Jet Evolution in Hot and Cold Matter

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Outline of the talk:

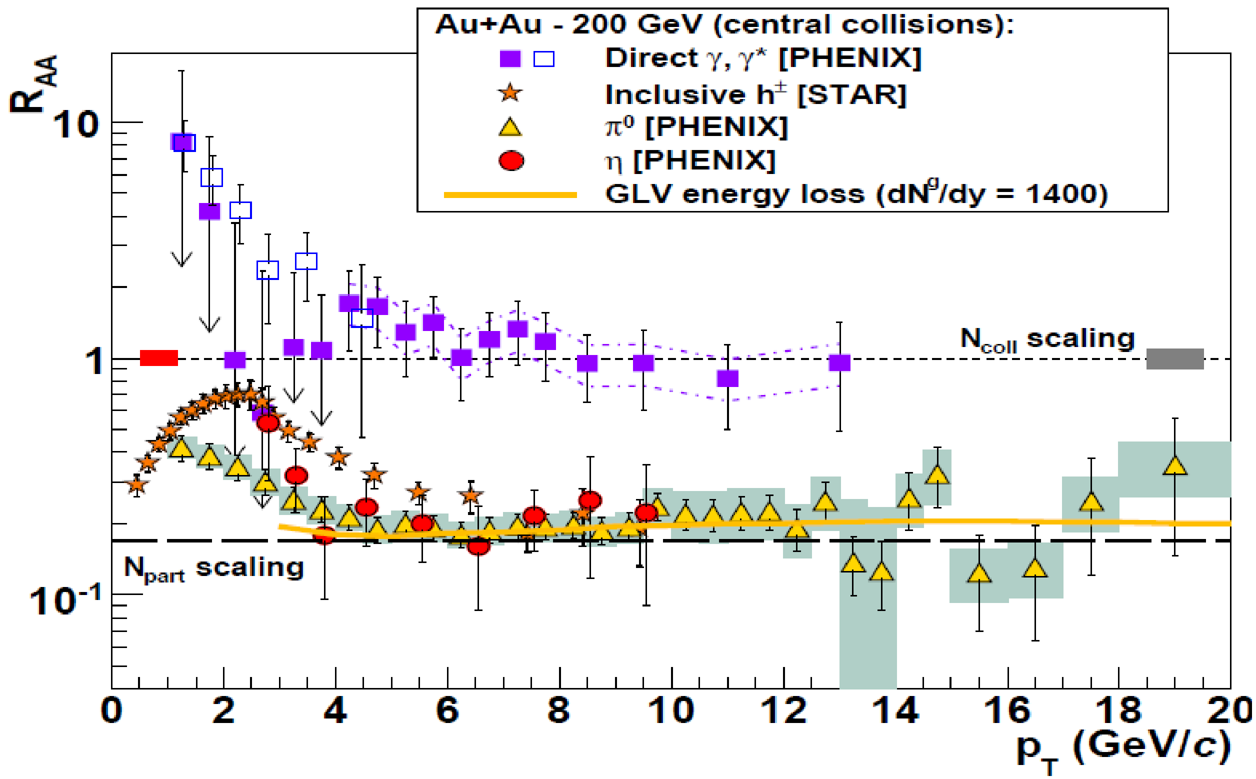
Hot matter: Nucleus-Nucleus

- Modification of the evolution equations in the quark gluon plasma
- R(AA) and dN/dlogx distribution of partons in the jet

Cold Matter: Lepton-Nucleus

- Ratio of produced hadrons
- Mean transverse momentum

High p_T-Suppression, due to parton energy loss ?



Time Scales

- Equilibration time τ_0 of the plasma, which is estimated to be of the order of 0.5 fm at RHIC but much smaller (< 0.2 fm) at LHC. [1][REFS]

Phenix, NPA 757 (2005)

- Life time of the plasma which we estimate from longitudinal Bjorken expansion []

Bjorken , Fermilab Pub 82-059

$$\tau_c = \tau_0 \left(\frac{T_0}{T_c} \right)^3 \tag{19}$$

For an initial temperature $T_0 = 0.3$ GeV at RHIC and $T_0 = 0.5$ GeV at LHC, we find $\tau_c = 3.3$ fm at RHIC and $\tau_c = 6.1$ fm at LHC.

- Time for evolution of the parton from Q_{max} to Q_0

$$\tau_{\mathrm{evo}} = \frac{E}{Q_0^2} - \frac{E}{Q_{\mathrm{max}}^2} \tag{20}$$

Different Hierarchies at RHIC and LHC

With $E = Q_{\text{max}} = 20$ GeV for RHIC and $E = Q_{\text{max}} = 100$ GeV for LHC (and $Q_0 = \sqrt{2}$ GeV), we find $\tau_{\text{evo}} = 2$ fm for RHIC and $\tau_{\text{evo}} = 10$ fm for LHC.

- For central AuAu collisions and central PbPb collisions, the size of the plasma is almost identical when measured in terms of the size of the nuclei involved: $R_{\text{Au}} = 6.9$ fm and $R_{\text{Pb}} = 7.1$ fm.

RHIC: Shower evolution time ≈ Plasma lifetime < Size

LHC: Size ≈ Plasma lifetime < Shower evolution time

Shower evolution and scattering in the plasma occur together

$$\frac{\partial D^m(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{\mathrm{d}z}{z} P(z) D^m\left(\frac{x}{z},Q^2\right) + S(x,Q^2).$$

Scattering term S(x,Q):

$$S(x,Q^2) \;=\; \frac{E}{Q^2}\bar{n}\int_x^1 \mathrm{d}w \int \mathrm{d}q_\perp^2 \frac{\mathrm{d}\bar{\sigma}}{\mathrm{d}q_\perp^2}\left(wD^m(w,Q^2) - xD^m(x,Q^2)\right) \times\delta\left(w - x - \frac{q_\perp^2}{2m_s E}\right)$$

n: plasma density, σ: cross section of quarks/gluons

Simplify scattering term:

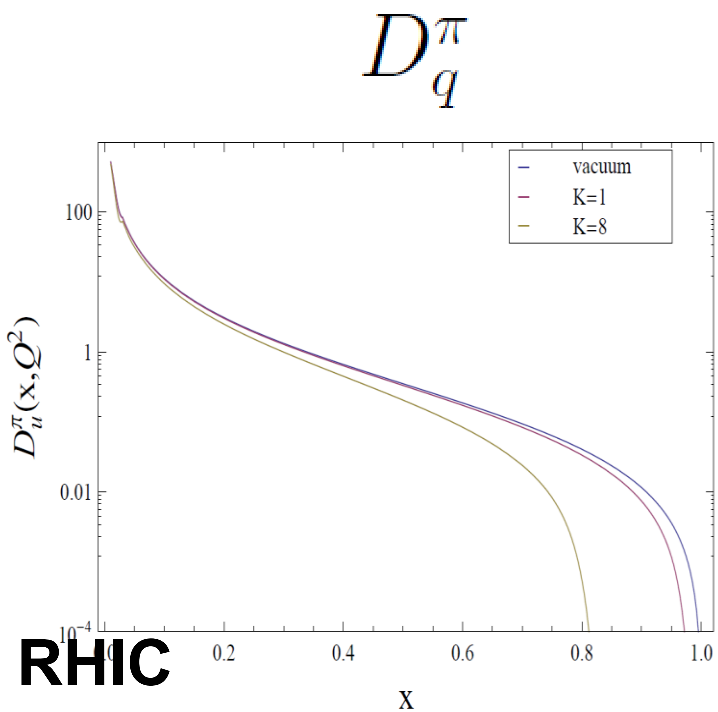
$$S(x,Q^2) = K\frac{\bar{n}\bar{\sigma}\langle q_\perp^2\rangle}{2m_sQ^2}\left(D^m(x,Q^2) + x\frac{\partial D^m}{\partial x}(x,Q^2)\right)$$

