$R_{pA}$ for single hadron production

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Outline

✧ What do we know?
✧ What we want to know?
✧ What we expect to see?
✧ What could be surprises?
✧ What …

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What do we know?

- **Cronin effect:**

\[ p + A \rightarrow \text{hadron}(p) + X \]

Fermilab fixed target with a proton beam of energy: 200, 300, 400 GeV

\[
E \frac{d\sigma^{hA}}{d^3p} \equiv E \frac{d\sigma^{hN}}{d^3p} A^\alpha(p)
\]

If \( R_{pA} \equiv E \frac{d\sigma^{hA}}{d^3p} / \left( A \times E \frac{d\sigma^{hN}}{d^3p} \right) \)

\[
\alpha(p) = 1 + \frac{\ln(R_{pA})}{\ln(A)} \approx 1 + \frac{\ln(R_{pA})}{A^{1/3}}
\]
What do we know?

Jet quenching at RHIC:

\[ R_{AB} = \frac{dN_{AB}}{dp_T d\eta} \frac{T_{AB} d\sigma_{pp}}{d\sigma_{pp}} \]

\( X > 0.01 \)
What do we know?

- Jet quenching at LHC: \[ A + A \rightarrow \text{hadron}(p) + X \]

- Stronger suppression than RHIC
- Change slope at large \( p_T \)
- Any cold medium effect?

\[ X \sim 0.1 \]
\[ X \sim 0.01 \]
What we want to know?

- **p-Pb as a benchmark for Pb-Pb at LHC:**
  - Calibration of probes – hadronic vs electroweak (e.g. $Z^0$ in p-Pb)
  - Initial condition for Pb-Pb collisions – influence on QGP formation?

- **p-Pb as a laboratory for quark-gluon nuclear physics:**
  - Nuclear parton distribution functions?
  - Coherent and incoherent QCD multiple scattering?
  - Low x physics – saturation, CGC, …

*Salgado et al.*
*J. Phys. G 2012*
What we expect to see?

- How is the high $p_T$ single hadron produced in p-Pb?
  - Every parton can participate in the hadronic collisions

$$d\sigma_{ppb} \propto \frac{1}{p_T} \left( \sum_{a/b \rightarrow c} \sigma_{LP}^{ab} \otimes f_{a/p} \otimes f_{b/Pb} \otimes D_{h/c} + \frac{Q_s^2}{p_T^2} \sigma_{NLP}^{ab} \otimes f_{a/p} \otimes T_{b/Pb}^{(4)} \otimes D_{h/c} \right) + \ldots$$

  - Collinear factorization – power expansion if $Q_s \ll p_T$

- If $Q_s \sim p_T >> \Lambda_{QCD}$, entering the saturation regime
  - Every term is equally important!
What we expect to see?

- **Single hard scattering – not too small x**
  - probes local parton densities
  - QCD dynamics – pQCD factorization
  - weak difference on target size

- **Independent/incoherent multiple scattering**
  - probes parton densities
    - at different impact parameters
  - changes the distribution, not total rate

- **Coherent hard multiple scatterings**
  - changes production rate
  - no additional scale – power suppressed
  - probe multiparton correlations
Nuclear parton distribution functions

- **Definition** – same operators as proton PDFs:

\[
\phi_{q/h}(x, Q) = \int \frac{dy^-}{4\pi} e^{+ixp^+y^-} \langle p|\overline{\psi}_q(0)\gamma^+U_n(0, y^-)\psi_q(y^-)|p\rangle
\]

\[
\phi_{q/A}(x, Q) = \int \frac{dy^-}{4\pi} e^{+ixp^+y^-} \langle P_A|\overline{\psi}_q(0)\gamma^+U_n(0, y^-)\psi_q(y^-)|P_A\rangle
\]

- ✦ **Same operators ⇔ Same evolution equations**
- ✦ **DGLAP evolution for nPDFs at the leading power**
- ✦ **All nuclear A-dependence from the input distributions at Q_0**
What DGLAP told us?

- No saturation:

Saturation of the ratio $\neq$ saturation of PDFs!

