Transverse momentum broadening in nuclear collisions

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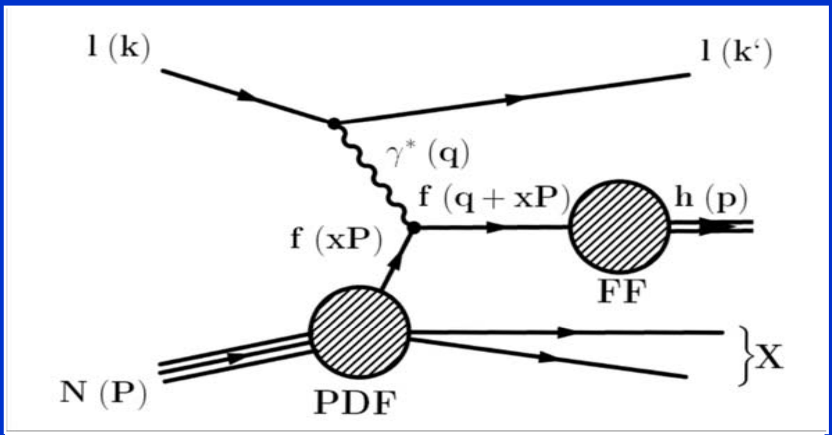
S. Domdey, D. Grünewald and H.J. Pirner, to be published , A.Accardi, D.Grunewald, V.Muccifora and H.J. Pirner, Nucl. Phys.A 761 (2005) 67 [arXiv:hep-ph/0502072] ,H.J. Pirner, S. Domdey, K. Zapp. J. Stachel,G. Ingelman J. Rathsmann, in Heavy Ion Collisions at the LHC - Last Call for Predictions," arXiv:0711.0974 [hep-ph] and to be published.

Outline

- Hadron p_t broadening in deep inelastic e-A scattering
- Evolution of p_t-broadening in the nucleus
- Cold (nuclear matter) versus hot medium (quark gluon plasma)

Broadening is a key feature which monitors the microscopic subprocesses rather accurately

1. Hadron p_t- broadening in deep inelastic scattering



Variable	Covariant	Lab. frame
Q^2	$-q^2$	$2Mx\nu$
ν	$\frac{q\,p}{\sqrt{P^2}}$	$E'-E$
x	$\frac{-q^2}{2Pq}$	$\frac{Q^2}{2M\nu}$
z	$\frac{p\,P}{q\,P}$	$\frac{E_h}{\nu}$
y	$\frac{q\,P}{k\,P}$	$\frac{\nu}{E}$
W^2	$(P+q)^2$	$M^2+2M\nu-q^2$

- Factorization theorem in QCD:

$$\left.\frac{d^2\sigma}{dx\,d\nu\,dz}\right|_{SIDIS} = \sum_f e_f^2 q_f(x,Q^2)\frac{d^2\sigma^{lq}}{dx\,d\nu}D_f^h(z,Q^2)$$

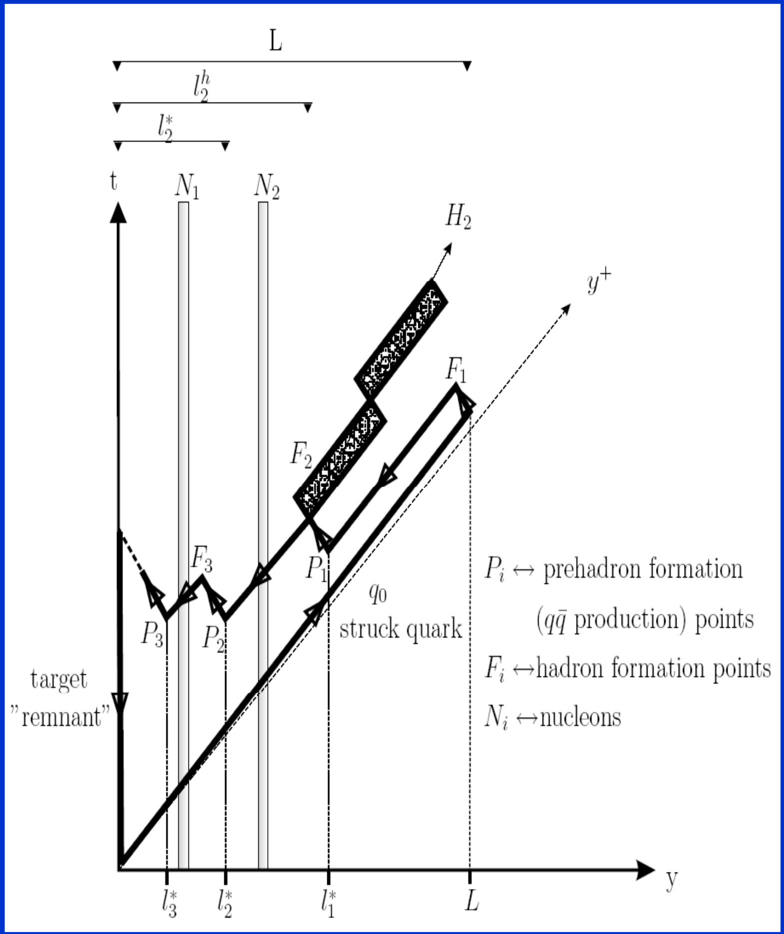
- Multiplicity:

$$M^h(z) = \frac{1}{N_A^{DIS}}\frac{dN_A^h(z)}{dz}$$

$$\frac{1}{N^{DIS}}\frac{dN^h(z)}{dz} = \frac{1}{\sigma^{lp}}\int_{\text{exp. cuts}} dx\,d\nu \sum_f e_f^2 q_f(x,Q^2)\frac{d\sigma^{lq}}{dx\,d\nu} \times D_f^h(z,Q^2)$$

$$\sigma^{lp} = \int_{\text{exp. cuts}} dx\,d\nu \sum_f e_f^2 q_f(x,\xi_A(Q^2)Q^2)\frac{d\sigma^{lq}}{dx\,d\nu}$$

String Fragmentation



- **First rank particle contains struck quark -> flavor dependent formation length**
- **String fragmentation function:**

$$f(u) \propto (1-u)^{D_a} \qquad D_q = 0.3 \text{ and } D_{qq} = 1.3$$

(Lund model)

-> dominantly quark production

-> diquark production is suppressed

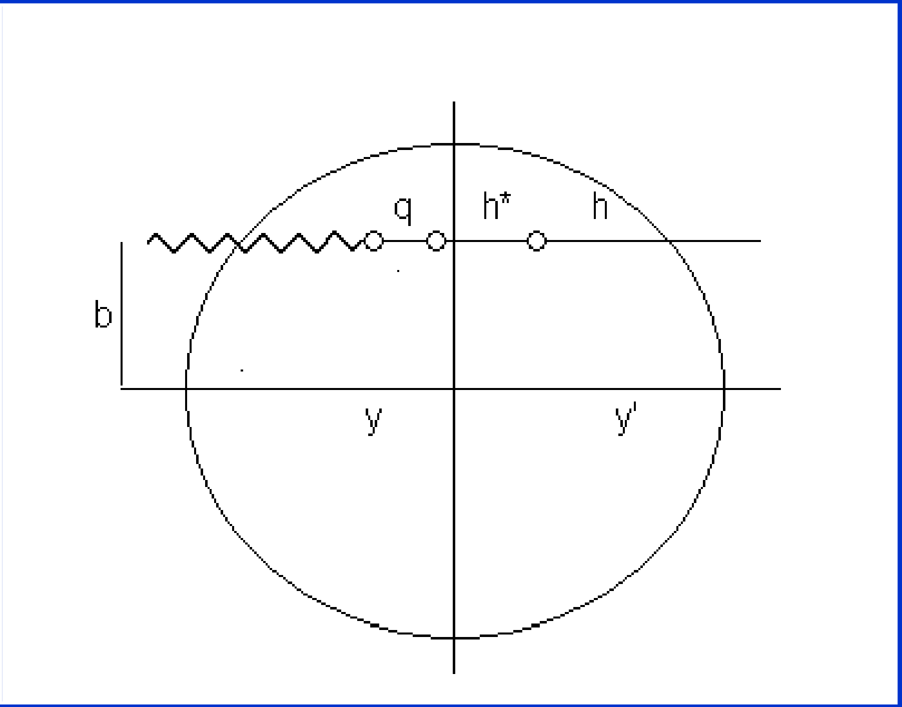
$$L = \frac{\nu}{\kappa} \qquad \kappa = 1GeV/fm$$

Turning point of struck quark:

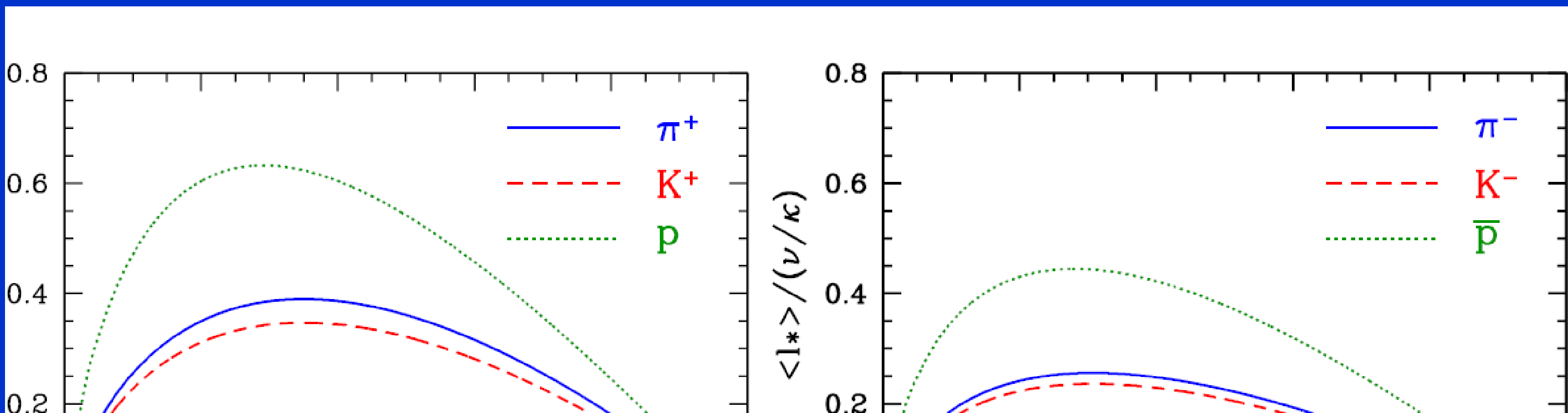
$$L_h = \frac{\nu\, \tau_h^2}{\kappa\, \tau_\pi^2}$$

Three stage picture (I)

- First stage: quark (q)-propagation , p_t broadening , elastic collisions
- Second stage: prehadron (h*)-propagation, elastic cross section is small compared to inelastic cross section, absorption no broadening
- Third stage : hadron (h)-propagation , full absorption, if still inside nucleus



Prehadron Formation Lengths
l*/(ν/κ)

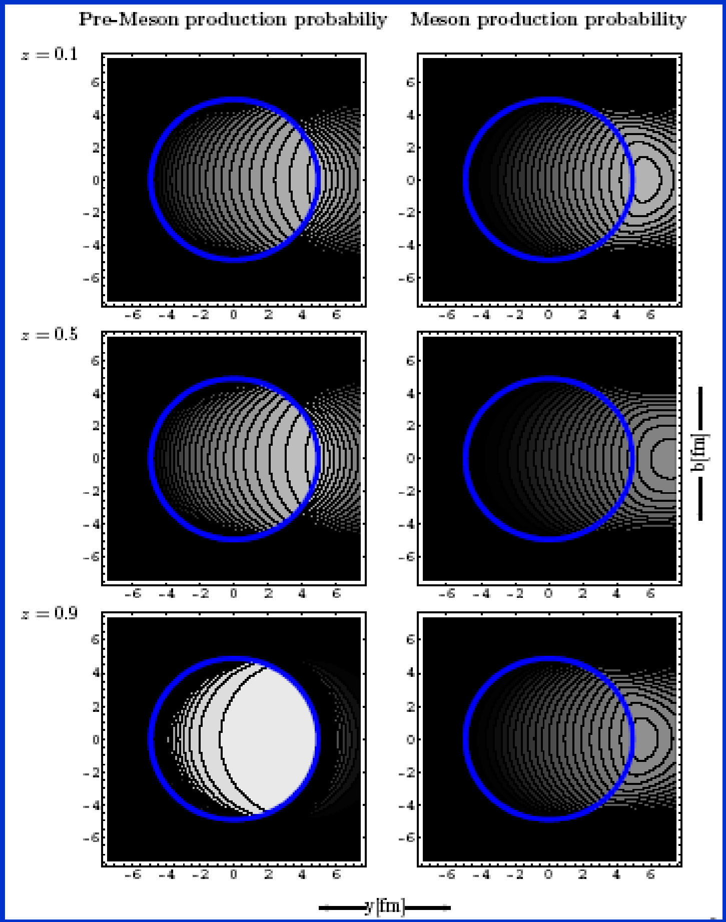


[redacted]

κ is the string tension

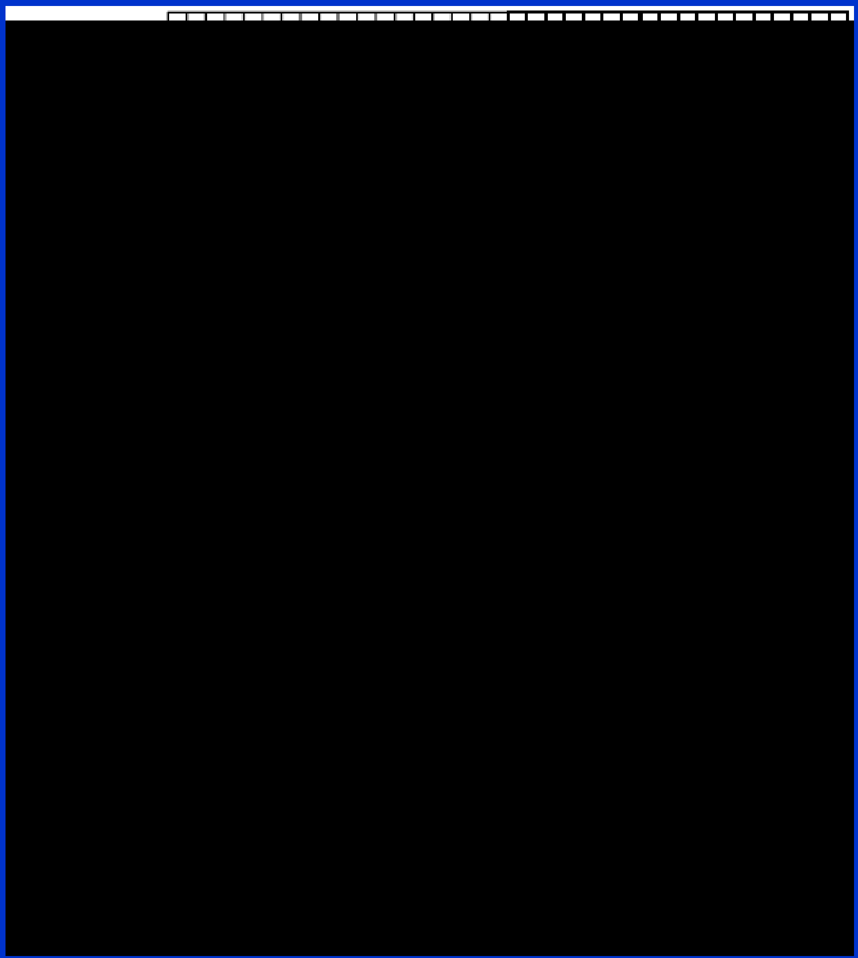
Scaled Hadron
f.l.=p.f.l.+z

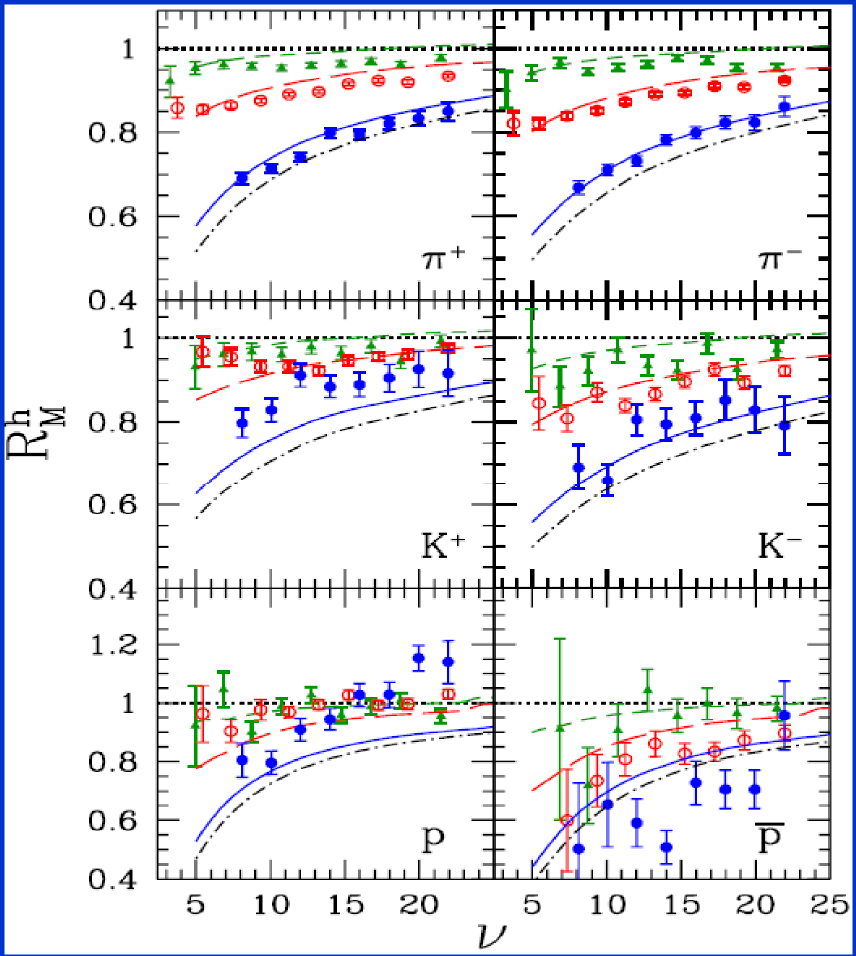
Prehadron und Hadron-Production probabilities at HERMES energies for Kr target without absorption



