Quark production in pA collisions

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1. VALENCE QUARKS

- Perturbative mechanism to generate a net baryon number transfer along a large rapidity gap: BARYON STOPPING.

2. SEA QUARKS  PRELIMINARY!!

- Determination of ‘cold nuclear'/saturation effects in quark production.
- In high energy nuclear collisions it is a 2 scale problem.

\[ m_{charm}^2 \sim Q_s^2(RHIC) \sim 2 \text{ GeV} \]
General Features

- The calculation is done in the light-cone gauge of the proton, $A^+=0$ using light-cone perturbation theory (time-ordered diagrams).

- Nuclear effects become manifest in the form of multiple rescatterings.

- Eikonal approximation: Recoil of energetic quarks and gluons in their interaction with the nucleus is neglected. Coordinate Space.

- Quasi-classical approximation: no more than 2 exchanged gluons per nucleon: resummation parameter: $\alpha_s^2A^{1/3}$ (McLerran-Venugopalan model).

- Quantum Evolution: The emission of extra soft gluons is enhanced by are resummed to all orders at leading logarithmic accuracy and in the large-$N_c$ limit (mean field approximation).
Small-x valence quarks

- **BARYON STOPPING**: Transfer of net baryon number along a large rapidity gap (from forward to the central rapidity regions).

- So far this phenomenon has been mainly approached in non-perturbative models for particle production (string junction models, gluonic mechanism).

  Perturbative approach:
  - Valence quarks are carriers of baryon number
  - Quasi-classical approximation (Cronin enhancement)
  - Quantum evolution (Suppression of Cronin enhancement)

Emission from the proton

The relevant diagrams in the high energy limit are:

\[
\frac{d\sigma}{dyd^2k} = \frac{d\sigma^a}{dyd^2k} + \frac{d\sigma^b}{dyd^2k}.
\]

\[
\frac{d\sigma^a}{d^2k dy} = \frac{1}{(2\pi)^2} \int d^2x d^2y d^2z e^{i k (x-y)} \frac{dn^q}{d^2z dy} \times \text{eikonal rescatterings}
\]

\[
\frac{dn^{\text{quark}}}{d^2z dy} = \frac{\tilde{\alpha}_s \alpha_1}{2\pi} \frac{(x-z) \cdot (y-z)}{(x-z)^2(y-z)^2}
\]

\[
[e^{-(x-y)^2 Q_{sq}^2/4} - e^{-x^2 Q_{sq}^2/4} - e^{-y^2 Q_{sq}^2/4} + 1]
\]

\[
Q_{sq \text{quark}} = \frac{4\pi \alpha_s^2 C_F}{N} T_A(b) \rho \ln \frac{1}{|x| \Lambda}
\]
Emission from the nucleus

\[
\frac{d\sigma^b}{d^2k\,dy} = \frac{1}{(2\pi)^2} \int d^2x\,d^2y\,d^2z \, e^{ik(x-y)} \frac{dn^g}{d^2z\,dy} \times \text{eikonal rescatterings}
\]

\[
\frac{dn^{\text{gluon}}}{d^2z\,dy} = \frac{\bar{\alpha}_s}{\pi} \frac{(x-z) \cdot (y-z)}{(x-z)^2(y-z)^2},
\]

\[
\hat{V}(x, y) = N\rho \int d^2l\,e^{i\cdot(l\cdot(x-y))} \frac{d\sigma^{G\rightarrow qG}}{d^2l}
\]

\[
\int_0^L du \, e^{-(x-y)^2Q_{sq}^2u/4L} \, \hat{V}(x, y) \, e^{-(x-y)^2Q_{sq}^2(L-u)/4L}
\]
Quasi-classical approximation