Nuclear gluon distributions and sea quark distributions grow as fast as that of proton at small $x$!

Need data at small-$x$!
Factorization and evolution

- **DGLAP evolution:**
  - Resum collinear (CO) logarithms: 
    \[ \ln^n \left( k_\perp^2 \right) \Rightarrow \frac{\partial G(x, \mu)}{\partial \ln(\mu)} \]
  - Evolution kernel: 
    \[ \propto \frac{dx'}{x'} \] Responsible for the growth at small-x
  - CO and UV are equivalent at leading power: DGLAP = RG

- **BFKL evolution:**
  - Resum: 
    \[ \ln \left( \frac{1}{x} \right)^n \Rightarrow \frac{\partial G(x, \mu)}{\partial \ln \left( \frac{1}{x} \right)} \]
  - Evolution kernel: 
    \[ \propto \frac{dk_\perp^2}{k_\perp^2} \]
  - BFKL is not a RG equation
When leading power QCD fails?

- Parton’s transverse momentum at the hard collision:
  - is not equal to $1/fm$ – typical scale in hadron wave function
  - Gluon shower from both initial state and final-state partons, and soft interaction between them can all change the $p_T$

$$\langle k_T^2 \rangle \propto \Lambda^2_{QCD} \left[ \ln(Q^2/\Lambda^2_{QCD}) \right] \ln(S/Q^2)$$

$$\rightarrow 2 \Lambda^2_{QCD} \left[ \ln(Q^2/\Lambda^2_{QCD}) \right] \ln(1/x) \propto 1/x^{1/3}$$

Leading power collinear factorization fails if $\langle k_T^2 \rangle \sim Q^2$

- Parton recombination at the same impact parameter:

Saturation scale:

$$Q_s(x) \propto A^{1/3} x G(x)$$

$$\propto \frac{A^{1/3}}{x^\lambda}$$
Recombination – nonlinear evolution

- Recombination of gluon at the same impact parameter:

- Factorization of collinear divergences: Gribov, Levin, Ryskin, 1983
  Mueller, Qiu, 1986

\[
\frac{\partial^2 xG(x, Q^2)}{\partial \ln(1/x) \partial \ln(Q^2)} = \frac{3\alpha_s}{\pi} xG(x, Q^2) - \frac{3\alpha_s^2}{\pi^2 R^2 Q^2} [xG(x, Q^2)]^2
\]

- A dynamical scale: \( Q_s(x)^2 = \frac{\alpha_s}{\pi R^2} xG(x, Q^2) \rightarrow 1/x^\lambda \)

- Question: high order and high power?

- Recombination in dipole model – BK equation: Balitsky, 1996
  Kovchegov, 1999

\[
\frac{\partial N(x, k^2)}{\partial \ln(1/x)} = \alpha_s K_{\text{BFKL}} \otimes N(x, k^2) - \alpha_s [N(x, k^2)]^2
\]

- Exact in the large \( N_c \) limit within dipole model
Negative gluon density at low Q?

- DGLAP evolution leads to negative gluon density at low Q.

- QCD resummation leads to small gluon density at low Q.

**Does it mean that we have no gluon for \( x < 10^{-3} \) at 1 GeV?**

**No!**

Gluon recombination slows down small-\( x \) evolution.
Role of recombination effect

Leading order power correction

\[
\frac{\partial \phi(x, \mu^2)}{\partial \ln \mu^2} = P(x) \otimes \phi(x, \mu^2) - \frac{1}{\mu^2} \rho(x, \mu^2)
\]

\[
\int \frac{\mu^2}{\mu_0^2} \frac{d \ln \mu^2}{\mu^2} = \frac{1}{\mu_0^2} - \frac{1}{\mu^2} \rightarrow \frac{1}{\mu_0^2} \text{ as } \mu \rightarrow \infty
\]

Power correction can build up a big effect to low \(Q^2\) distribution

 Corrections to nPDFs do not go away as \(1/\mu^2\)!

What about higher power corrections?