Comparison with HERMES data

Hermes Coll. A.Airapetian et al. Phys. Lett. B577 (2003) 37-Xe,Kr,Ne,He target





D.Grunewald, V.Muccifora and H.J. Pirner, Nucl. Phys.A 761 (2005) 67

2. Evolution of p_t-broadening in the nucleus

Nuclear p_t-broadening at HERMES

Yves Van Haarlem[1], Anton Jgoun[2], Pasquale Di Nezza[3]
on behalf of the HERMES Collaboration

Paper gives p_t broadening as a Function of the momentum fraction z_h, of the produced hadron or as a function of the photon energy v and photon resolution Q^2

Theoretical expectations:

- When z_h becomes larger the prehadron formation occurs earlier ->less p_t.
- In smaller Ne and Kr nuclei the size of the nucleus terminates the process earlier

Δp_t^2 of hadrons

- z_h->1 indicates a smaller Δp_t^2
- Photon energy ν does not increase Δp_t^2 ?
- Larger Q^2 shows enhanced Δp_t^2 due to parton evolution in the medium with scattering

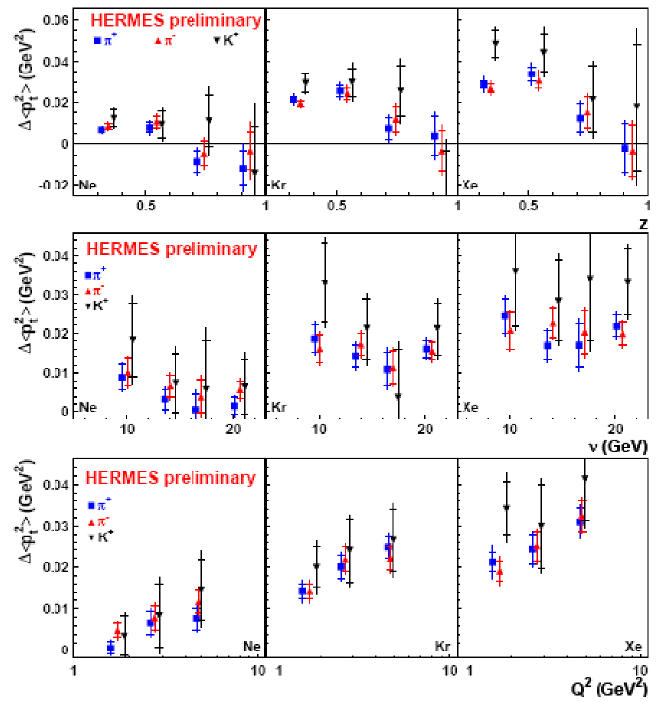
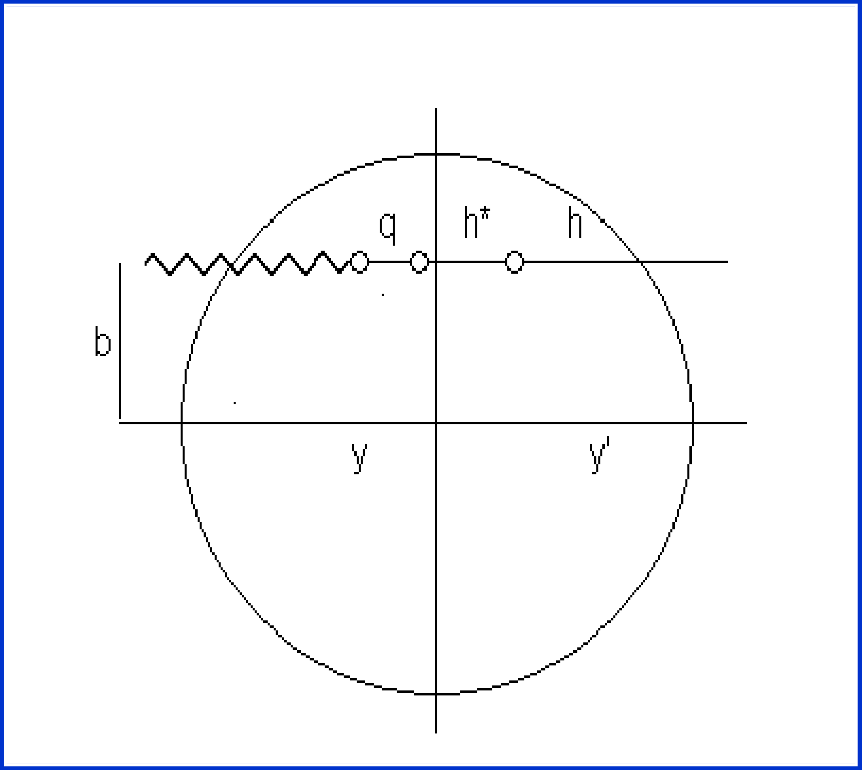


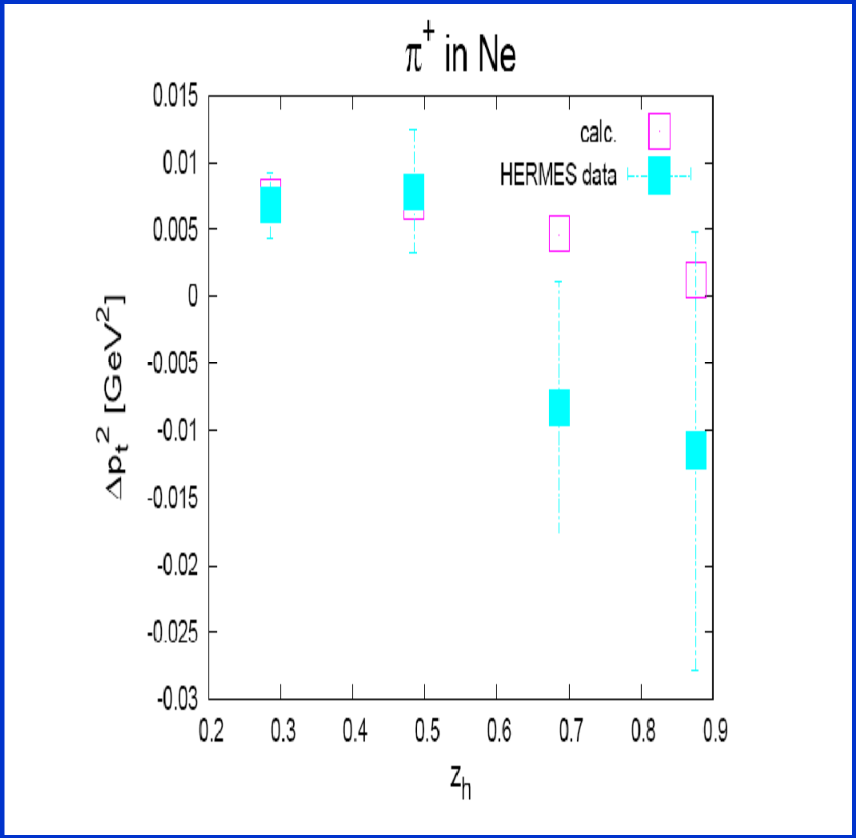
Figure 1: p_t-broadening for different hadron types produced from Ne, Kr, and Xe targets as a function of z (upper panel), ν (middle panel), and Q^2 (lower panel). The inner error bars represent the statistical error and the outer ones the quadratic sum of the statistical and systematic uncertainties.

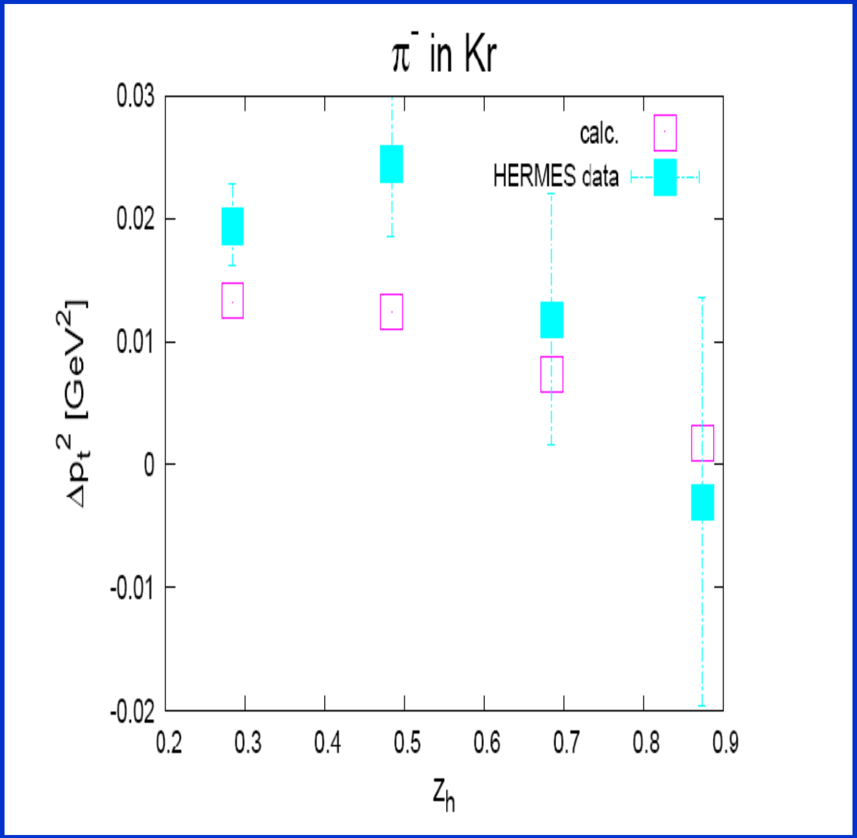
Three stage picture (II)

- Only the path of quark (q) is important , since the prehadron and hadron have small elastic cross sections
- Prehadron (h*)-formation limits the length l* where broadening occurs
- $<\sigma\, p_t^2>$ from quark nucleon scattering defines the magnitude of broadening and can be calculated from the dipole nucleon cross section $\sigma = C\, r^2$: $<\sigma\, p_t^2> = 2\, C$.



