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Hadron Production in Particle Nucleus Scattering

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These are preliminary lecture notes, intended only for distribution to participants
Hadron production in particle nucleus scattering

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Outline

- Hadron Production in deep inelastic e-A scattering
- Space time development of hadron production
- Scaling in high pt hadron production
- Conclusions
I. Semi-inclusive deep inelastic scattering

- Factorization theorem in QCD:

\[ \frac{d^2\sigma}{dx d\nu dz}\bigg|_{SIDIS} = \sum_f e_f^2 q_f(x, Q^2) \frac{d^2\sigma_{lq}}{dx d\nu} D_f^h(z, Q^2) \]

- Multiplicity:

\[
M^h(z) = \frac{1}{N^DIS_A} \frac{dN^h_A(z)}{dz} \\
\frac{1}{NDIS} \frac{dN^h(z)}{dz} = \frac{1}{\sigma^{lp}} \int dx d\nu \sum_f e_f^2 q_f(x, Q^2) \frac{d\sigma_{lq}}{dx d\nu} \times D_f^h(z, Q^2)
\]

\[
\sigma^{lp} = \int dx d\nu \sum_f e_f^2 q_f(x, \xi_A(Q^2) Q^2) \frac{d\sigma_{lq}}{dx d\nu}
\]
The Calculation of Absorption

\[ \frac{1}{N_A^{DIS}} \frac{dN^h_A(z)}{dz} = \frac{1}{\sigma^{lA}} \int dx dv \sum_f e_f^2 q_f^A(x, \xi A Q^2) \frac{d\sigma^{lq}}{dx dv} \times D^h_f(z, \xi A Q^2) N_A(z, \nu), \]

Rescaling of Parton Distribution, Rescaling of Fragmentation Function
Calculation of the mean formation times of the prehadron and hadron
Calculation of the Nuclear Absorption Factor $N_A$, using formation times
Rescaling of PDF and FF

• Assume change of confinement scale in bound nucleons $\lambda_A > \lambda_0$
• Two consequences:
  1.) $Q_A\lambda_A = Q_0\lambda_0$
  2.) $Q_A < Q_0, Q$

• Rescaling implies a longer DGLAP evolution (increased gluon shower)
String Fragmentation

- First rank particle contains struck quark -> flavor dependent formation length
- String fragmentation function:
  \[ f(u) \propto (1-u)^{D_q} \]
  \[ D_q = 0.3 \text{ and } D_{qq} = 1.3 \]
  proportional to
  \[ \exp \left( -\frac{\pi \mu^2}{\kappa} \right) \]
  -> dominantly quark production
  -> diquark production is suppressed
  \[ L = \frac{\nu}{\kappa} \]
  \[ \kappa = 1 \text{GeV/fm} \]
  Turning point of struck quark:
  \[ L_h = \frac{\nu T_h^2}{\kappa T^2} \]
Prehadron Formation Lengths

Fig. 3. Computed prehadron formation lengths when an up quark is struck by the virtual photon. *Left:* When a $\pi^+$, $K^+$ or $p$ is observed, the corresponding prehadron can be created at rank $n \geq 1$. *Right:* When a $\pi^-$, $K^-$ or $\bar{p}$ is observed, the corresponding prehadron can be created only at rank $n \geq 2$.

Scaled Hadron
f.l.=p.f.l.+z
Absorption model

- Inelastic scattering of (pre)hadrons on nucleons removes them from the considered \((z,\nu)\) bin, absorption rate is determined by the prehadron mean free path—Fitted prehadron-nucleon absorption cross section is about \(1/3\) of hadron nucleon cross section

\[
\frac{\partial P_q(y, y^\ast)}{\partial y^\ast} = \frac{P_q(y, y^\ast)}{\langle l^\ast \rangle} - \frac{P_q(y, y^\ast)}{\langle \Delta l \rangle} - \frac{P_q(y, y^\ast)}{\lambda_q(y^\ast)}, \quad P_q(y, y^\ast = y) = 1
\]

\[
\frac{\partial P_\nu(y, y^\ast)}{\partial y^\ast} = \frac{P_\nu(y, y^\ast)}{\langle l^\ast \rangle} - \frac{P_\nu(y, y^\ast)}{\langle \Delta l \rangle} - \frac{P_\nu(y, y^\ast)}{\lambda_\nu(y^\ast)}, \quad P_\nu(y, y^\ast = y) = 0
\]

