK works and strongly constrains “MV” I.C.
- **AM**: pAu @ RHIC ... DHJ/rcBK nicely works
- **AD**: AA @ LHC ...... MC-KT/rcBK nicely works

Combining these aspects: HF-Itakura-Kitadono-Nara

### MC-DHJ/rcBK model
- Initial configuration of the nucleus is prepared w/ Monte-Carlo
- rcBK performed **locally** on transverse plane w/ $Q^2_{sA}(x_0) = Q^2_{sp}(x_0) \times N$
  - no additional parameter
- Study various aspects of the forward physics in DHJ formalism
- Status report to this goal

HF, K. Itakura, Y. Kitadono, Y. Nara  Particle multiplicity from CGC
The first result of MC-DHJ/rcBK

- this preliminary result (parameter sets: MV and h’) fits data very well
- $Q^2_{s0A}$ fixed by MC; no free parameter besides $K$
- MV gives slightly harder spectrum at $\eta = 2.2$, but no difference at $\eta = 3.2, 4.0$
Initial condition for rcBK

- Adopted I.C. at $x_0 = 0.01$:

$$\mathcal{N}(r, x_0) = 1 - \exp\left[-\frac{(r^2 Q^2 s_0)}{4} \ln \left(\frac{1}{\Lambda r} + e\right)\right]$$

<table>
<thead>
<tr>
<th></th>
<th>$\gamma$</th>
<th>$Q^2_{s0A}$</th>
<th>$C$</th>
<th>$\Lambda$</th>
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<td>MV</td>
<td>1.0</td>
<td>0.2</td>
<td>1.0</td>
<td>0.2</td>
</tr>
<tr>
<td>h'</td>
<td>1.119</td>
<td>0.168</td>
<td>1.715</td>
<td>0.241</td>
</tr>
</tbody>
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N.B.: for a larger $\gamma \mathcal{N}(k)$ has negative values.

- Another possible I.C.: running coupling (rc) MV

$$\mathcal{N}(r, x_0) = \frac{\alpha_s(\mu)}{\alpha_s(r)} \left(1 - \exp\left[-\frac{r^2 Q^2_A}{4}\right]\right)$$

N.B. $Q^2_A$ is not tuned, but fixed $Q^2_s = Q^2_A \ln(Q^2_s/\Lambda^2)$
To my surprise, rcMV also does a good job (preliminary)
DHJ marginally describes pp @ RHIC at the same $K$ as dA
MV does a better job among three (preliminary)
Summary

- The $rcBK$ eqn provides a useful tool for phenomenology. $rcBK$ for DIS, MC-KT/$rcBK$ for $pp/AA$, DHJ/$rcBK$ for $pA$

- Combining the above, we optimized our description for $pA$: $MC-DHJ/rc-BK$

- $MC-DHJ/rcBK$ fits the forward data nicely

- New possibility for I.C. – $rcMV$ – is proposed

Outlook:
- More analyses on forward physics at RHIC to be done
- Applications to forward physics at LHC and in cosmic ray
- see an example -
Hadron productions ($\pi^0, K^0$ and $n$) at $\eta = 8.5$ at 7 TeV (LHCf) is being studied.