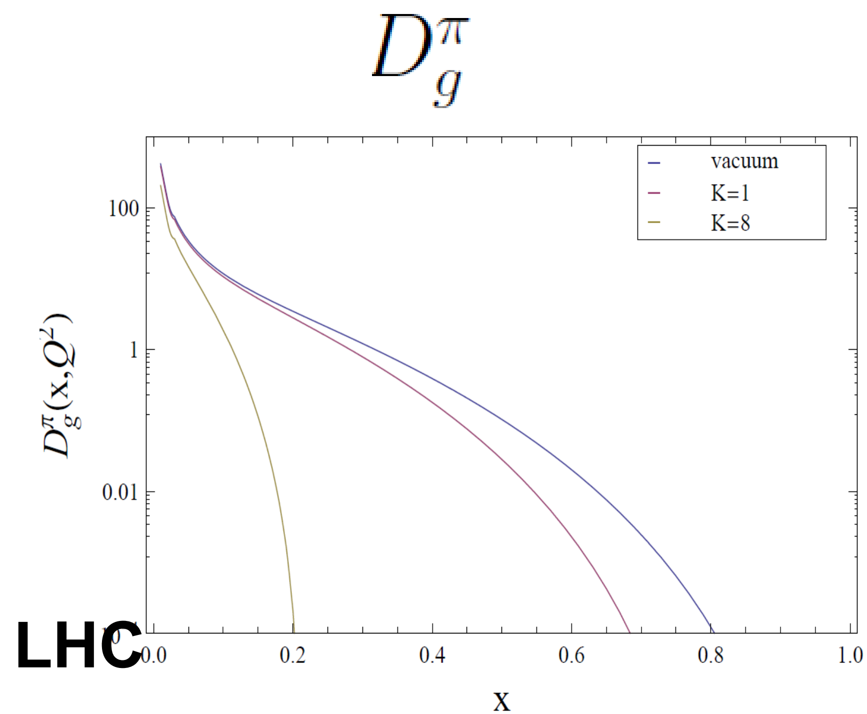
$$\hat{q} \simeq \bar{n}\bar{\sigma}\langle q_\perp^2\rangle$$

q as jet transport parameter, ms as thermal gluon mass, K defines a possible enhancement factor

$\hat{q}$ [GeV^2/fm]	$T = 0.3$ GeV	$T = 0.5$ GeV
Scenario 1 (parton energy loss + absorption), $K = 1$	0.5	5.2
Scenario 2 (large parton energy loss), $K = 8$	4.0	41.9

Modified Fragmentation Functions in the Plasma



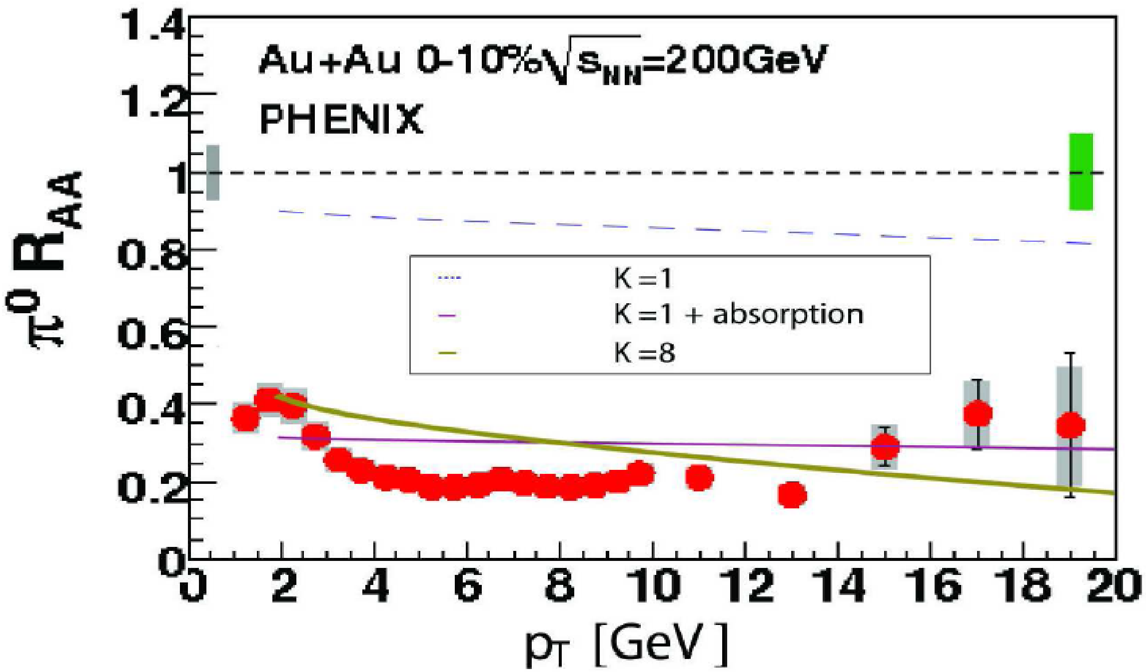


Left: quark fragmentation, max Q=20 GeV, T=0.3 GeV
Right: gluon fragmentation, max Q=100 GeV, T=0.5 GeV

Modification factor for RHIC:

$$R_{AA}(p_\perp) \simeq \frac{\int \mathrm{d}z\,\mathrm{d}q_\perp^2 \frac{\mathrm{d}\sigma}{\mathrm{d}q_\perp^2} D^m(z,Q^2)\delta(zq_\perp - p_\perp)}{\int \mathrm{d}z\,\mathrm{d}q_\perp^2 \frac{\mathrm{d}\sigma}{\mathrm{d}q_\perp^2} D^v(z,Q^2)\delta(zq_\perp - p_\perp)}$$

Dashed blue curve only parton energy loss, Full blue curve with prehadron absorption

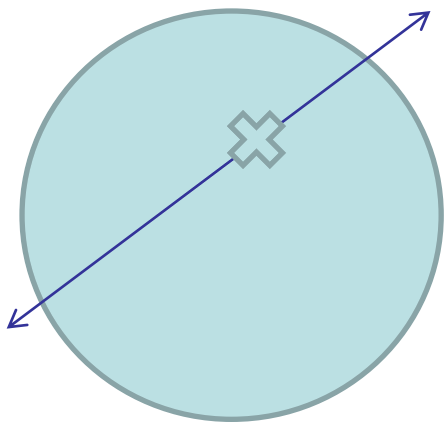


Effect of prehadron absorption at RHIC

- Since the lifetimes of the plasma and of the shower (2 fm) end before the exit out of the hot zone, there is the possibility of resonance matter formation and absorption of the preconfined hadron in this matter. Estimate absorption rate, with σres=30 mb, density of resonance gas nres ≈ Tc^3 at the critical temperature

Absorption Rate in Resonance matter:

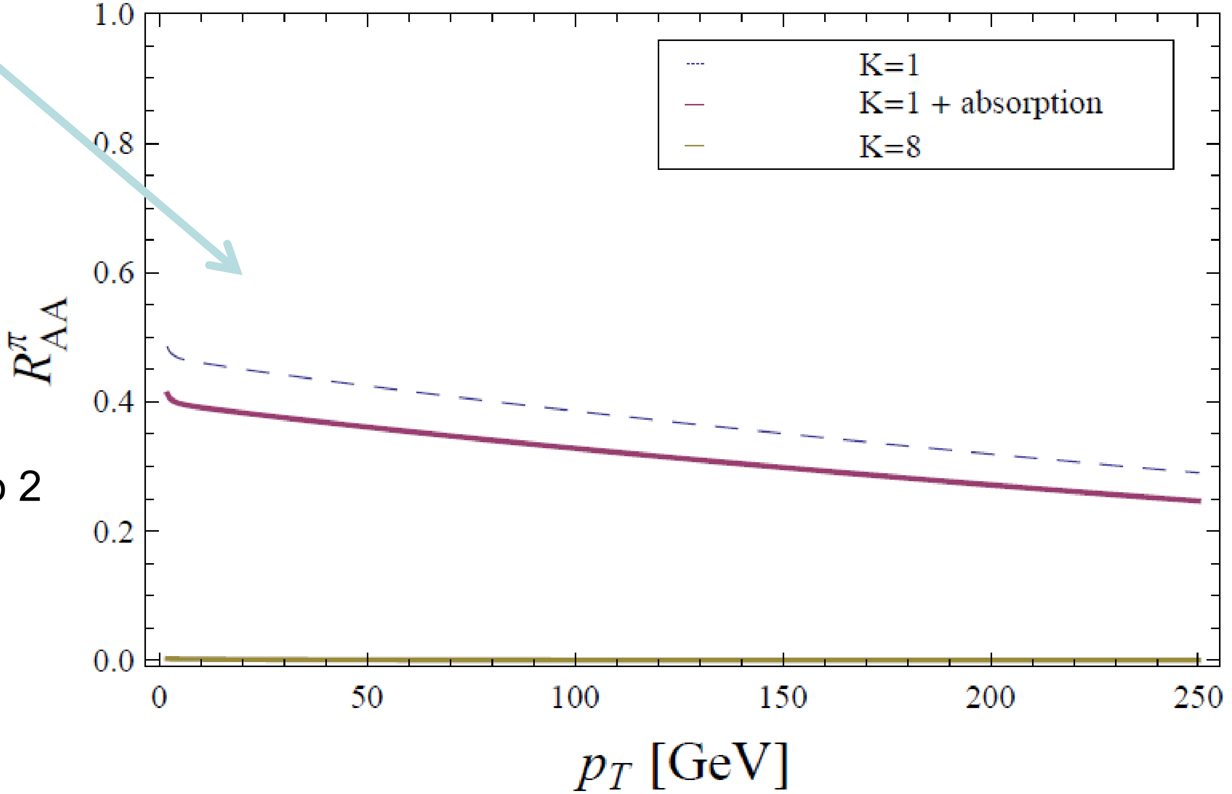
$$r_{\rm abs} = \frac{1}{2\pi}\frac{1}{\pi R^2}\int \mathrm{d}^2\mathbf{x}_0\,\mathrm{d}\phi_l \frac{1}{2}\left(e^{-n_{res}\sigma_{\rm res} l_1(R,x_0,\phi_l)} + e^{-n_{\rm res}\sigma_{\rm res} l_2(R,x_0,\phi_l)}\right)$$



- Parton can leave the hot zone in both directions on paths of length l1 or l2, remaining after τ (shower), we get for RHIC an absorption factor r =0.35, for LHC r = 0.9

Modification factor for LHC:

LHC will differentiate between scenario 1 and scenario 2



For K=1, the effect of absorption is strongly reduced,
For K=8 ,R(AA) = nil

Resume 1:

$$S(x,Q^2) = \epsilon \alpha_s (Q^2)^2 \frac{T^2}{Q^2} \left(D(x,Q^2) + x \frac{\partial D(x,Q^2)}{\partial x} \right)$$

The scattering term affects the fragmentation at LHC much more than at RHIC, since gluons interact stronger than quarks and the temperature Is higher, A small parton energy loss at RHIC + prehadron absorption in the resonance matter forming after 2 fm, i.e.
K=1 scenario, seems to be preferred, LHC can experimentally decide which scenario is correct. Extreme suppression would confirm the K=8 enhanced energy loss parameter.
Scattering term is higher twist (HT), similar HT-calculation is done by X.N. Wang et al. who modify the splitting function by a medium dependent term.

Jets become important at LHC

10^11/month

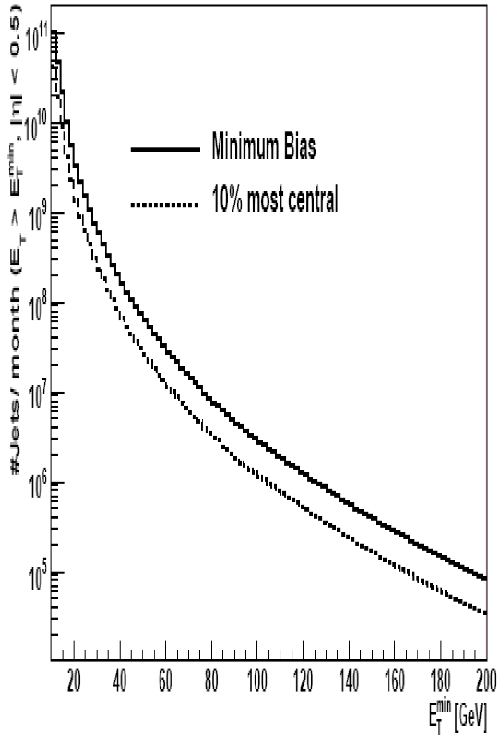


Figure 6.2: Number of jets with $E_T > E_T^{min}$ and $|\eta| < 0.5$ produced in Pb–Pb collisions in one effective month of running (10^6 s). The minimum bias rate (solid line) is compared to the rate in 10% most central collisions (dashed line).

100/event

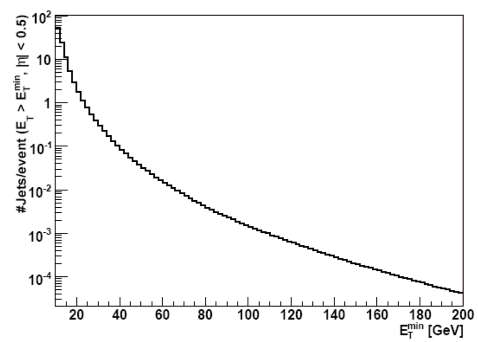


Figure 6.3: Average number of jets with $E_T > E_T^{min}$ and $|\eta| < 0.5$ per event in the 10% most central Pb–Pb collisions.

Modified Parton Distributions in the Jet at small x

- For small x, the evolution equation has to take into account „soft gluon suppression“.

$$\frac{\partial D(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{\mathrm{d}z}{z} P(z) D\left(\frac{x}{z}, z^2 Q^2\right) + S(x,Q^2)$$

