Coherent Multiple Scattering Effect in DIS

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Hard Probe 2006, Pacific Grove, CA

The observed nuclear dependence

—— change of particle production rate with nuclear target compared to that of nucleon target

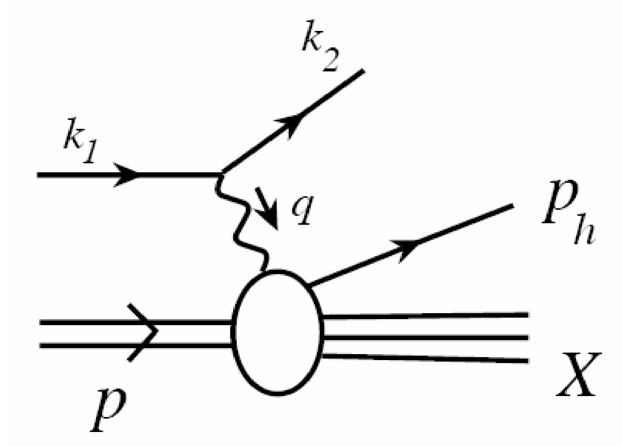
—— result of all sources of nuclear effects

- nuclear dependence in parton distributions
- interaction of incoming partons before the hard collision

  --- initial state interaction
- interaction of final state parton when it propagates through the nuclear medium

  --- final state interaction
- coherent multiple scattering that changes the parton production rate

Use semi-inclusive deeply inelastic scattering (DIS) to explore the effect of coherent multiple scattering



- **variables**

$$q = (k_1 - k_2) \qquad Q^2 = -q^2$$

$$x_B = Q^2/(2p \cdot q)$$

$$z \equiv \frac{p \cdot p_h}{p \cdot q} = \frac{2x_B p \cdot p_h}{Q^2}$$

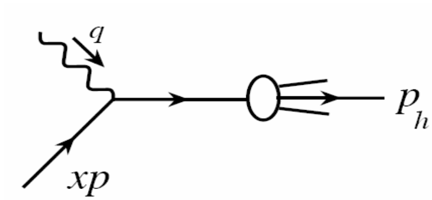
Consider single hadron production in DIS

$$R^A = \frac{d\sigma_{eA\to ehX}}{dx_B dQ^2 dz} \Bigg/ \frac{d\sigma_{eA\to eX}}{dx_B dQ^2}$$

for different nuclear targets

Cross section: $\sigma \sim |M|^2$

M =



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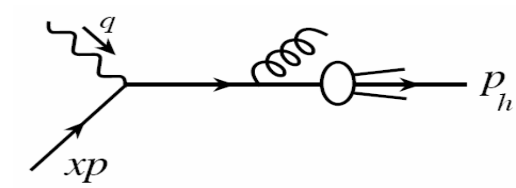

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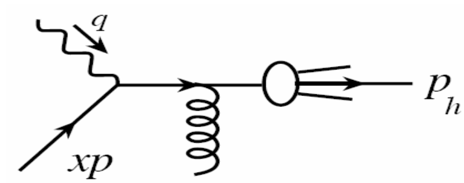

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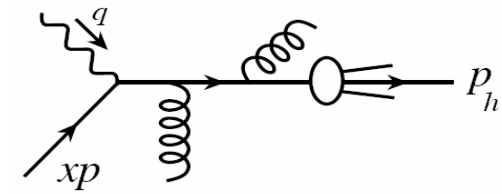

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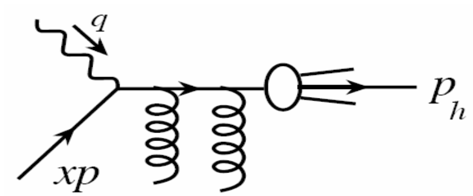