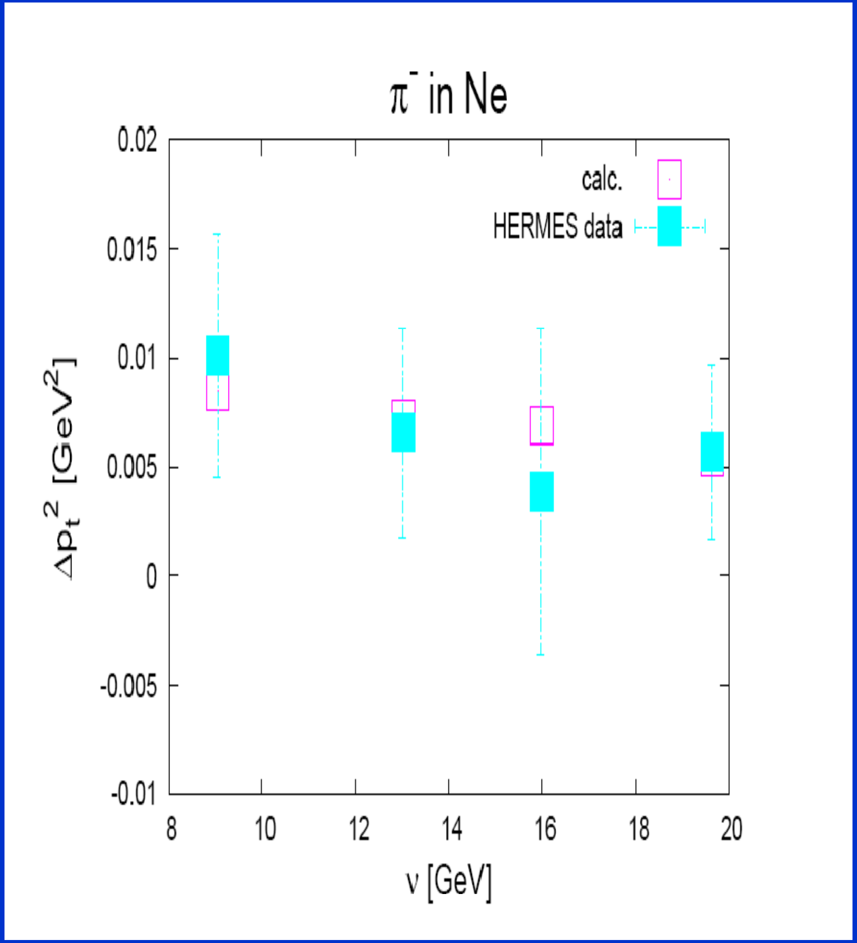
Mean Δp_t^2 of pions in Ne and Kr as a function of z_h





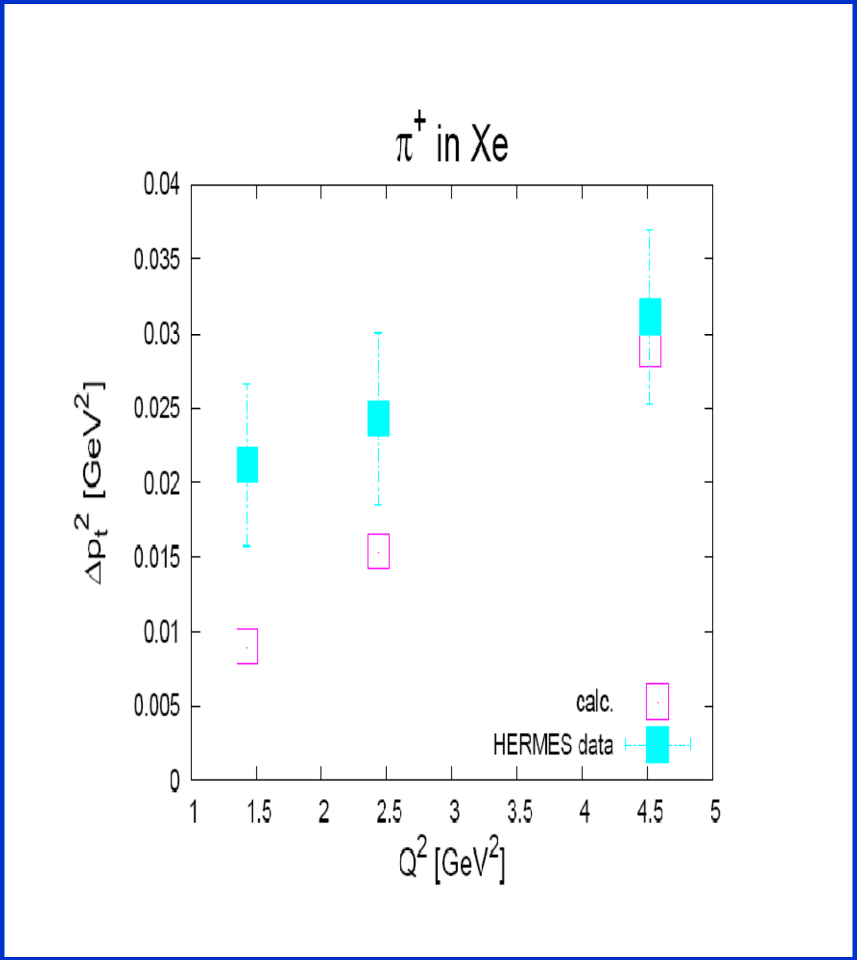
Mean Δp_t^2 of pions as a function on the photon energy ν

- For the ν-dependence of the Hermes data, it is very important to have the correct ν –acceptance and its correlation with z_h
- Otherwise one would expect a linear increase, because of longer prehadron formation length $l_p \sim \nu$



Experimental data confirm this hypothesis

- Hermes data show a linear increase with Q^2 over a small interval 1 $GeV^2 < Q^2 < 5$ GeV^2
- Compatible with the theoretical calculation (open squares)



General Parton evolution by branching processes

- We use a distribution function which includes the additional important transverse momentum variable p_t
- Momentum fraction is *z*, the virtuality (mass squared) is Q^2 .
- We start from the initial condition:

$$D_i^j(z, Q_0^2, \vec{p}_t) = \delta(i,j)\delta(x-1)\delta^2(p_T) \tag{18}$$

and the equation is:

$$Q^2 \frac{D_i^j(z, Q^2, \vec{p}_t)}{\partial Q^2} = \tag{19}$$

$$= \frac{\alpha_s(Q^2)}{2\pi} \int_z^1 \frac{du}{u} P_i^r(u, \alpha_s(Q^2)) \frac{d^2\vec{q}_t}{\pi} \delta(u(1-u)Q^2 - Q_0^2/4 - q_t^2) D_r^j(z/u, Q^2, \vec{p}_t - z/u\vec{q}_t)$$

A. Bassetto, M. Ciafaloni and G. Marchesini, Nucl. Phys. B **163** (1980) 477.

What happens in the hot quark gluon plasma?