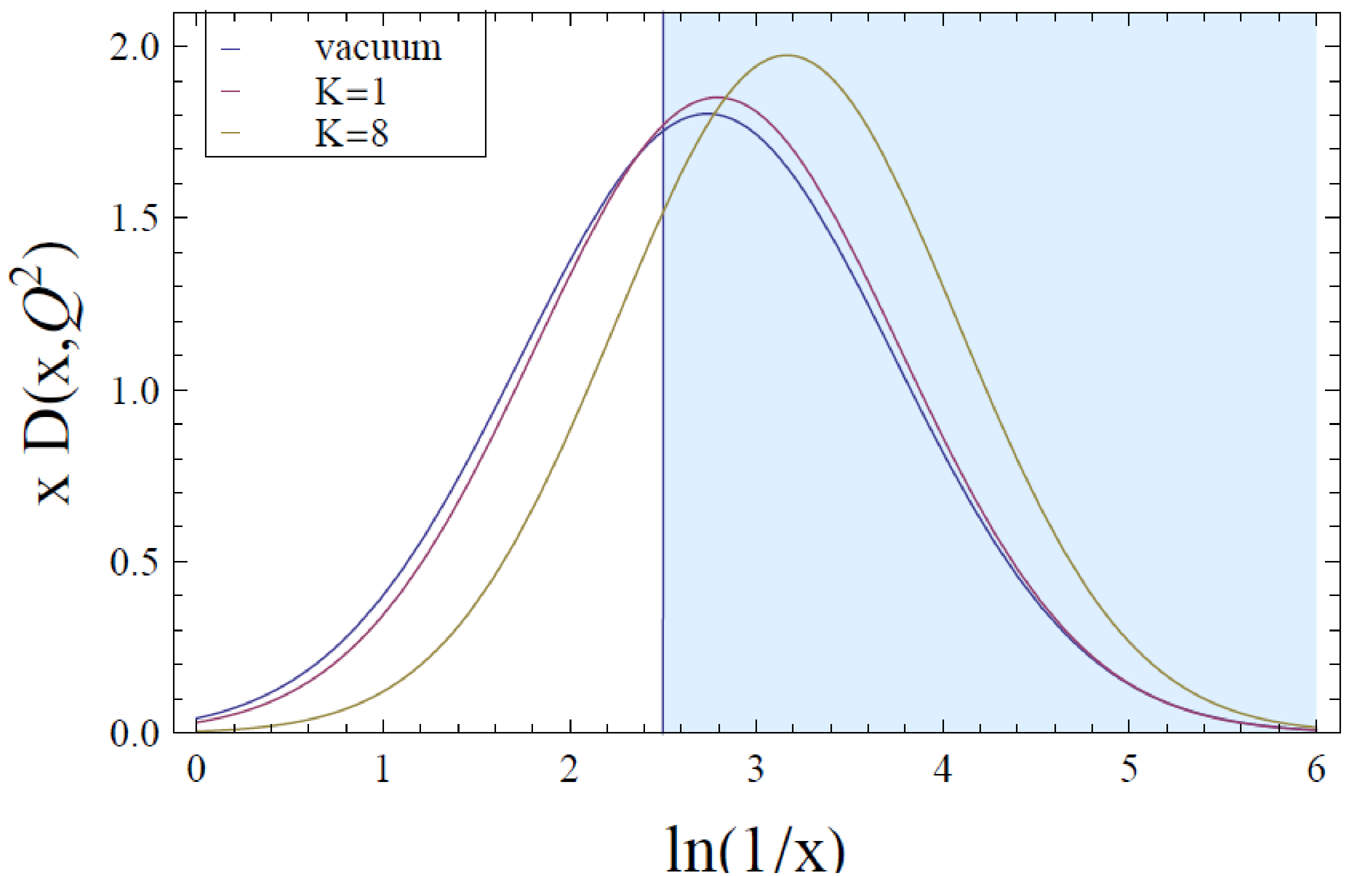
Using the scale (z Q) reduces gluon radiation at small z, get finite multiplicity

Method of full Solution:

- Use Mellin transform to solve the equation
- Make a Taylor expansion of the anomalous dimension around the Mellin moment (J=1) defining the multiplicity.
- The inverse Mellin transform in the complex J plane along the imaginary axis gives a Gaussian multiplicity distribution in ln(1/x)
- The zeroth order term is the normalization, the linear term gives the maximum, the quadratic the width of the Gaussian distribution in ln (1/x)
- The maximum and width are influenced by the medium

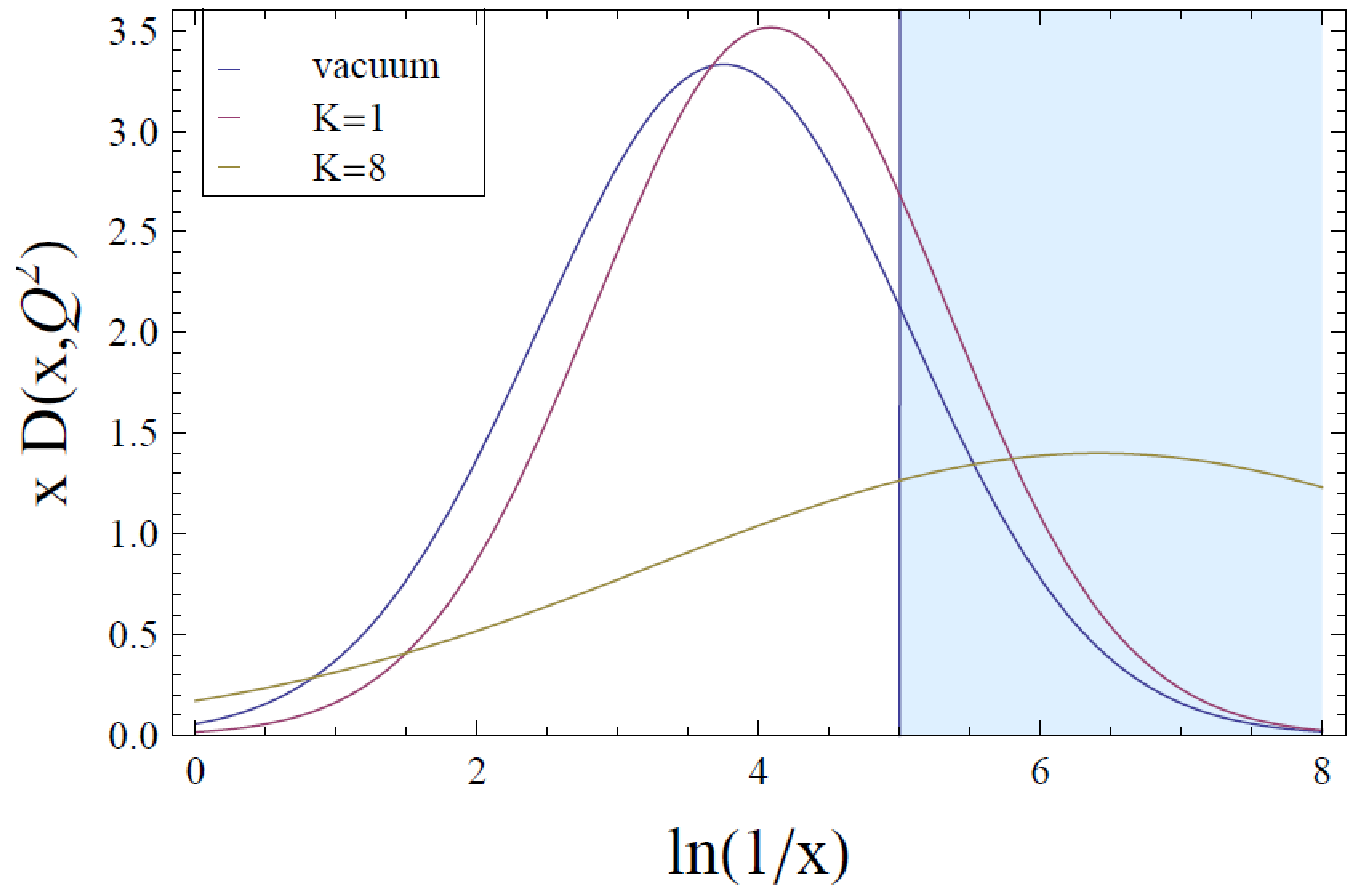
$$x\,D(x,Q^2) = \frac{n(Q^2)}{2\sqrt{\pi a_2}} \exp\left(-\frac{\left(\ln(\frac{1}{x}) - a_1\right)^2}{4a_2} \right).$$

Jet particle spectrum in vacuum and in the quark gluon plasma



At RHIC, the humped back plateau is obscured by plasma particles (blue area) , small shift to lower x

Jet particle spectrum in vacuum and in the quark gluon plasma



At LHC, K=8 would lead to a totally different jet structure

Modified moments:

	vacuum	medium
a_0	$\frac{1}{b}\sqrt{\frac{2C_A}{\pi\alpha_s}}$	0
a_1	$\frac{1}{4b\alpha_s}$	$-\frac{\epsilon}{2}\frac{T^2}{Q^2}\alpha_s^2$
a_2	$\sqrt{\frac{\pi}{2C_A}}\frac{1}{24b}\alpha_s^{-3/2}$	$\frac{\epsilon}{4}\sqrt{\frac{\pi}{2C_A}}\frac{T^2}{Q^2}\alpha_s^{3/2}$