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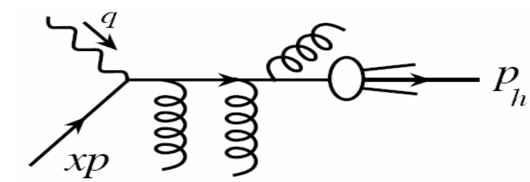
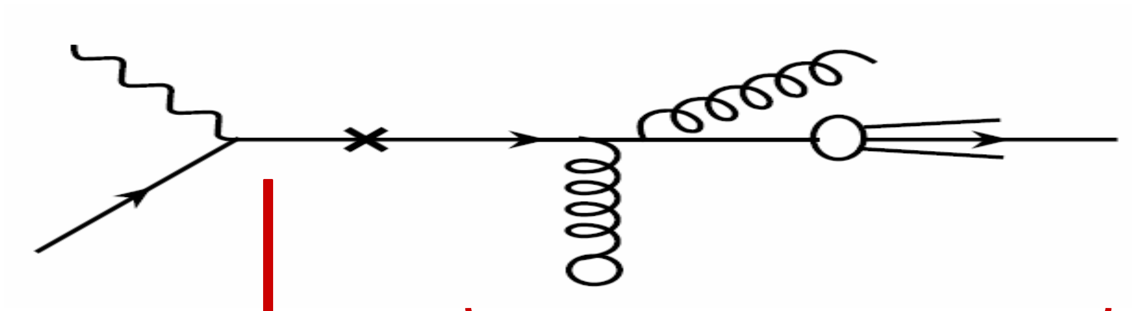


+ ……

- **sum of all amplitudes with the same final states**
- **Integrate over all possible phase space**

Modification of fragmentation functions



Long-distance propagation

Short-distance hard scattering

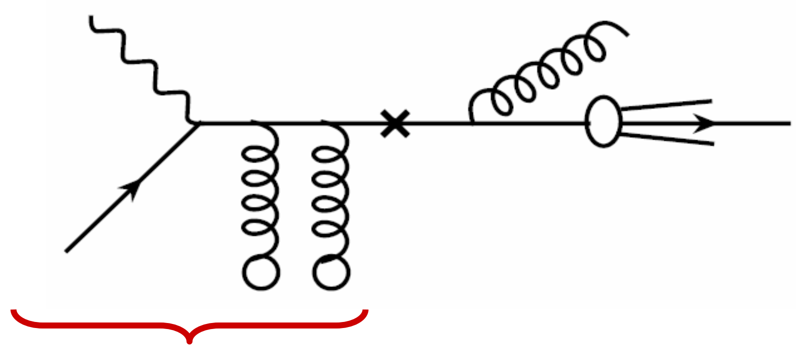
- First scattering determines the production rate
- Interaction with the medium when propagating

  → modify the evolution of the fragmentation functions

  → change the spectrum

Guo, Wang PRL 2000, …

Modification of the production rate



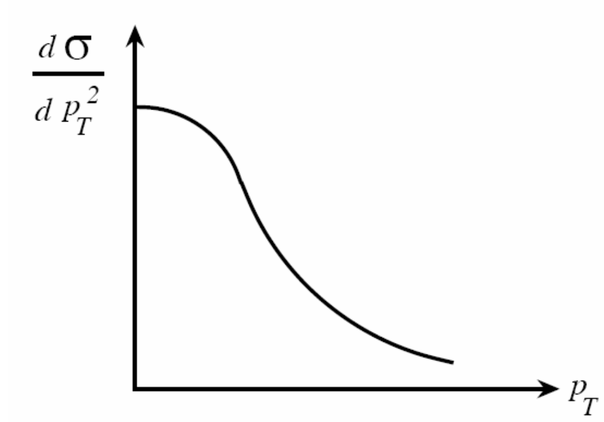
Coherent with the first scattering

- **power suppressed**

  a factor of $1/Q^2$ for each additional scattering
- **enhanced by the nuclear size**
- **requires coherence**