- Instead of the l_p in the cold medium the life time of the parton between splittings enters as E/Q^2
- Instead of colliding with nucleons the parton collides with quarks and gluons
- The density of plasma particles $n_g=2\ T^3$
- The cross section is determined by Debye-screened gluon exchange

Modification of DGLAP-evolution equation in the quark gluon plasma

$$Q^2 \frac{\partial D_i^j(z, Q^2, \vec{p}_t)}{\partial Q^2} =$$

$$= \frac{\alpha_s(Q^2)}{2\pi} \int_z^1 \frac{du}{u} P_i^r(u, \alpha_s(Q^2)) \frac{d^2\vec{q}_t}{\pi} \delta(u(1-u)Q^2 - Q_0^2 - q_t^2) D_r^j(z/u, Q^2, \vec{p}_t - z/u\vec{q}_t) + S(Q^2, \vec{p}_t) \tag{23}$$

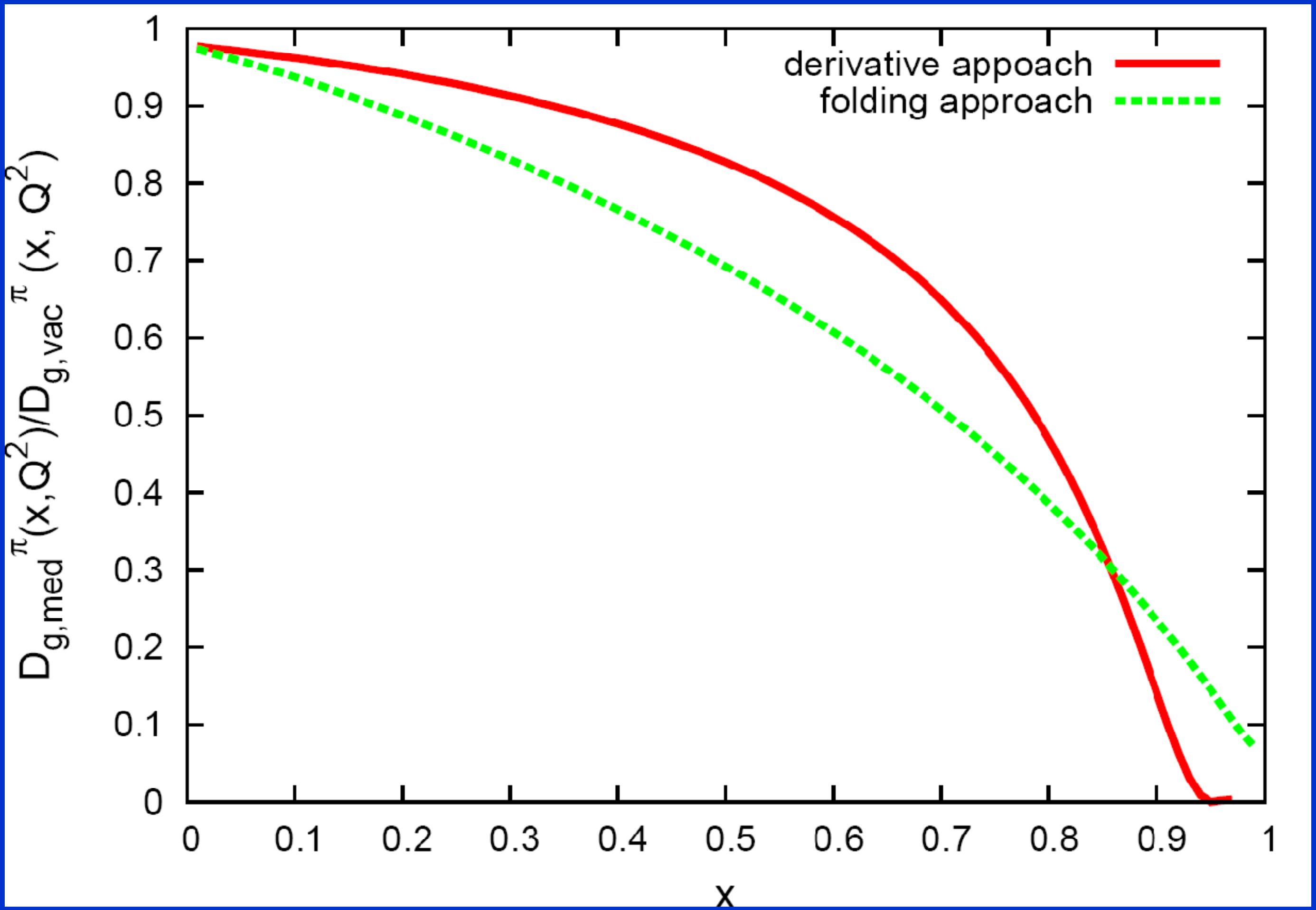
with the scattering term $S(Q^2, p_t)$, note The Lorentz factor is really zE .

$$S(Q^2, \vec{p}_t) = zE/Q_0^2 n_g \int_z^1 dw \int d^2\vec{q}_t \frac{d\sigma_i^r}{d^2\vec{q}_t} (D_r^j(w, Q^2, \vec{p}_t - w\vec{q}_t) - D_r^j(z, Q^2, \vec{p}_t)) \delta(w - z - \frac{q_t^2}{2m_g E}). \tag{24}$$

As before, we limit ourselves to the gluon cascade

Results for jet quenching in the Quark Gluon Plasma

See talk of S. Domdey



Conclusions

- Parton- Scattering is main agent for Δp_t^2 broadening in cold and hot medium
- Δp_t^2 broadening tests the three stage picture of hadron formation in the cold nucleus
- Radiation and scattering are interleaved in parton fragmentation in cold and hot matter (DGLAP-eq. with splitting and scattering term)

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>>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

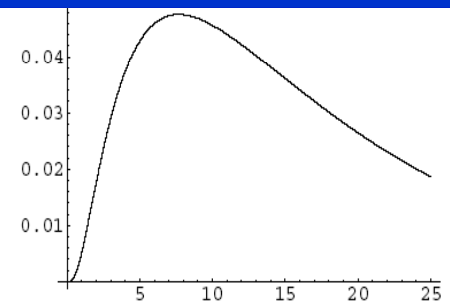
$$z_c D'_{h/c}(z_c, Q_c^2) = z'_c D_{h/c}(z'_c, Q_{c'}^2) + N_g z_g D_{h/g}(z_g, Q_g^2) \; ;$$

$$z'_c = \frac{p_h}{p_c - \Delta E_c(p_c, \phi)} , \quad z_g = \frac{p_h}{\Delta E_c(p_c, \phi)/N_g} ,$$

Modification of fragmentation function separated from energy loss is not justified

Space time development (Initial virtuality t0=100 Gev^2-→t1)

p

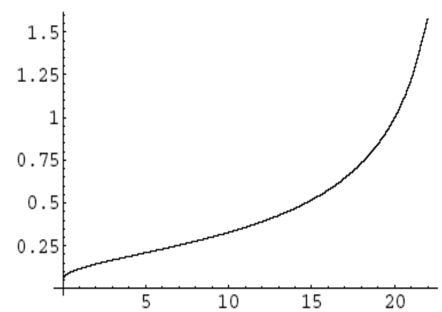


Out[45]= - Graphics -

- Probability Distribution of radiated virtualities t1 when original virtuality is t0=10 GeV^2

In[46]:= Plot[{.2*T[t]}, {t, 0.1, 22}]

t[fm]



Out[46]= - Graphics -

- Mean Time in fm for radiation as a function of radiated virtuality t1 [GeV^2]

