Hadron Attenuation and $p_T$ Broadening at CLAS and HERMES

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- **Motivation**
- **Model**
  - Pythia, GiBUU, prehadronic FSI
- **Results**
  - EMC@100-280, Hermes@27, CLAS@5
  - Hermes: $\Delta p_T$
Motivation

- Elementary reactions ($eN, \gamma N$) on nucleon:

  ![Diagram of elementary reactions]

  - Formation time: estimation via hadronic radius
    \[ \tau_F \geq \frac{r_h}{c} = 0.5 \cdots 0.8 \text{ fm} \]
  - Time dilatation: \[ t_F = \gamma \tau_F \] \( (\sim 10 \text{ fm}) \)

- Nuclear reactions ($eA, \gamma A$ @ GeV energies):

  - Interactions with nuclear medium during formation
  - Space-time picture of hadronization \[ \sigma^*/\sigma_H \sim t^{0, 1, 2, \cdots} \]

- Cold nuclear matter as baseline for Heavy Ion Collisions

  - Reaction products hadronize long before they reach the detector
Model

- $g^* N \rightarrow X$ using PYTHIA
  - *additional*:
    - binding energies
    - Fermi motion
    - Pauli blocking
    - coherence length effects
  - *extended for exclusive channels*

- propagation of final state $X$ within GiBUU transport model

http://gibuu.physik.uni-giessen.de

- elastic/inelastic scatterings (coupled channels)
- experimental acceptance
Model: Hadronization in String Model (Pythia/Jetset)

- 3 times/points per particle:
  - "Production 1" String-Break
  - "Production 2" String-Break
  - "Formation" Line Meeting

- leading vs. non-leading

- XS evolution scenarios:
Results: EMC & Hermes

\[ \frac{\sigma^*}{\sigma_h} = \frac{r_{\text{lead}}}{Q^2} + \left( 1 - \frac{r_{\text{lead}}}{Q^2} \right) \left( \frac{t - t_P}{t_F - t_P} \right) \]

EMC@100...280 GeV
and
Hermes@27 GeV
described simultaneously

Color transparency?
...small effect!
Hermes@27: A. Airapetian et al., NPB780(2007)1

Pions

\[ \pi^0, \pi^+, \pi^- \]

\[ ^2d_1, ^4He_2, ^{20}Ne_{10}, ^{84}Kr_{36}, ^{131}Xe_{54} \]

No diffractive
CLAS@5, $\pi^+$ : selected ($\nu,Q^2$) bins

$Q^2 = 1.0 \ldots 1.25$ GeV$^2$

$Q^2 = 1.85 \ldots 2.4$ GeV$^2$

Data:
- CLAS preliminary
- no error bars shown

Calculations:
- not tuned !!!
- no Fermi Motion
  (W<2 GeV possible)
- no potentials

As good as at higher energies!
$\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D$

Default: normal attenuation

In-Medium modifications:

$$\langle k_T^2 \rangle_{Xe} = (0.44 \text{ GeV})^2 \rightarrow (0.50 \text{ GeV})^2$$

$$\langle \sigma_p \rangle_{Xe} = 0.36 \text{ GeV} \rightarrow 0.40 \text{ GeV}$$

data: Y. van Haarlem et al., arXiv:0704.3712 [hep-ex]
**Hermes@27: $p_T$ Broadening**

\[ \Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D \quad \text{and} \quad R_A(p_T) \]

**Default:**

**In-Medium modifications:**

normal attenuation

\[
\langle k^2_T \rangle_{Xe} = (0.44 \text{ GeV})^2 \quad \rightarrow \quad (0.50 \text{ GeV})^2
\]

\[
\langle \sigma_p \rangle_{Xe} = 0.36 \text{ GeV} \quad \rightarrow \quad 0.40 \text{ GeV}
\]

**Graphs:**

- Data: A. Airapetian et al., NPB 780 (2007) 1
**Conclusions**

- **GiBUU:**
  - coupled channel transport code (semi classical)
  - from some MeV to tens of GeV (Pythia v6.4 for high energy)
  - multi purpose: $p, \pi, \gamma^*, \nu$ – induced reactions
    - Heavy Ion Collisions

- **pre-hadron cross section:** linear in time
  - (EMC,Hermes,CLAS)

- **Transverse momentum broadening**
  - attenuation leads to broadening
  - medium modification of fragmentation parameters ???