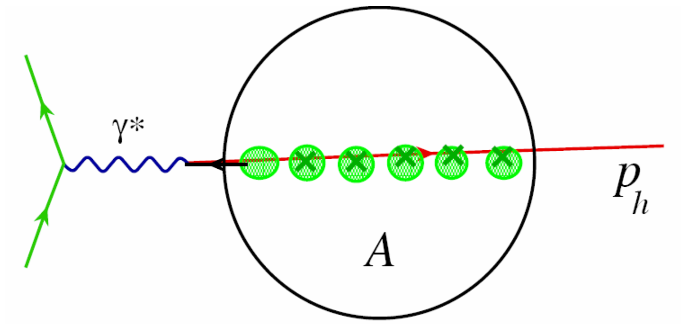
Coherence in semi-inclusive DIS

- **For p_T-integrated cross section**
  dominant contribution comes from small p_T region



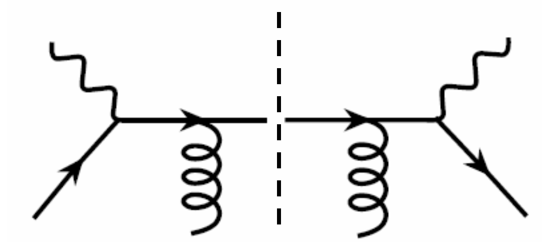
- **In Breit frame, at small p_T,**

  stuck quark rescatters coherently with the "remnant" of the nucleus



Multiple scattering

❖ without quantum interference



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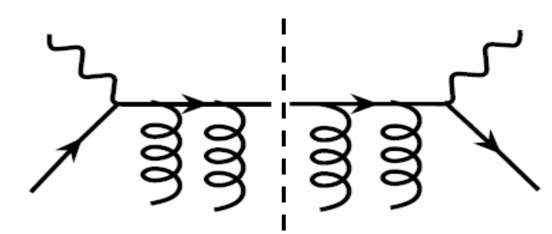

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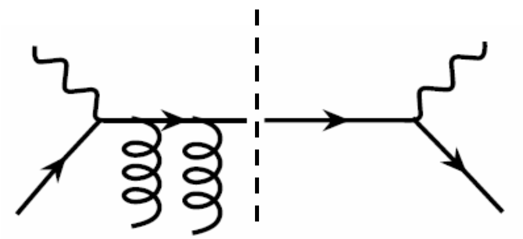
→ more production channel

increase production rate

❖ with quantum interference



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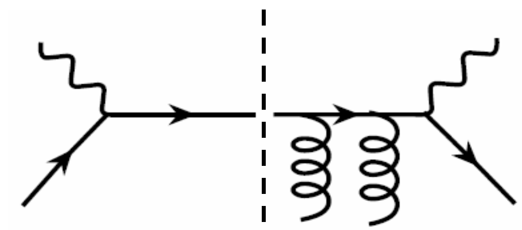
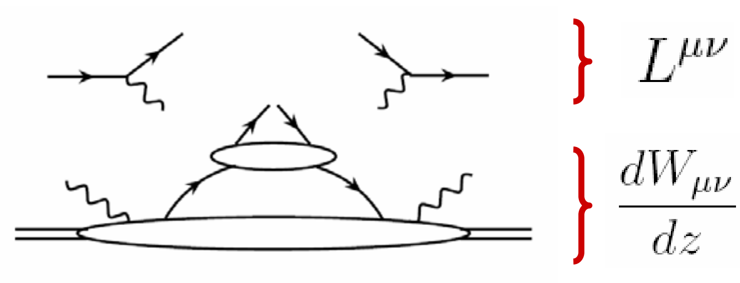


→ lead to suppression

Factorized formula for semi-inclusive DIS

$$\frac{d\sigma_{eA\to ehX}}{dx_B dQ^2 dz} \sim L^{\mu\nu}(k_1,k_2)\frac{dW_{\mu\nu}}{dz}$$