Take RHIC case:
Mean final virtuality [GeV^2] of radiated gluons is t1=10 GeV^2

Mean time for radiation
<t>=0.7 fm/c

This changes the picture of high p_T Suppression

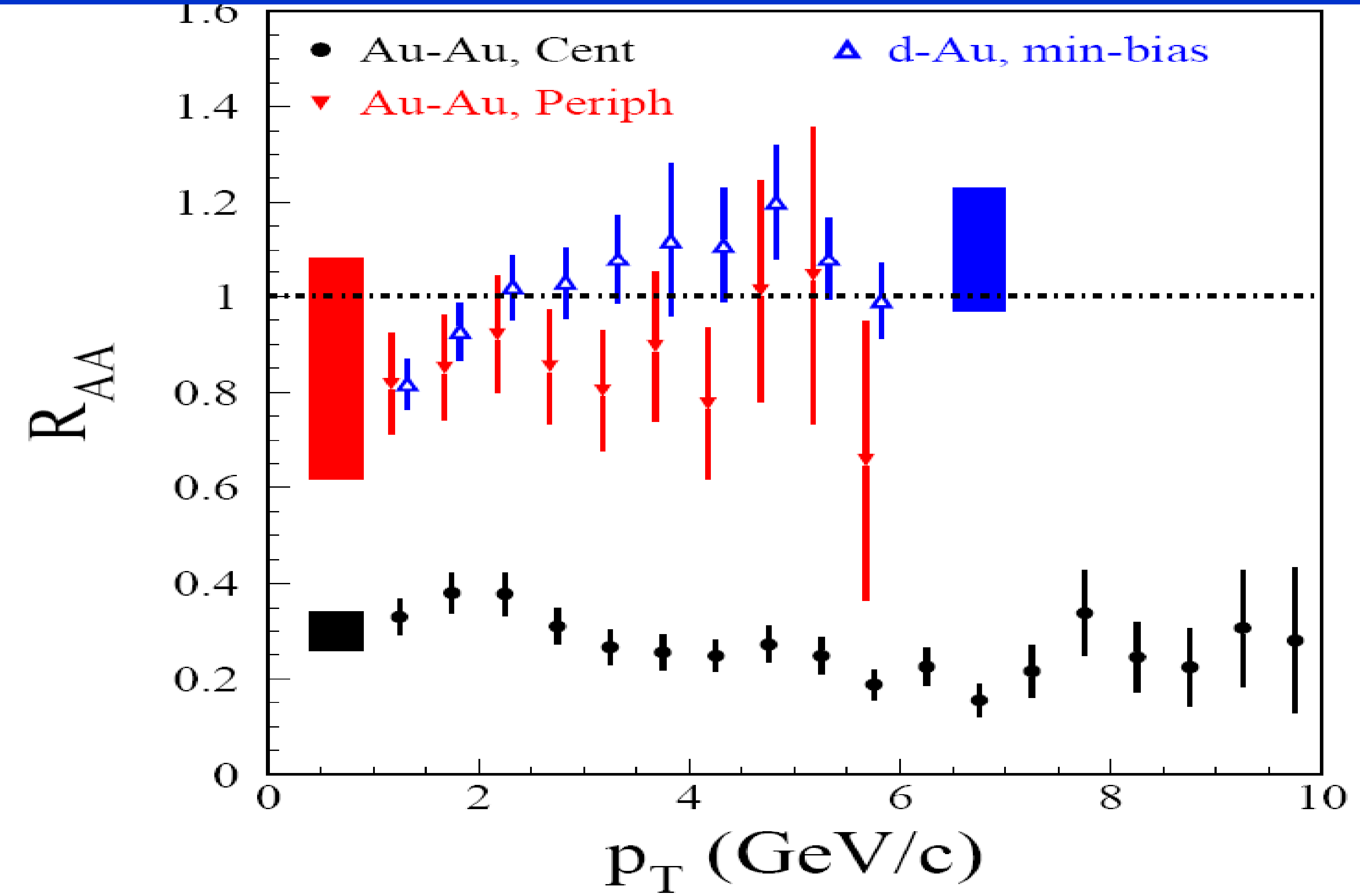


Fig. 36. π^0 $R_{AA}(p_T)$ for central (0–10 %) and peripheral (80–92 %) Au+Au collisions

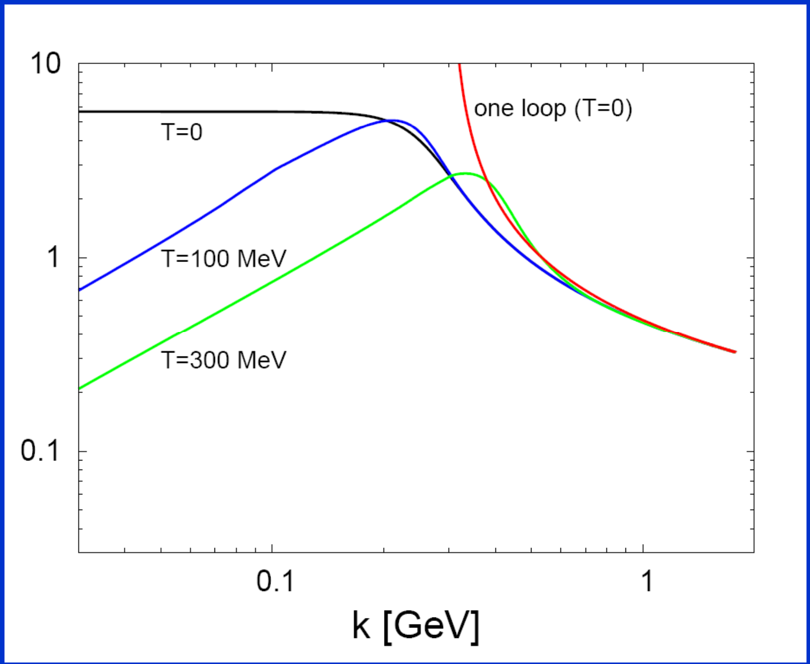
High p_t Suppression

- 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=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)

$$d\sigma_i / dq_{\perp i}^2 \approx C_i \frac{4\pi\alpha^2}{(q_{\perp i}^2 + \mu^2)^2}$$



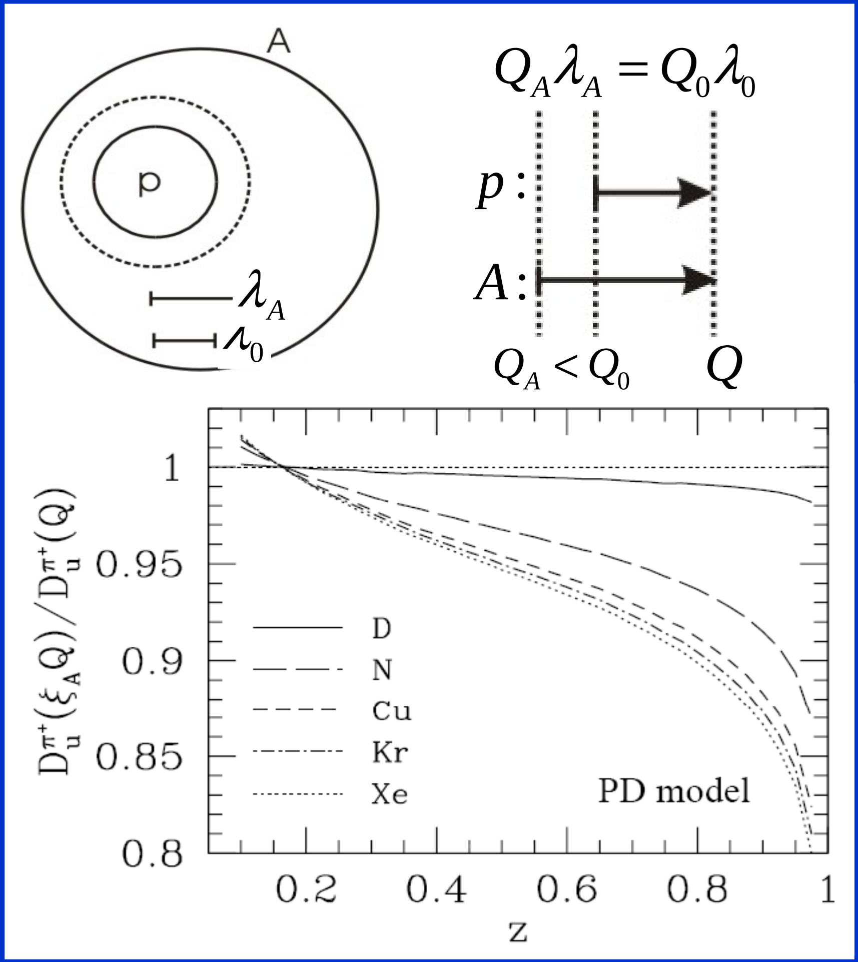
III. Binary Scaling and Hard Scattering

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

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

$$E\frac{d^3\sigma}{d^3p} = \frac{1}{p_T^n}F(x_T) = \frac{1}{\sqrt{s}^n}G(x_T)\ ,$$

Rescaling of PDF and FF



- Assume change of confinement scale in bound nucleons $\lambda_A > \lambda_0$
- Two consequences:

1.)

$$\frac{1}{A} q_f^{N|A}(x, Q^2) = q_f^N(x, \xi_A(Q^2) Q^2)$$

$$D_f^{h|A}(z, Q^2) = D_f^h(z, \xi_A(Q^2) Q^2)$$

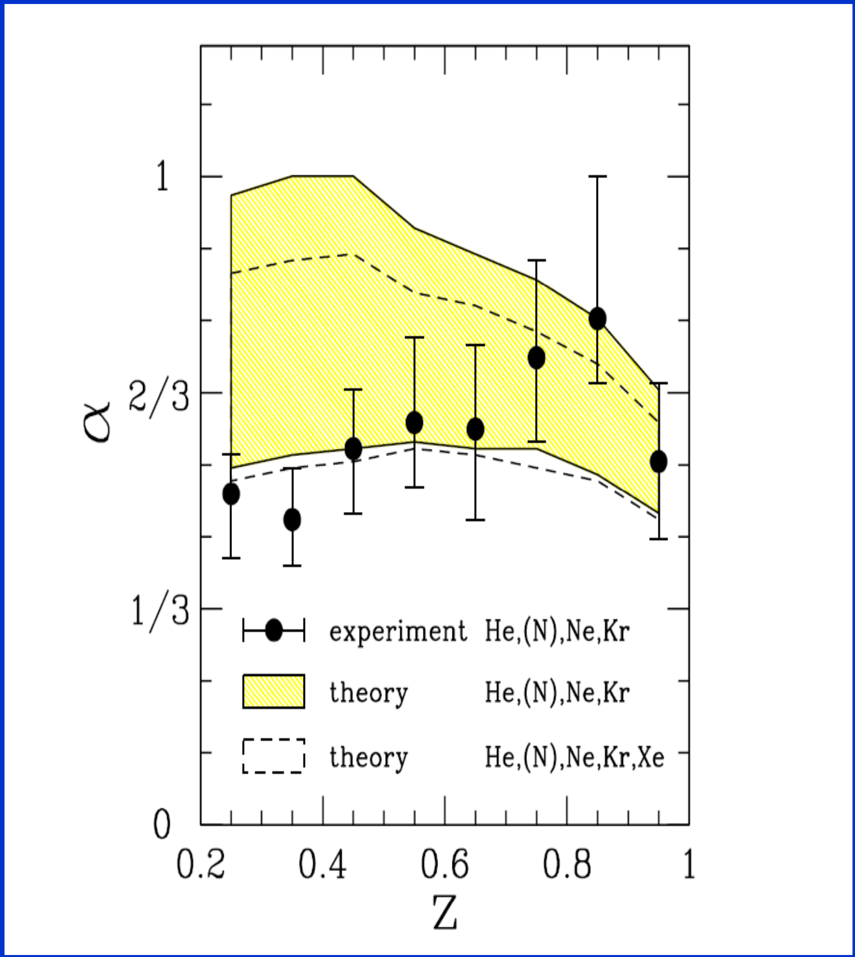
$$\xi_A(Q^2) = \left(\frac{\lambda_A}{\lambda_0}\right)^{\frac{\bar{\alpha}_s}{\alpha_s(Q^2)}}$$