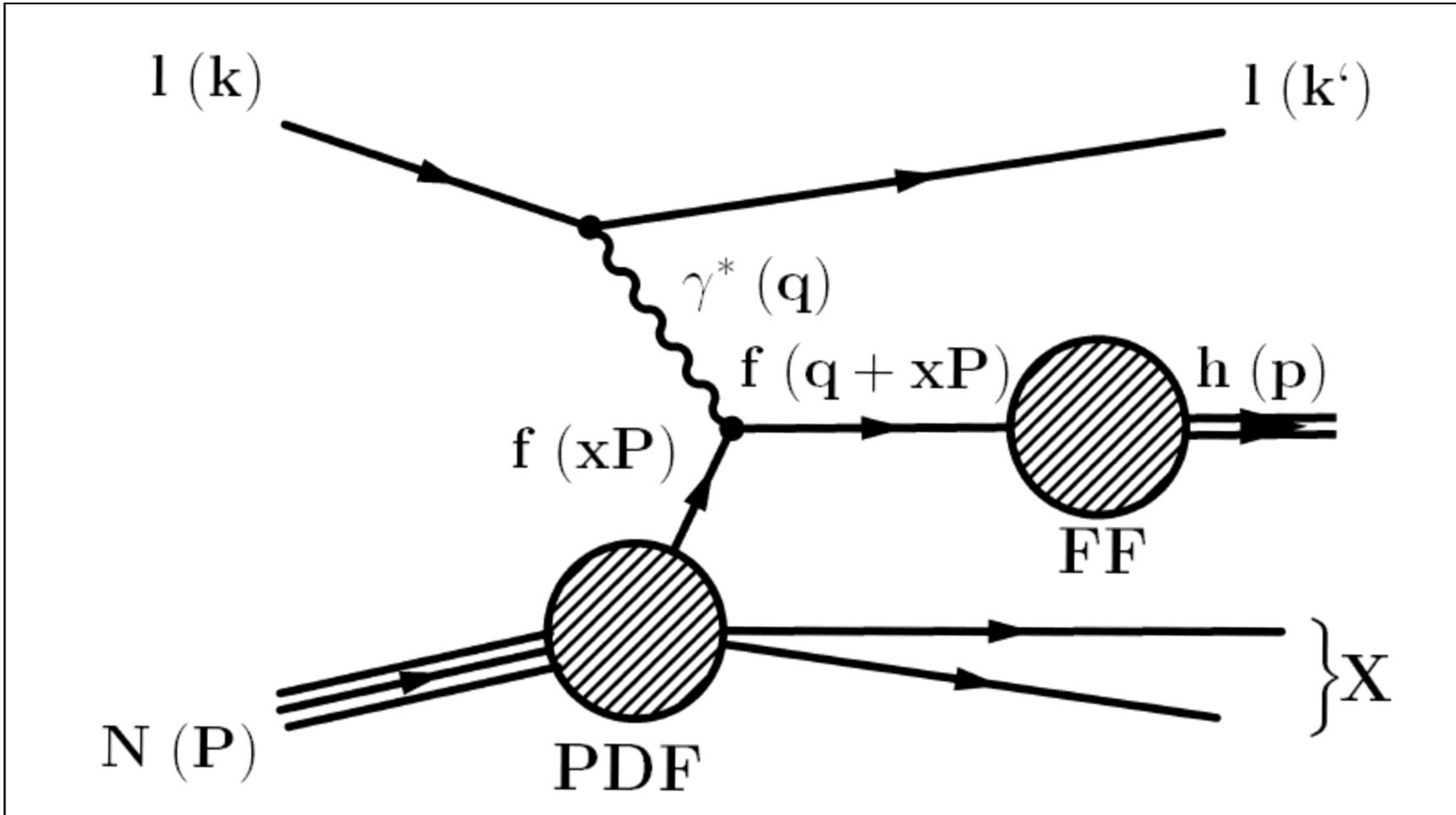
Tab. 2: *Leading terms of the Gaussian coefficients of the partons distributions in a jet in Mellin space, i.e.* $d(J, Q^2) \simeq \exp(a_0 + a_1(J-1) + a_2(J-1)^2)$ *which are related to multiplicity, peak position and width. The first column gives the value in vacuum while the second one shows the correction due to the medium in a Taylor series with respect to* ε. *We use a shorthand notation here: One should take* $\alpha_s \to \alpha_s(Q^2)$ *in every term and subtract the same term with* $\alpha_s \to \alpha_s(Q_0^2)$.

ε= 5.4 K for quark jet , ε=12.2 K for gluon jet.

Resume 2:

- The leading log vacuum evolution + HT scattering term describe jet evolution in the plasma
- Results of evolution equations show the same multiplicity shifted to lower x with a slightly increased width
- Solutions can be calculated parametrically as a function of plasma density or temperature
- Complement Monte Carlo simulations (e.g. Jewel by U. Wiedemann and K.Zapp)
- Jets at LHC are not influenced by prehadron formation, and finalize the choice between the two scenarios (K=1 and K=8)

Parton evolution in cold matter

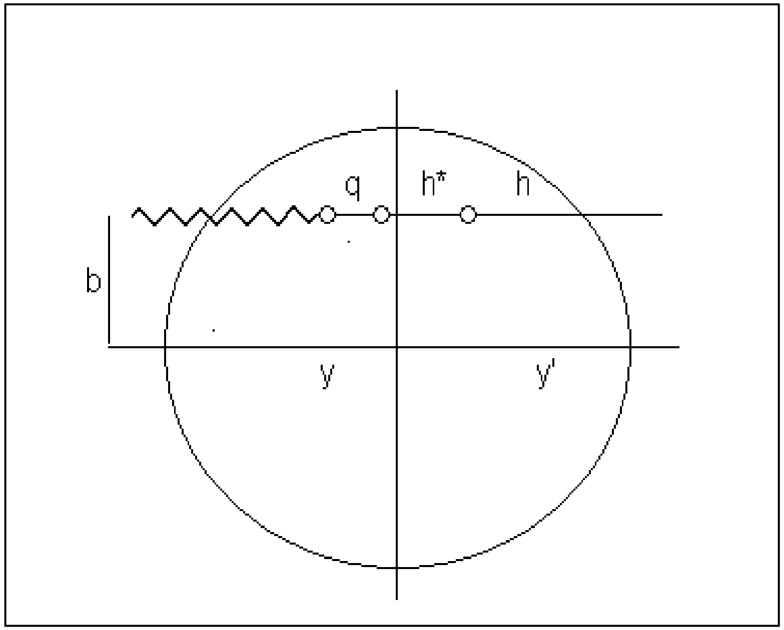


Differentiate between medium x and low x:

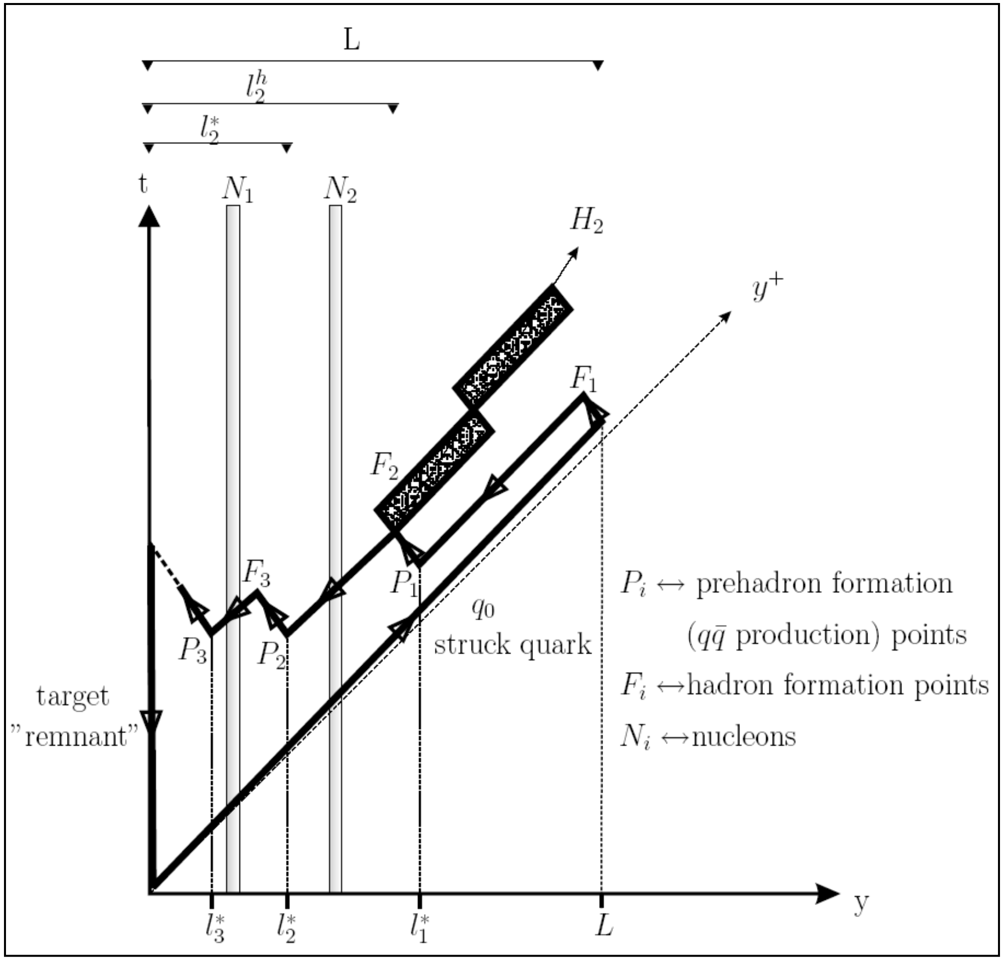
- Medium x, e.g. favoured at Hermes makes it possible to follow the evolution of a single quark
- Low x favoured at EIC e.g. leads to a photon transforming into a dijet in the rest frame of the nucleus, one can study this dijet (quark-antiquark) evolution (e.jet 2-axis out of plane photon+jet1)

Medium x and not too high Q:

- 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



Hermes favours a string picture, since <Q> ≈2.5 GeV



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

Prehadron Formation Lengths l*/(ν/κ)

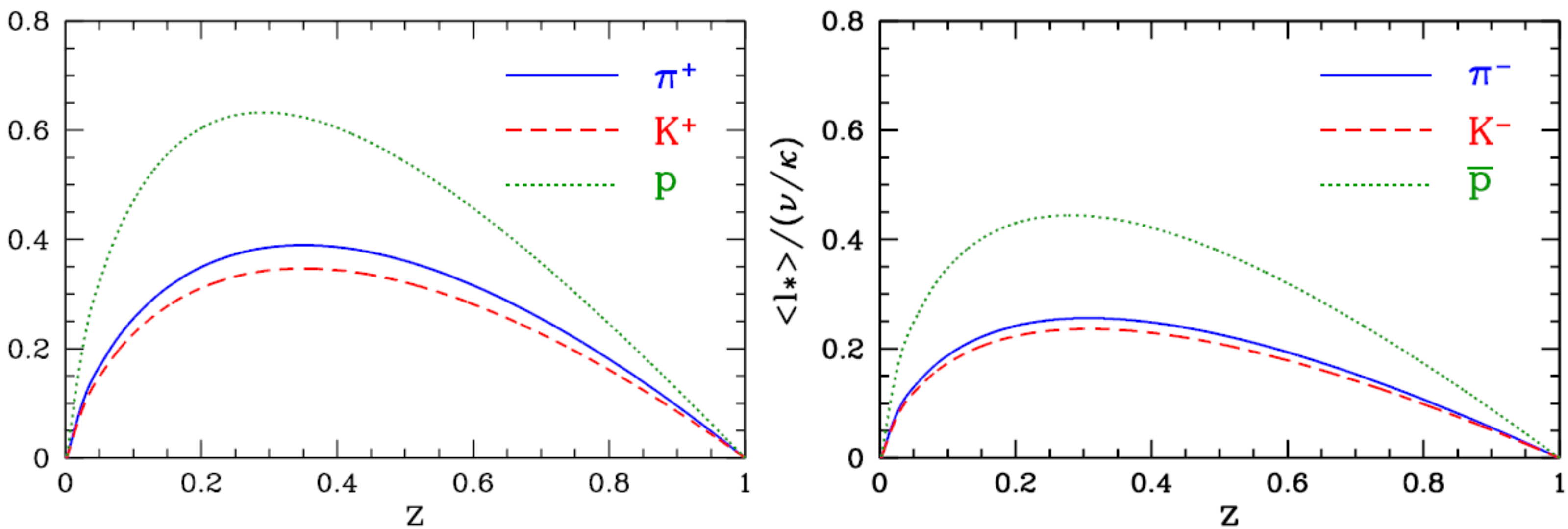
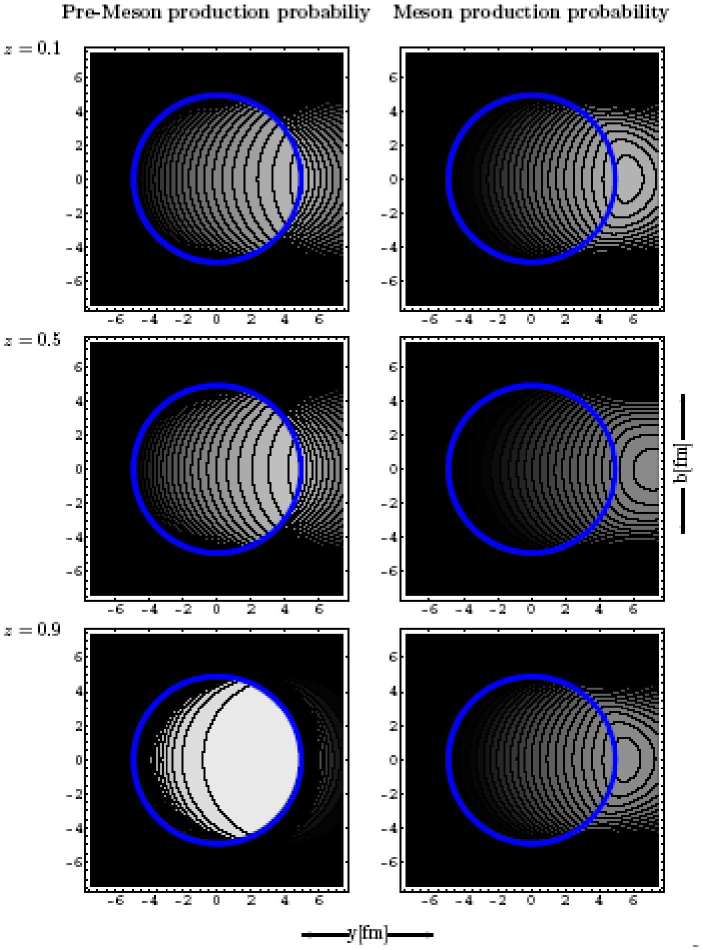


Fig. 3. Computed prehadron formation lengths when an up quark is struck by the virtual photon. *Left:* When a π^+, K^+ or p is observed, the corresponding prehadron can be created at rank $n \geq 1$. *Right:* When a π^-, K^- or $\bar{p}$ is observed, the corresponding prehadron can be created only at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