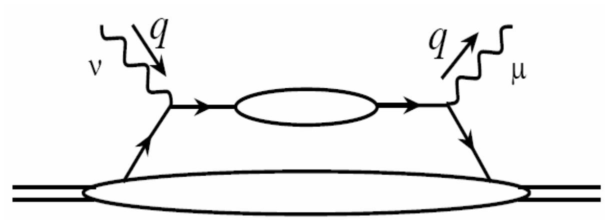
Lowest order

$$\frac{dW_{\mu\nu}}{dz} = \sum_f \int \frac{dx}{x} dz' \delta\left(z' - \frac{2xp\cdot p_h}{Q^2}\right)\phi_f(x,Q^2)\, H^S_{\mu\nu}\, D_f(z',Q^2)$$

parton distribution **fragmentation function**

partonic part

$$H^S_{\mu\nu} = \frac{1}{2}e^T_{\mu\nu}\sum_f xQ_f^2\delta\left(x - \frac{Q^2}{2p\cdot q}\right)$$

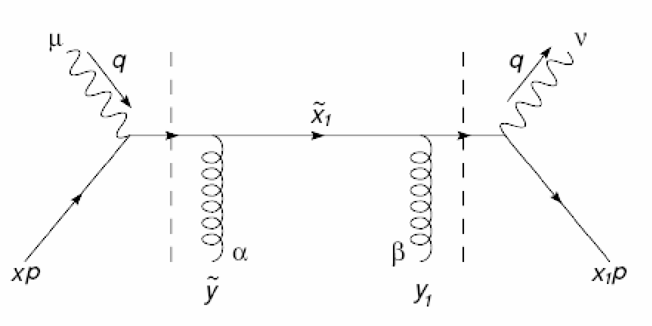


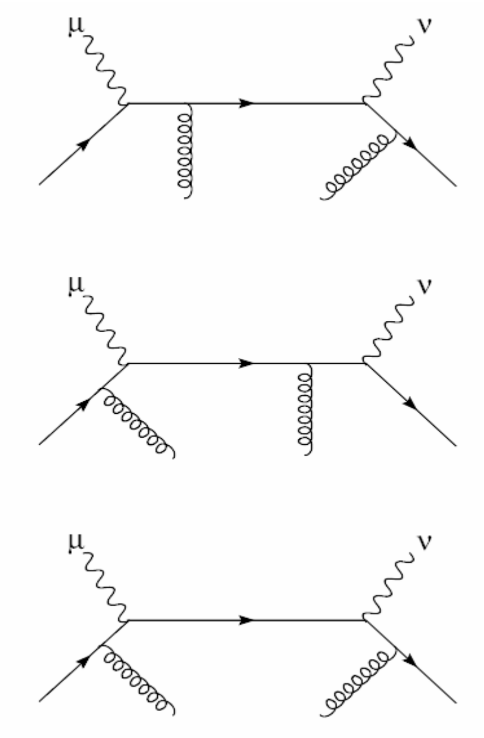
$$\Rightarrow \quad \frac{dW_{\mu\nu}}{dz} = \frac{1}{2}e^T_{\mu\nu}\sum_f \phi_f(x_B,Q^2)\, D_f(z,Q^2)$$

Double scattering contribution

gauge invariance

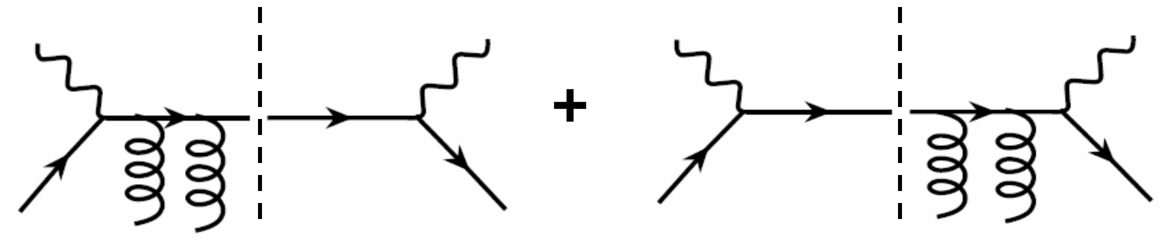
need all 4 diagram





- **do not have nuclear size enhancement**
- **contribute to the weak A-dependence of nuclear parton distribution**