2.)

$$\kappa_A \lambda_A^2 = \kappa \lambda_0^2$$

- Rescaling implies a longer DGLAP evolution (increased gluon shower)

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

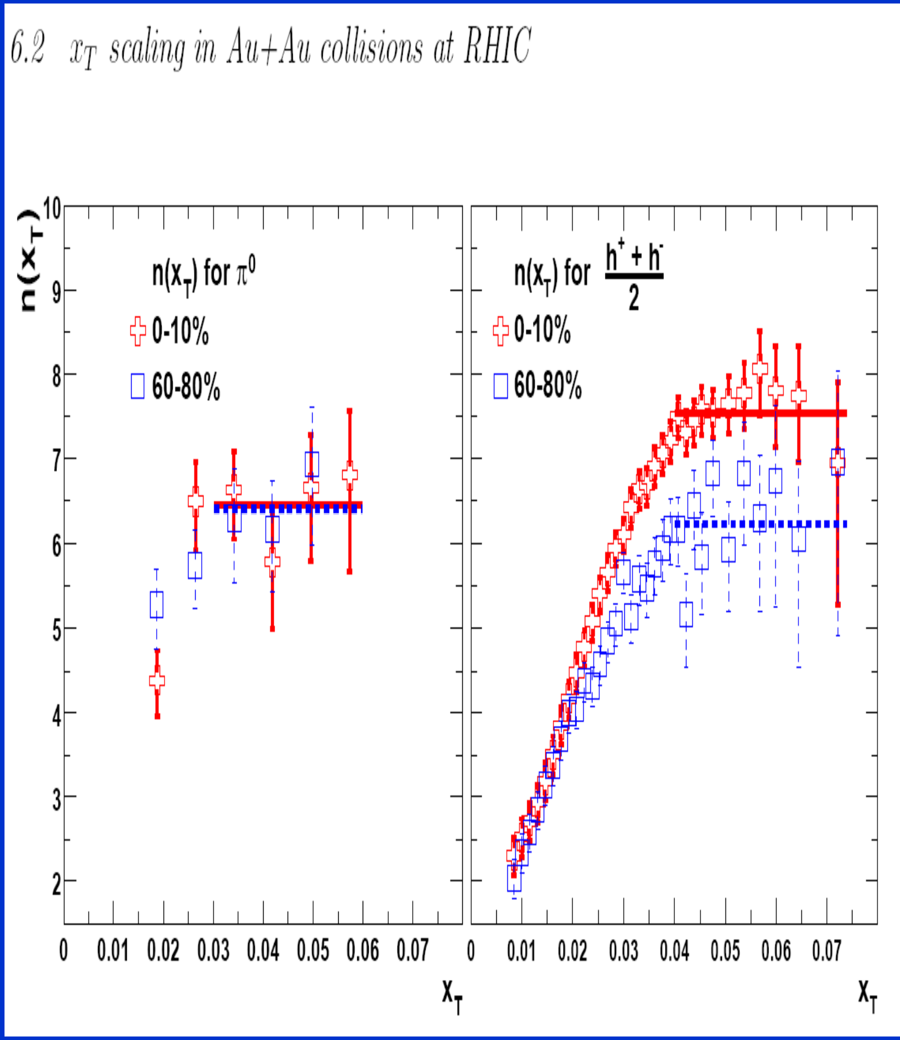
Pure dimensional counting of the number of active participants determines the exponent

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

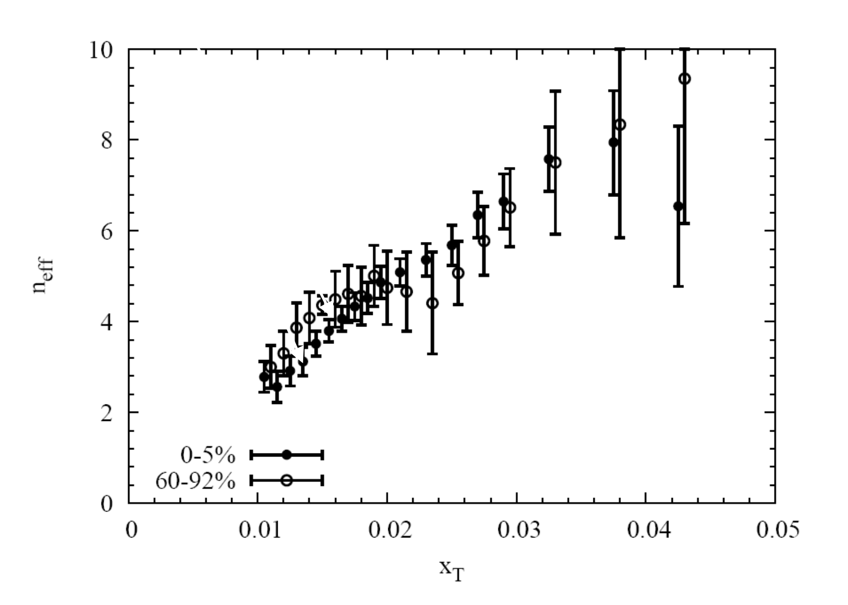
- n(y,x_R)=2*n(active with hard pt)-4 ; (x_R=xt at y=0)
- 4 active participants give n(y,x_R)=4
- RHIC measures n=6.3 or n=7.8,depending on particle species
- The smaller number n=6 is compatible with hard gluon radiation NLO calculations
- The larger number n=8 points to more complicated processes e.g. for proton production (q+q->qqq+qbar)

Data show nonscaling behaviour for protons

Phenix analysis



Protons



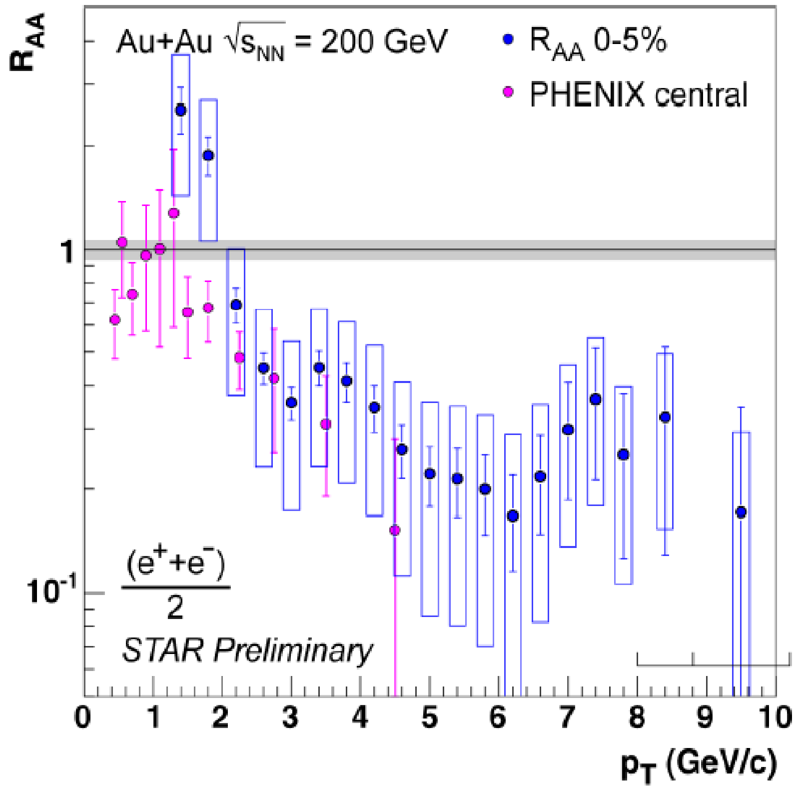
Final state interaction may change the scaling behaviour ¢ n would decrease with x_t if energy loss like in BDMPS occurs

Conclusions

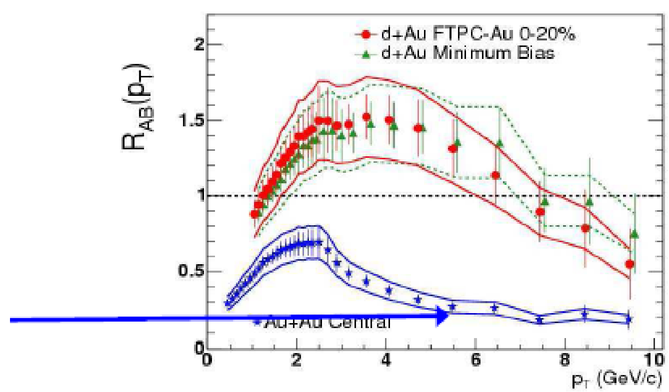
- Meson production at low $\langle Q^2 \rangle = 2.5\ GeV^2$ in Hermes is well described by the string model with prehadron formation and absorption
- Data with high $\langle pt^2 \rangle = 100 GeV^2$ at RHIC or LHC need a correct treatment of vacuum energy loss
- The gluon radiation time of the time 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 then expected from BDMPS-energy loss picture