κ is the string tension

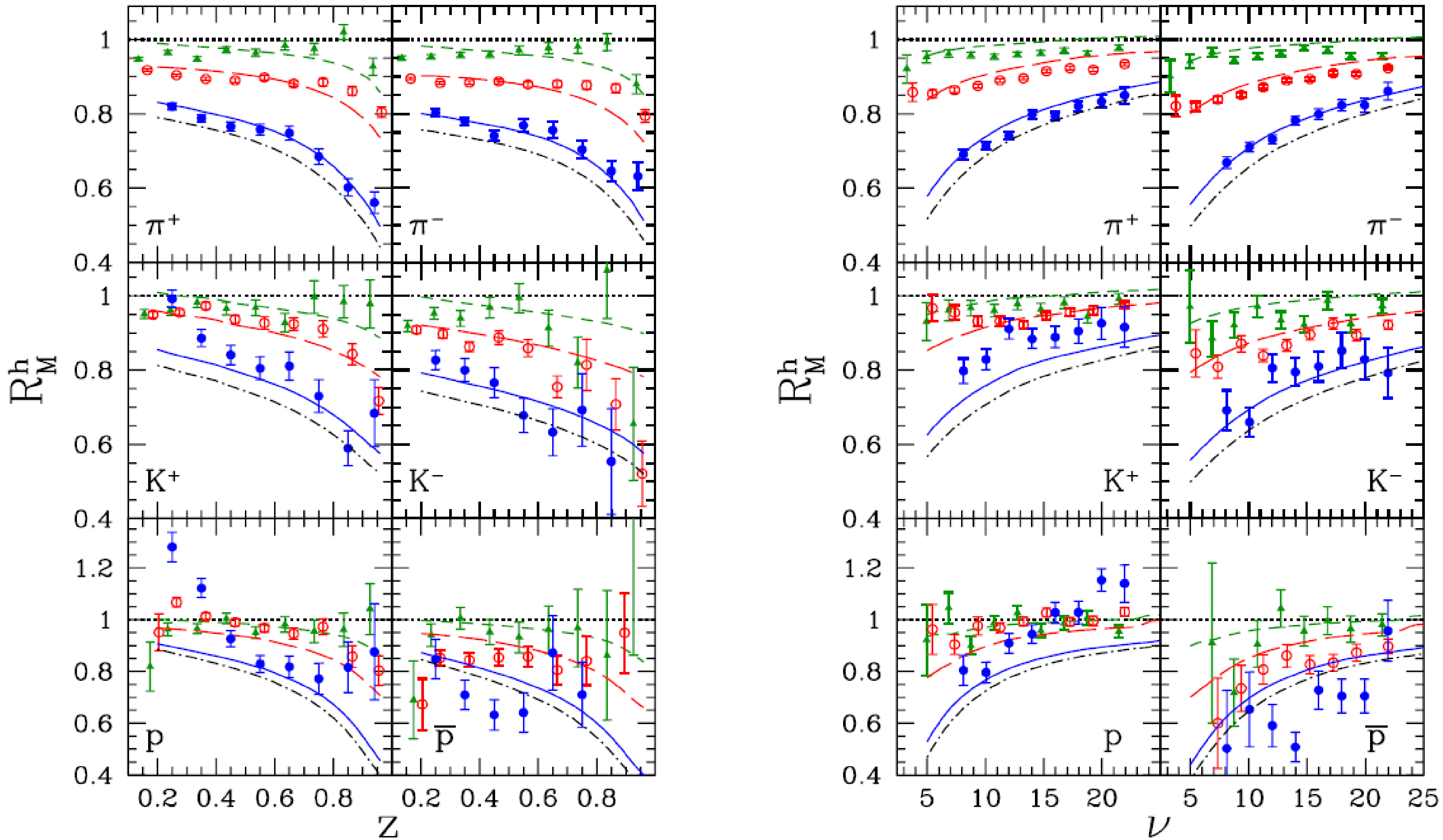
$$l_p \simeq 1.19 \, \frac{\nu}{\kappa} \, z_h^{0.61} \, (1 - z_h)^{1.09}$$

Prehadron und Hadron-probabilities at HERMES energies for Kr target



Comparison with HERMES data

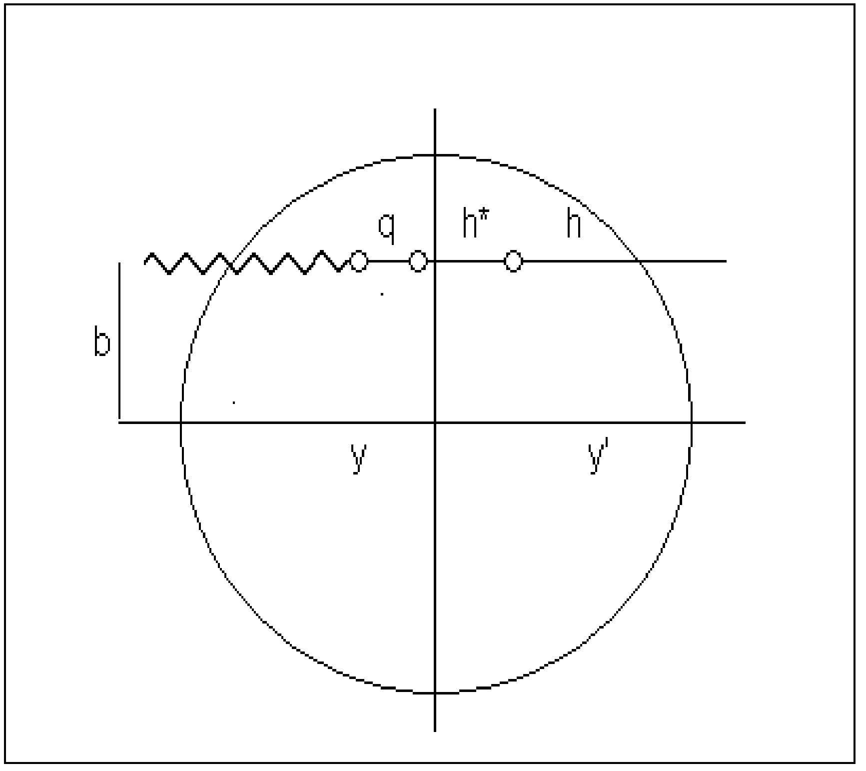
Hermes Coll. A.Airapetian et al. Phys. Lett. B577 (2003) 37-Xe,Kr,Ne,He target



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

Three stage picture (II)

- Only the length of the quark (q) path is important for hadron transverse momentum broadening , 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 $\sigma = C\, r^2$: $<\sigma\, p_t^2> = 2\, C$.



Transport parameter in cold matter

$$\sigma_{dN}(\vec{r}_\perp) = 2\int d^2b\left(1 - \frac{1}{N_c}\left\langle \mathrm{Tr}\left[V^\dagger(\vec{b}+\vec{r}_\perp)\,V(\vec{b})\right]\right\rangle\right)\,. \tag{9}$$

We define the quantity $\langle \sigma q_\perp^2 \rangle$ as the integral over transverse momentum $d^2 q_\perp$ of the differential cross section given in Eq. (8) multiplied by $q_\perp^2$. Differentiating the phase factor appearing in Eq. (8) twice with respect to the transversal separation and performing the integral over $d^2 q_\perp$ one sees that $\langle \sigma q_\perp^2 \rangle$ is related to the dipole nucleon cross section.

$$\begin{aligned}
\left\langle \sigma q_\perp^2 \right\rangle &\equiv \int d^2 q_\perp \frac{d\sigma}{d^2 q_\perp} q_\perp^2 \\
&= \frac{1}{(2\,\pi)^2}\int d^2 q_\perp \int d^2b\, d^2 r_\perp \left(-\nabla_\perp^2 e^{i\vec{q}_\perp \vec{r}_\perp}\right)\frac{1}{N_c}\left\langle \mathrm{Tr}\left[V^\dagger(\vec{b}+\vec{r}_\perp)\,V(\vec{b})\right]\right\rangle \\
&= \frac{1}{2}\,\nabla_\perp^2 \sigma_{dN}(\vec{r}_\perp)\Big|_{r_\perp=0}\,. \qquad (10)
\end{aligned}$$