Medium enhanced double scattering contribution



gauge invariant subset

Sum over all interference terms

$$\frac{dW^{(1)}_{\mu\nu}}{dz} = \frac{1}{2}e^T_{\mu\nu}\sum_f Q_f^2\left(\frac{4\pi^2\alpha_s}{3}\right)\frac{z}{Q^2}T^A_{qg}(x_B,Q^2)\,\frac{dD(z,Q^2)}{dz}$$

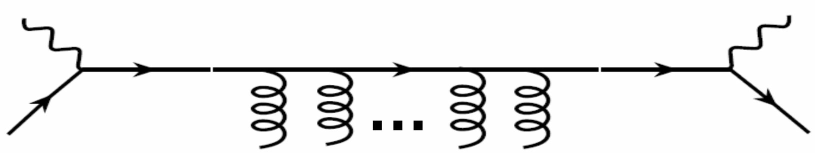
$$+\ \frac{1}{2}e^T_{\mu\nu}\sum_f Q_f^2\left(\frac{4\pi^2\alpha_s}{3}\right)\frac{x_B}{Q^2}\,\frac{d}{dx_B}T^A_{qg}(x_B,Q^2)\,D(z,Q^2)$$

Important when x < 0.1, γ^* probe covers more than one nucleon (Qiu and Vitev, PRL ,2004)

$T^A_{qg}(x_B,Q^2)$ **— twist-4 quark-gluon correlation function**

Generalize to n-additional scattering

add pairs of gluon interactions



$$\frac{dW_{\mu\nu}^{(n)}}{dz} \approx \frac{1}{2} e_{\mu\nu}^{T} \sum_{f} Q_f^2 \left[z \frac{4\pi^2 \alpha_s}{3Q^2} \right]^n \frac{1}{n!} M_A^{(n)}(x_B, Q^2) \frac{d^n}{dz^n} D_f(z, Q^2)$$

multi-field operator

$$M_A^n(x, Q^2) = \int \frac{dy_0^-}{2\pi} e^{ixp^+ y_0^-} \langle P_A | \bar{\psi}_f(0) \frac{\gamma^+}{2} \psi_f(y_0^-) \prod_{i=1}^{n} \left[\int p^+ dy_i^- \, \theta(y_i^-) \hat{F}^2(y_i^-) \right] | P_A \rangle$$

Operator $\hat{F}^2(y_i^-)$ is related to gluon density

$$\langle p | \hat{F}^2(y_i^-) | p \rangle \approx \lim_{x \to 0} \frac{1}{2} x \, G(x, Q^2)$$

Sum of all medium enhanced contributions

$$\frac{dW_{\mu\nu}}{dz} \approx \frac{1}{2} e^T_{\mu\nu} \sum_f Q_f^2\, A\phi_f(x,Q^2) \sum_{n=0}^{N} \frac{1}{n!} \left[\frac{z\kappa^2(A^{1/3}-1)}{Q^2}\right]^n \frac{d^n D_f(z,Q^2)}{d^n z}$$
$$\approx A\,\frac{1}{2} e^T_{\mu\nu} \sum_f Q_f^2\, \phi_f(x,Q^2)\, D_f\left(z + \frac{z\kappa^2(A^{1/3}-1)}{Q^2}, Q^2\right),$$

- **effect of coherent multiple scattering**
  of propagating quark (not a pre-hadron state)
  —— equivalent to a shift of z in fragmentation function