Heavy Flavor R_{AA}

STAR



Charged Hadron 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,Bielcik(5c)

Calculation of Prehadron Formation Lengths

$$\langle l^*_{\geq 1} \rangle = \frac{1+D_a}{1+C+(D_a-C)z}(1-z)\,z\,L$$

$$\times\left[1+\frac{1+C}{2+D_a}\frac{(1-z)}{z^{2+D_a}}\,{}_2F_1\left(2+D_a,2+D_a;3+D_a;\frac{z-1}{z}\right)\right]$$

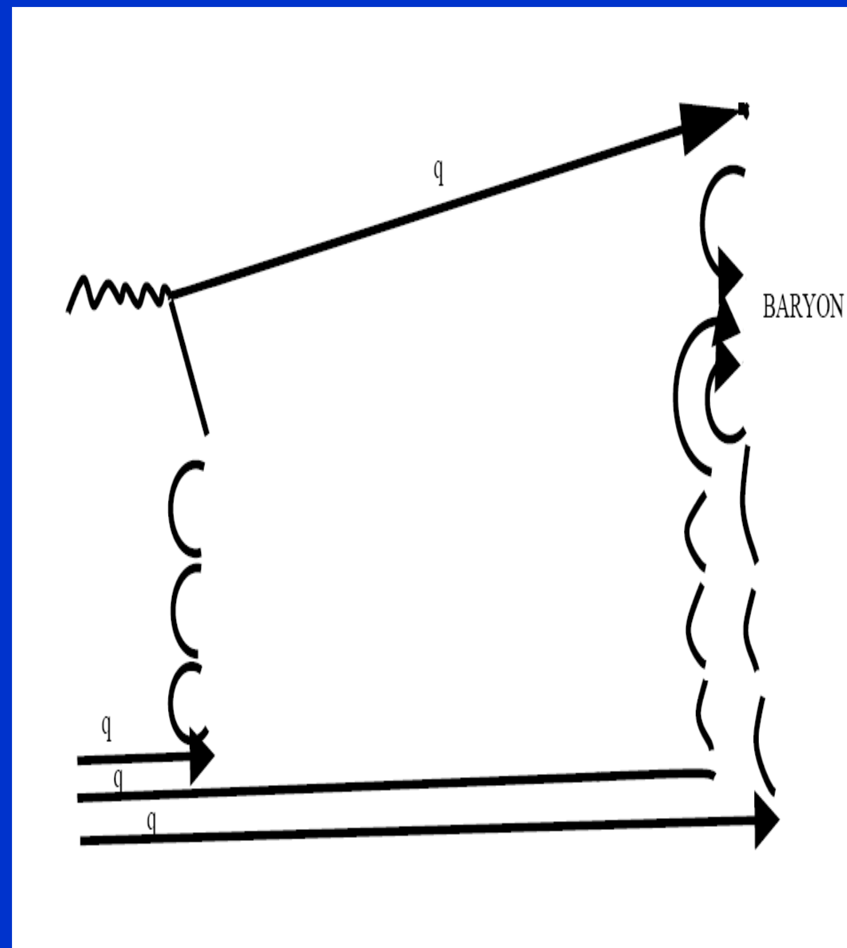
F- Hypergeometric Function, C=0.3, D arise from the string fragmentation f(u)=(1-u)^D
Dq=0.3 for producing a quark and Dqq=1.3 for producing a diquark

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

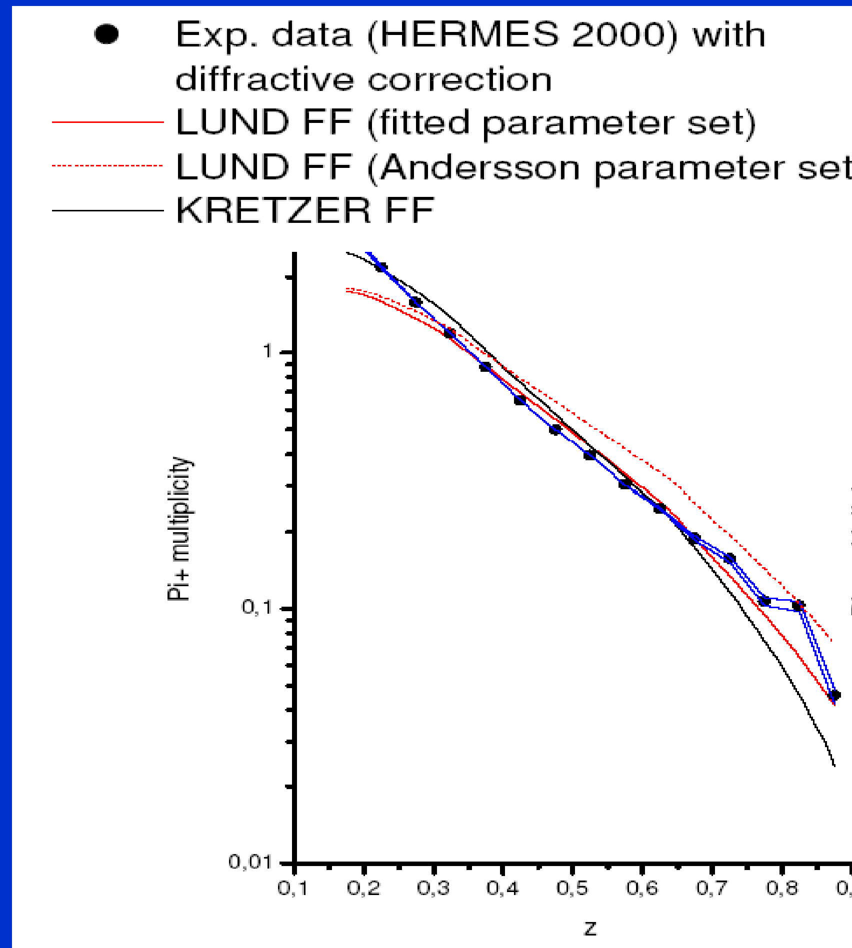
2) String branching

- 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)



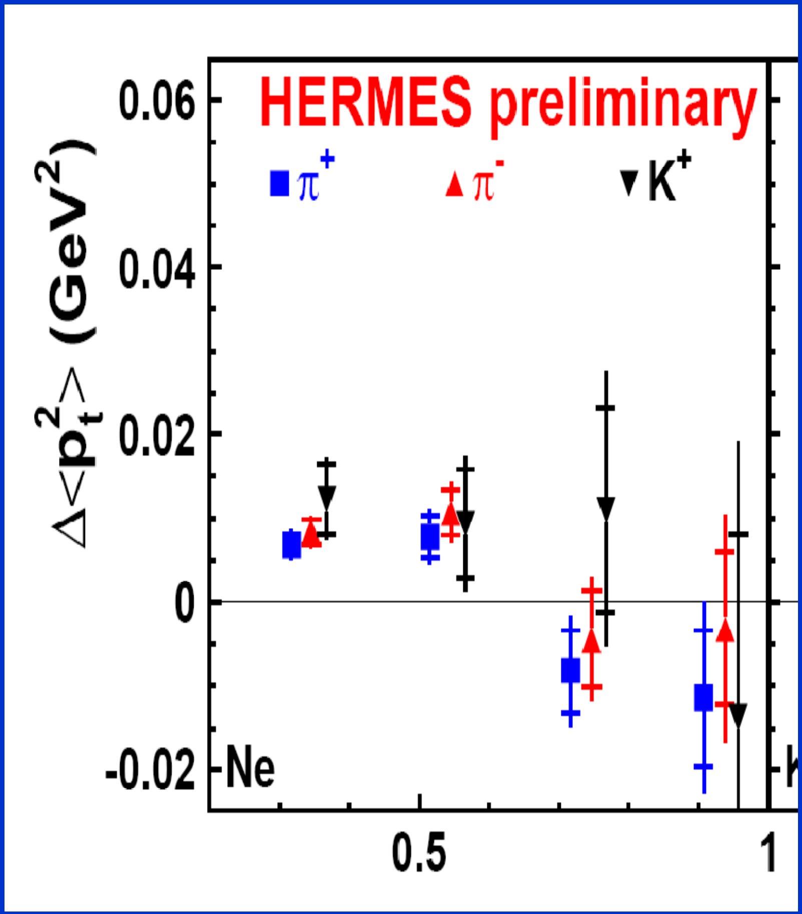
Pion Multiplicity on the Proton

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



Additional indication for prehadron formation from new Hermes Data

GeV^2



- Variation of mean produced hadron pt^2 shows that only the pt acquired by the propagating quark does contribute
- When z becomes larger the prehadron formation occurs earlies ->less p-t.
- In smaller Fe and C nuclei the size of the nucleus terminates the process earlier

<-z of the produced hadron

The Calculation of Absorption

$$\frac{1}{N_A^{DIS}}\frac{dN_A^h(z)}{dz} = \frac{1}{\sigma^{lA}} \int_{\text{exp. cuts}} dx d\nu \sum_f e_f^2 q_f^A(x, \xi_A Q^2) \frac{d\sigma^{lq}}{dx d\nu} \times D_f^h(z, \xi_A Q^2) N_A(z, \nu),$$

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