Qiu, 1987
Color glass condensate approach

- An effective theory approach:
  Integrate out large x partons into effective color density,
  **McLerran-Venugopalan Model**

- Small-x gluons:
  Effectively given by the classical field $A[\rho]$ that is radiated by fast partons ($x' > x$) having a color charge density

- Large-x partons – charge density $\rho$:
  Effectively frozen (time dilation) in some random configurations and have the probability charge distribution, $W_Y[\rho]$.

- JIMWLK equation:
  \[
  \frac{\partial W_Y[\rho]}{\partial Y} = -H \left[ \rho, \frac{\delta}{\delta \rho} \right] W_Y[\rho]
  \]
  Lower x, more phase space for fast partons and their radiation
How to “see” the saturation?

“Phase diagram” for the gluon “density”:

Proton is dilute enough:

Use nuclear target - $A^{1/3}$ enhancement!
QCD collinear factorization:

A^{1/3}-enhanced power correction is factorizable!

Coherent multiple scattering at 1/p_T

resummation of \( \left( \alpha_s \frac{A^{1/3}}{p_T^2} \right)^n \)

- shift in x, small if \( p_T \gg Q_s \)
- important for steep falling distribution

Multiple scattering during hadronization

resummation of \( \left( \alpha_s \frac{A^{1/3}}{Q_s^2} \right)^n \)

- shift in z
- effective energy loss – but, not relevant for jet production!

Initial-state shower (Sudakov type) – broadening

nPDFs entering the resummation formalism – Thursday’s talk on Z^0
“Shadowing” from power corrections

- Nuclear shadowing = nPDFs + power corrections:

\[ x_B^N \left[ (-1)^N \frac{1}{N!} \frac{d^N}{dx^N} \delta(x - x_B) \right] \]

\[ F_T(x_B, Q^2) = \sum_{n=0}^{N} \frac{1}{n!} \left[ \frac{\xi^2}{Q^2} \left( A^{1/3} - 1 \right) \right]^n x_B^n \frac{d^n}{dx^n} F_T^{(0)}(x_B, Q^2) \]

\[ \approx F_T^{(0)}(x_B(1 + \Delta), Q^2) \]

\[ \Delta \equiv \frac{\xi^2}{Q^2} \left( A^{1/3} - 1 \right) \]

\[ \xi^2 = \frac{3\pi\alpha_s}{8R^2} \langle F^+F_\alpha^+ \rangle = 0.09 - 0.12 \text{ GeV}^2 \]

- Maximum power corrections
- Neglect shadowing from nPDFs
**R_{pA} of single hadron production – RHIC**

- **Power corrections to the hard part:**

  - Keep t-channel only – dominates the forward region
  - Same x-shift from inclusive DIS
  - Large pT suppression from “energy loss” – important for RHIC energy
  - Initial-state shower is less important at RHIC – edge of phase space

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Qiu, Vitev, 2006
\(R_{pA}\) of single hadron production – LHC

- Numerical predictions are not quite ready yet
- Coherent multiple scattering at short-distance
  
  \[
  \text{resummation of } \left( \alpha_s \frac{A^{1/3}}{p_T^2} \right)^n
  \]
  
  – Smaller than RHIC – larger \(p_T\)
- Multiple scattering during hadronization
  
  \[
  \text{resummation of } \left( \alpha_s \frac{A^{1/3}}{Q_s^2} \right)^n
  \]
  
  – Smaller effect due to smaller effective \(z\)
- Initial-state shower (Sudakov type) – broadening
  
  – Bigger effect due to a larger phase space for shower (at small \(p_T\))
  
  – Suppression from nPDFs at \(\mu = 1/b\), when \(b\) is sufficiently large

Should see more suppression in the forward region!
pA @ LHC should have a rich physics program to explore QCD nonlinear dynamics and coherence

Single hadron production in pA at LHC should be suppressed, but not as much as forward dAu at RHIC

More suppression is expected for single hadron production in the forward region

Suppression should be smaller for single jet production at the same parent parton energy

What the data will tell us?

Thank you!