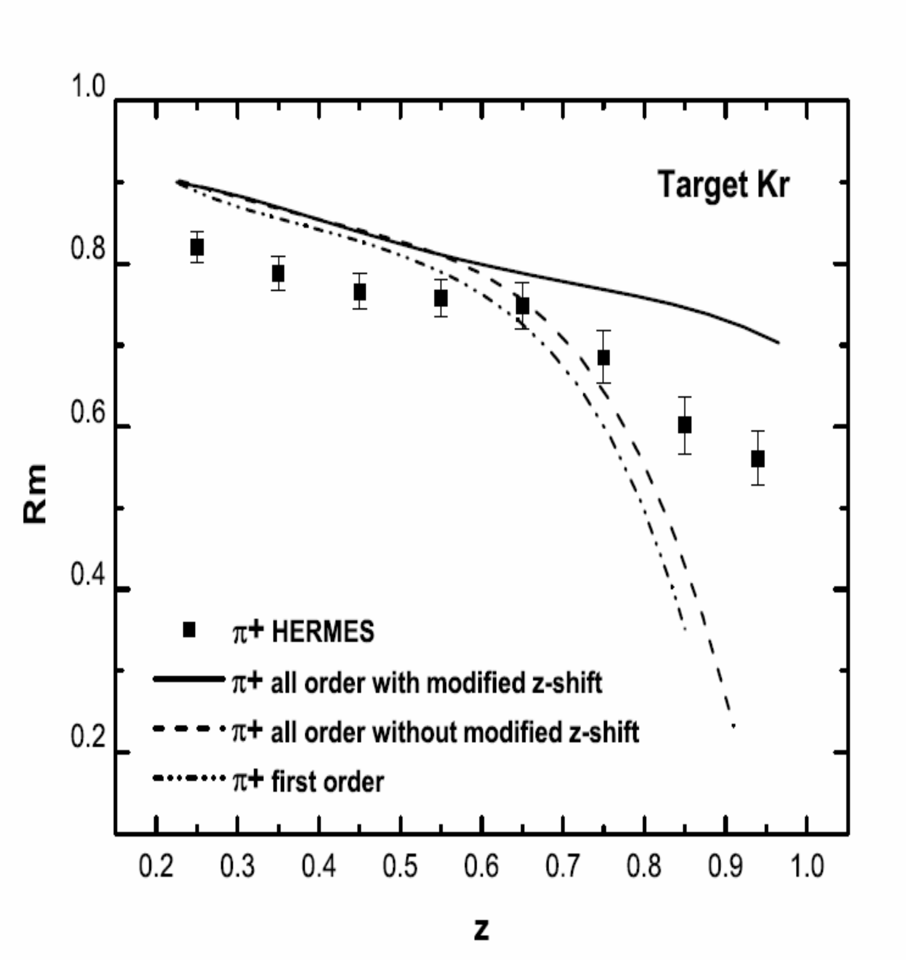
- **shift** $$\Delta z = z\frac{\kappa^2(A^{1/3}-1)}{Q^2}$$ **depends on**

one parameter $$\kappa^2 = \frac{3\pi\alpha_s(Q^2)}{4\, r_0^2} \langle p|\, \hat{F}^2(y_i)\, |p\rangle$$

quark interaction with the medium

Compare with HERMES data

ratio of multiplicity with target A and target D



- **Large z:**
  pre-hadron state forms early
  sum to all order not applicable
- **Formation time ~ (1-z)**
  (A. Accardi,)
  modify z-shift for large z,