- Absorption factor:

\[
N_A = \lim_{y^\ast \to \infty} \int d^2 b \int_{-\infty}^\infty dy \rho_A(b, y) P_h(y^\ast, y)
\]

\[
= \int d^2 b \int_{-\infty}^\infty dy \rho_A(b, y) \int dx^\ast \int_{-\infty}^\infty dx \frac{e^{-\frac{x^\ast - y}{\langle \Delta l \rangle}}}{\langle l^\ast \rangle} e^{-\int ds A_A(s)} \sigma_A \int dx \rho_A(s) \times \frac{e^{-\frac{x^\ast - s}{\langle \Delta l \rangle}}}{\langle \Delta l \rangle} e^{-\int ds A_A(s)}
\]
Prehadron und Hadron-Production probabilities at HERMES energies for Kr target without absorption
Additional indication for prehadron formation from JLAB-data (W. Brooks)

- Variation of mean produced hadron $p_t^2$ shows that only the $p_t$ acquired by the propagating quark does contribute (Kopeliovich and Nemcik, work in preparation)
- In large Pb-nucleus, when the nucleus dependent formation of the prehadron occurs outside of the nucleus, no more $p_t$ can be acquired. The process terminates.
- In smaller Fe and C nuclei the size of the nucleus terminates the process earlier

$\Delta p_t^2$ vs $\nu (\text{GeV})$

$<-\text{Energy transfer to the quark}$
Comparison with HERMES data

A-dependence of model

- The absorption model gives an A-dependence $A^{(2/3)}$ in agreement with the data.
- The figure represents a fit of the exponent at each $z$ to the theoretical calculation for different sets of nuclei.
- The A dependence cannot be used to differentiate between energy loss picture and absorption.
II. Space time Structure of hadron production

- In pp or AA collisions, the produced parton has time like virtuality $t_0 > 0$ and loses energy even in vacuum (vacuum energy loss). (Thesis: C. Zapp)
- No difference in decay time between charm quarks and light quarks because $t_0 \gg mc$
- Each new virtualty $t' = kt^2/z$ has to be lower than the original virtuality
- Most descriptions treat first the energy loss of an on-shell quark in the medium and then hadronization
- (Induced) radiation and fragmentation, however, can not be separated

\[
\bar{z}_c D'_{h/c}(z_c, Q_c^2) = z'_c D_{h/c}(z'_c, Q'_c) + N_g z_g D_{h/g}(z_g, Q_g^2);
\]
\[
z'_c = \frac{p_h}{p_c - \Delta E_c(p_c, \phi)}, \quad z_g = \frac{p_h}{\Delta E_c(p_c, \phi)/N_g},
\]

Modification of fragmentation function separated from energy loss is not justified
Space time development (Initial virtuality $t_0=100 \text{ GeV}^2 \rightarrow t_1$)

Take RHIC case:

Mean final virtuality $[\text{GeV}^2]$ of radiated gluons is $t_1=10 \text{ GeV}^2$

Mean time for radiation $<t>=0.7 \text{ fm}/c$
This changes the picture of high $p_{T}$ Suppression

Fig. 36. $\pi^0 R_{AA}(p_T)$ for central (0–10 %) and peripheral (80–92 %) Au+Au collisions
High $p_t$ Suppression

- Quantum coherence (like in angle ordered MLLA of gluon radiation in the vacuum) may be destroyed in propagation through QGP.
- Medium enhances emission of gluon radiation, effective QCD coupling in hot quark gluon plasma is larger than fixed $\alpha_s=0.5$.
- If gluon radiation is hard, then the gluon can neutralize the original radiating source.
- Consequently prehadron formation may be also important at RHIC.
Medium induced scattering