Final result

\[
\frac{d\sigma_{pA}^{qA}}{d^2k \, dy} = \frac{d\sigma^a}{d^2k \, dy} + \frac{d\sigma^a}{d^2k \, dy}
\]

\[
\frac{d\sigma^a}{d^2k \, dy} = \frac{1}{(2\pi)^2} \frac{\bar{\alpha}_s N}{2\pi} e^{y-Y/2} |k| \int d^2x \, d^2y \, d^2\beta e^{ik(x-y)} \frac{x \cdot y}{x^2y^2} \left[ e^{-(x-y)^2Q_{sq}^2 \ln(1/|x-y|\Lambda)/4} - e^{-x^2Q_{sq}^2 \ln(1/|x|\Lambda)/4} - e^{-y^2Q_{sq}^2 \ln(1/|y|\Lambda)/4} + 1 \right]
\]

\[
\frac{d\sigma^b}{d^2k \, dy} = \frac{1}{(2\pi)^2} \frac{2\bar{\alpha}_s}{\pi} C_F e^{-y+Y/2} \frac{1}{1 - \frac{C_F}{N}} \frac{1}{\sqrt{s} |k|} \int d^2x \, d^2y \, d^2\beta e^{ik(x-y)} \frac{x \cdot y}{x^2y^2} \left[ e^{-(x-y)^2Q_{sq}^2 \ln(1/|x-y|\Lambda)/4} - e^{-(x-y)^2Q_{sq}^2 \ln(1/|x-y|\Lambda)/4} \right]
\]

- Suppressed by powers of the cm energy of the collision, \( s \)
- More sensitivity to the ultraviolet: Scales as \(~ 1/k_T^3\) for large momentum.
Cronin enhancement

Comparison to pp collisions: Nuclear modification factor

\[ R_{pA} = \frac{d\sigma^{pA}}{d\mathbf{y}d^2\mathbf{k}} \]
\[ R_{pA}(|k| \ll Q_s) < 1 \]
\[ R_{pA}(|k| \gg Q_s) > 1 \]
\[ R_{pA}(|k| \rightarrow \infty) = 1 \]

Analogously to gluon production, small-x valence quark production presents a Cronin peak at \( k_T \sim Q_s \).
Quantum evolution

At higher rapidities quantum effects become important: $\alpha_s \ln 1/x \sim 1$
They have been included in the large-$N_c$ limit of QCD (dipole model)

- Harder gluons ($y' > y$): linear DLA reggeon evolution (Itakura et al)

- Softer gluons ($y' < y$): Non-linear Balitsky-Kovchegov evolution

\[
\frac{d\sigma}{d^2k\,dy}(z_{10},\alpha_1) = \frac{1}{(2\pi)^2} \frac{\bar{\alpha}_s N_c}{2\pi} \frac{\alpha}{\alpha_1} \int d^2x\,d^2y\,d^2z_1\,d^2z \, e^{ik(x-y)} \frac{(x-z) \cdot (y-z)}{|x-z|^2 |y-z|^2} \times \left[N(x,z,y) + N(y,z,y) - N(x,y,y)\right],
\]

\[
r(z_0,z_1,\alpha_1;\bar{z},\alpha) = \delta^2(z_0z_1) + \frac{\bar{\alpha}_s}{2\pi} \int_{\alpha_1}^{\alpha} \frac{d\alpha'}{\alpha'} \frac{d^2z_2}{z_{12}^2} r(z_1,z_2,\alpha';\bar{z},\alpha)
\]

\[
\frac{\partial N_{xy}}{\partial Y} = \frac{\bar{\alpha}_s}{\pi} \int d^2z \, \frac{(x-y)^2}{(x-z)^2(y-z)^2} \left[N_{xs} + N_{ys} - N_{xy} - N_{xs}N_{ys}\right]
\]
Quantum evolution

DLA linear reggeon evolution

Non-linear BK evolution

Y proton

a nucleus
Quantum evolution erases the Cronin enhancement present at central rapidity when moving towards the proton fragmentation function.

The suppression is driven by the non-linear evolution. Linear reggeon evolution cancels out in the nuclear modification factor.