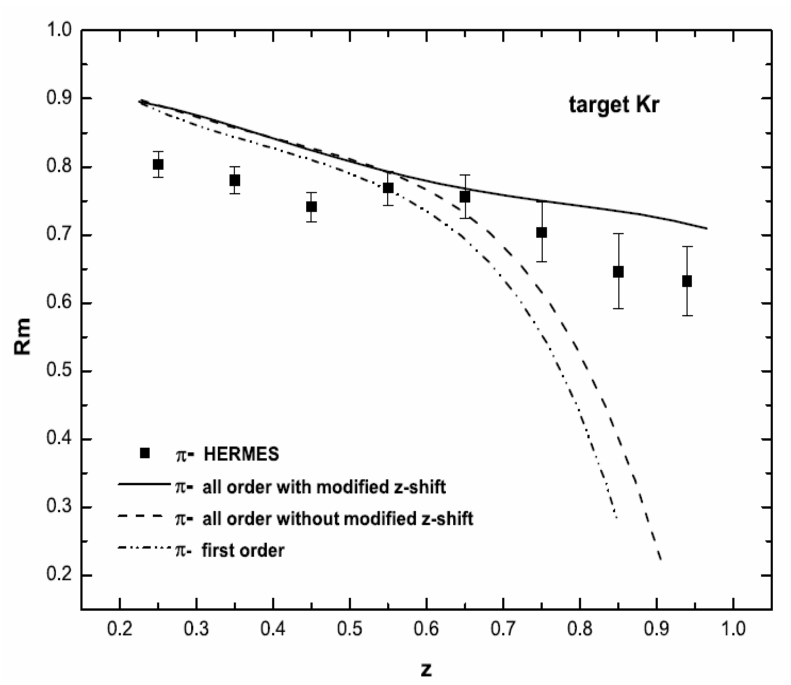
  $\Delta z^* = \Delta z\ (1- z)/(1- z_c)$

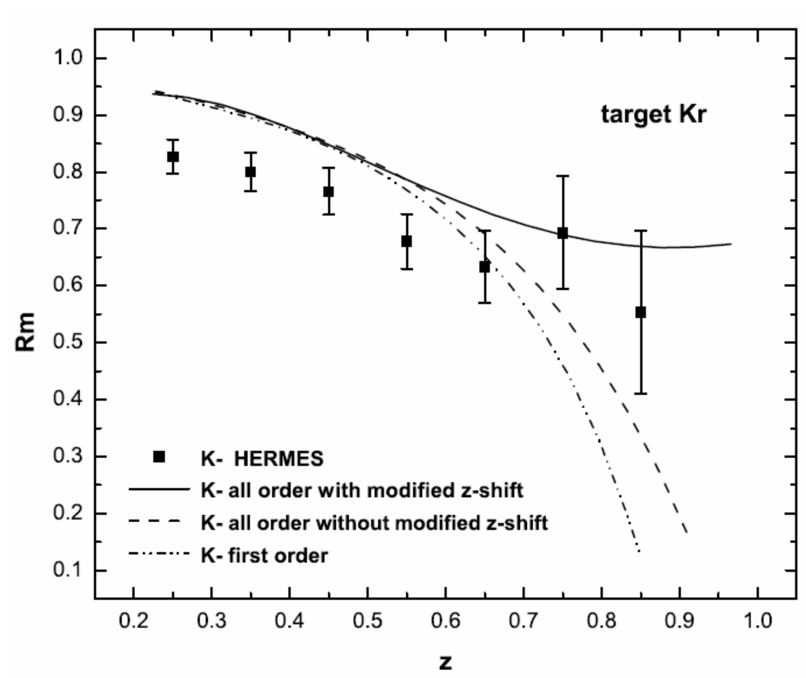
  (fit z_c=0.6)

- **Complement to the effect from modification of fragmentation function**

More figures

ratio of hadron multiplicity for target A and that of target D





•Summary

- The observed A-dependence are results of all sources of nuclear effects
- Medium induced radiation

  ----modify the evolution of parton fragmentation
- Coherent multiple scattering

  ----change the parton production rate
- Quantum interference of coherent multiple scattering

  ---- suppression in parton production
- When summed to all order, the suppression

  --- equivalent to a shift of z for D(z)