- Mean free path is shorter due to larger coupling \( \alpha(k,T) \)
- Debye Mass can be determined selfconsistently from strong coupling \( \alpha(k,T) \)
- Running \( \alpha(k,T) \) at finite temperature is calculated from RG equation (J. Braun, H. Gies, hep-ph/0512085 and J. Braun and H.J. Pirner work in progress)

\[
\frac{d\sigma_i}{dq_{\perp i}^2} \approx C_i \frac{4\pi \alpha^2}{(q_{\perp i}^2 + \mu^2)^2}
\]
III. Binary Scaling and Hard Scattering

- Fixed Angle, e.g. $y=0$ 90° in cm-system
- Compare various energies, same $x_t$
- Expect $n=4$ from lowest order pQCD

$$x_T = \frac{2p_T}{\sqrt{s}}.$$ 

$$E \frac{d^3\sigma}{d^3p} = \frac{1}{p_T^n} F(x_T) = \frac{1}{\sqrt{s}^n} G(x_T),$$
Pure dimensional counting of the number of active participants determines the exponent

\[ E \frac{d^3 \sigma(h_a h_b \rightarrow hX)}{d^3 p} = \frac{F(y, x_R)}{p_T^{n(y, x_R)}}. \]

- \( n(y, x_R) = 2n(\text{active with hard pt}) - 4 ; (x_R = x_t \text{ at } y=0) \)
- 4 active participants give \( n(y, x_R) = 4 \)
- RHIC measures \( n=6.3 \) or \( n=7.8 \), depending on particle species
- The smaller number \( n=6 \) is compatible with hard gluon radiation NLO calculations
- The larger number \( n=8 \) points to more complicated processes e.g. for proton production \((q+\bar{q} \rightarrow qqq+q\bar{q})\)
Data show nonscaling behaviour for protons

Phenix analysis

6.2 $x_T$ scaling in Au+Au collisions at RHIC

Final state interaction may change the scaling behaviour if energy loss like in BDMPS occurs
Conclusions

- Meson production at low $<Q^2> = 2.5$ GeV$^2$ in Hermes is well described by the string model with prehadron formation and absorption.
- Data with high $<pt^2> = 100$ GeV$^2$ at RHIC or LHC need a correct treatment of vacuum energy loss.
- The gluon radiation time of the time like parton is of the same size as its mean free path.
- The initial gluon cascade for fragmentation is entwined with induced medium scattering.
- Violation of xt-scaling relations behave differently than expected from BDMPS-energy loss picture.
Heavy Flavor $R_{AA}$

- $R_{AA}$ to 10 GeV/c in non-photonic electrons
- Suppression is approximately the same as for hadrons
- B contribution? Challenge for radiative picture?

See talk, Bielecki(5c)

QM05: Hard Probes at STAR, Dunlop
Calculation of Prehadron Formation Lengths

\[
\langle l^*_\geq 1 \rangle = \frac{1 + D_a}{1 + C + (D_a - C)z} (1 - z)zL
\]

\[
\times \left[ 1 + \frac{1 + C}{2 + D_a} \frac{(1 - z)}{z^2 + D_a} \right]_{2F1} \left( \begin{array}{c} 2 + D_a, 2 + D_a; 3 + D_a \end{array} \frac{z - 1}{z} \right)
\]

F- Hypergeometric Function, C=0.3, D arise from the string fragmentation f(u)=(1-u)^D
Dq=0.3 for producing a quark and Dqq=1.3 for producing a diquark
Result of Absorption Model

- Rescaling + absorption are able to describe the data
- Flavor dependence is reproduced in accordance with the first and second rank description
- Proton multiplicities are not reproduced well
2) String branching

- Cut off (4 Gev) excludes target fragmentation at low z
- But string cannot only break, but also branch into two strings (cf. X.N. Wang et al., nucl-th/0407095)
- Main mechanism of baryon flow (Garvey, Kopeliovich, Povh, hep-ph/0006325)
Pion Multiplicity on the Proton

- D. Grünewald (Diploma Thesis) has calculated meson and baryon multiplicities in this Lund picture.
- Unfortunately, experimental baryon multiplicities are not available to compare with.