The rate of suppression is similar to the one found for inclusive gluon production.


Experimental measurement could provide an extra insight in the small-x CGC dynamics.
Quark pair production

Quar pairk production

The emission wavefunction is convoluted with the eikonal propagation of the systems:

\[ \Xi_{11}(x_1, x_2, z_k; y_1, y_2, z_l; \alpha) = e^{-\frac{1}{4} (x_1-y_1)^2 Q_1^2 \ln(1/|x_1-y_1|/\Lambda)} - \frac{1}{4} (x_2-y_2)^2 Q_2^2 \ln(1/|x_2-y_2|/\Lambda)} \]

\[ \Xi_{13}(x_1, x_2, z_k; y_1, y_2, z_l; \alpha) = e^{-\frac{1}{4} (x_1-z_l)^2 Q_1^2 \ln(1/|x_1-z_l|/\Lambda)} - \frac{1}{4} (x_2-z_l)^2 Q_2^2 \ln(1/|x_2-z_l|/\Lambda)} \]

... which is given by Glauber-Mueller propagators.
Quark pair production

At the quasi-classical level:

\[
\frac{d\sigma}{d^2k_1 d^2k_2 dy d\alpha d^2b} = \frac{1}{4(2\pi)^6} \int d^2x_1 d^2x_2 d^2y_1 d^2y_2 e^{-ik_1 \cdot (x_1 - y_1) - ik_2 \cdot (x_2 - y_2)} \\
\times \sum_{i,j=1}^{3} \Phi_{i,j}(x_1, x_2; y_1, y_2; \alpha) \Xi_{i,j}(x_1, x_2; y_1, y_2; \alpha).
\]

Including quantum evolution:

\[
\frac{d\sigma}{d^2k_1 d^2k_2 dy d\alpha d^2b}(\vec{z}_{01}) = \frac{1}{4(2\pi)^6} \int d^2w_0 d^2w_1 n_1(\vec{z}_0, \vec{z}_1; w_0, w_1; Y - y) \\
\times d^2x_1 d^2x_2 d^2y_1 d^2y_2 e^{-ik_1 \cdot (x_1 - y_1) - ik_2 \cdot (x_2 - y_2)} \\
\times \sum_{i,j=1}^{3} \sum_{k,l=0}^{1} (-1)^{k+l} \Phi_{i,j}(x_1 - w_k, x_2 - w_k; y_1 - w_l, y_2 - w_l; \alpha) \Xi_{i,j}(x_1, x_2, w_k; y_1, y_2, w_l; \alpha, y).
\]
Multiplicity:

Mass dependence: shows an infrared Divergence associated to the collinear singularity.

Non trivial number of participants Dependence for large masses.
**Charm**

Much harder spectrum

**Strange**

Finite at $p_t=0$

Asymptotically $\sim 1/p_t^4$
Enhancement?

\[ R_{pA} = \frac{\frac{d\sigma^{PA}}{dyd^2k}}{A \frac{d\sigma^{pp}}{dyd^2k}} \]

**NUCLEAR MODIFICATION FACTOR**

- No Cronin enhancement for heavy quarks.
- (Qualitative agreement with experimental data)
- \( R_{pA} \) decreases after inclusion of quantum evolution effects.
- Strong indication that 'leading twist' contribution is actually leading.

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
The formalism for sea/valence quark production in the CGC-saturation framework has been presented.

Quasiclassical approximation + quantum evolution effects (linear and non-linear dynamics)

Single quark production:
- Right qualitative asymptotic behaviour
- Non-trivial atomic size dependence of the total multiplicity
- Absence of Cronin enhancement for charm mass

Valence quark production:
- Suppressed by powers of cme
- Cronin effect at central rapidity, washed out by non-linear quantum evolution at more forward rapidities.

Next:
- Hadronization/fragmentation effects
- Improvement in the implementation of quantum evolution (recent developments)
- Large-N?