The momentum scale Qs for broadening

$$\sigma_{dN}(\vec{r}_\perp) = \sigma_0(s)\left[1 - \exp\left(-\frac{\vec{r}_\perp{}^2}{r_0^2(s)}\right)\right]$$

is called saturation momentum Q_s. For a quark propagating a path-length L in nuclear medium of density ρ_0 the saturation momentum reads

$$(Q_s^A)^2 = \frac{1}{2}\,\rho_0\,L\,\sigma_0\,(Q_s^N)^2, \qquad (13)$$

where σ_0 and $(Q_s^N)^2 = 4/r_0^2$ are defined in terms of the saturated form [23,24] of

Saturation Scale QsN^2(Hermes)=0.07 GeV^2, QsN^2(EIC)=0.39 GeV^2, QsAu^2(EIC)=0.84 GeV^2. ---EIC ,Au 100 GeV-7 fm--

Mean Δp_t^2 of the quark

- We calculate only the additional Δp_t^2 which comes from the presence of the nucleus.
- Δp_t^2 depends on the length l_p (=l*)after which the prehadron h* is formed and the dipole nucleon cross section
- The production length l_p is calculated from the Lund model

$$\langle \Delta p_\perp^2 \rangle_q = \langle \sigma q_\perp^2 \rangle \frac{1}{\langle S_* \rangle} \int_{-\infty}^{\infty} d^2b\, dz\, \rho_A\left(\vec{b}, z\right) \int_{z}^{z+l_p} dz' \rho_A\left(\vec{b}, z'\right) \cdot \exp\left(-\sigma_* \int_{z+lp}^{\infty} dz''\, \rho_A\left(\vec{b}, z''\right)\right) ,$$

$$\langle S_* \rangle = \int_{-\infty}^{\infty} d^2b\, dz\, \rho_A\left(\vec{b}, z\right) \exp\left(-\sigma_* \int_{z+lp}^{\infty} dz'\, \rho_A\left(\vec{b}, z'\right)\right)$$

S. Domdey, D. Gruenewald, B.Z. Kopeliovich and H.J. Pirner Nucl.Phys. 2009

Mean Δp_t^2 of the hadron

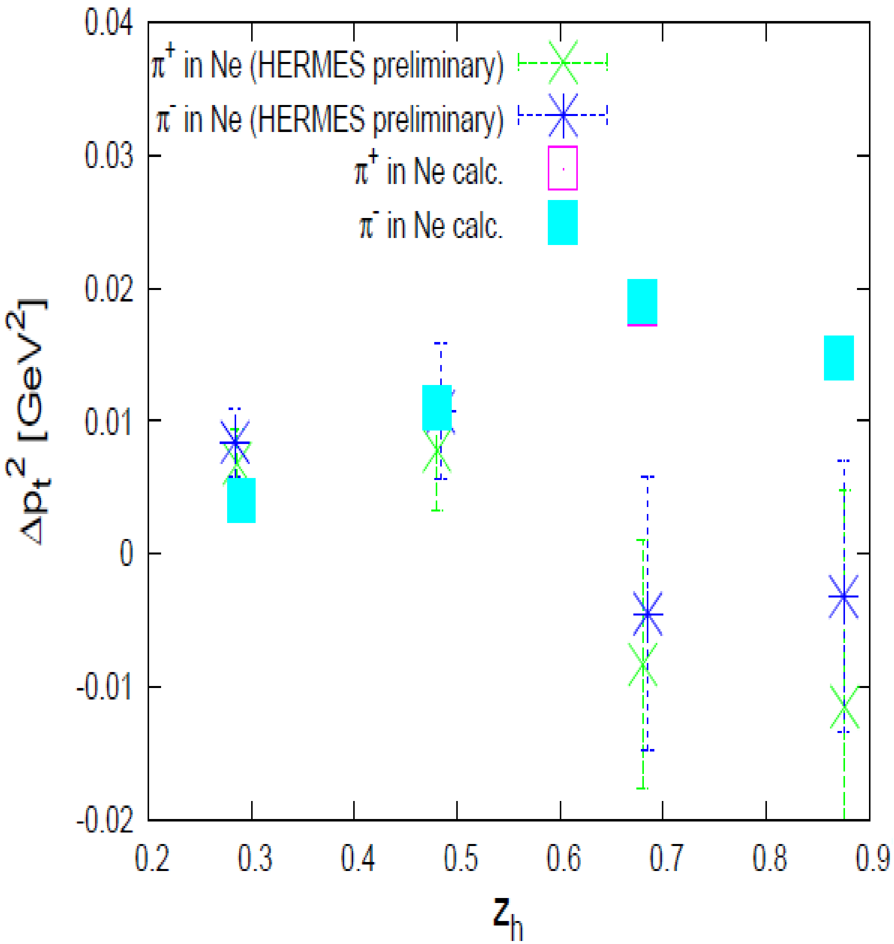
The relevant mean transverse momentum squared per unit length in cold matter is much smaller (1/15) than in the plasma

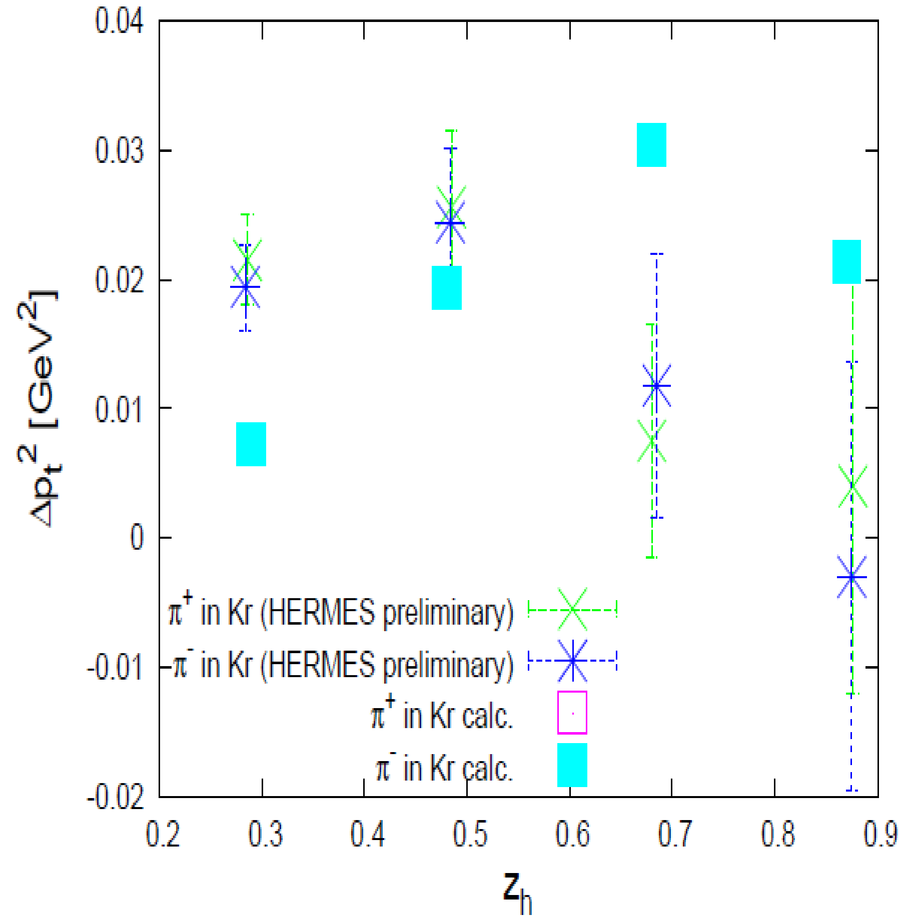
$$\hat{q}_F = \langle \sigma q_\perp^2 \rangle \rho_0 \text{ which is given as } \hat{q}_F = 0.035 \text{ GeV}^2/\text{fm}$$

- The measured hadronic broadening is reduced compared with the quark broadening:

$$(\Delta p_\perp^2)_h = z_h^2 (\Delta p_\perp^2)_q .$$

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





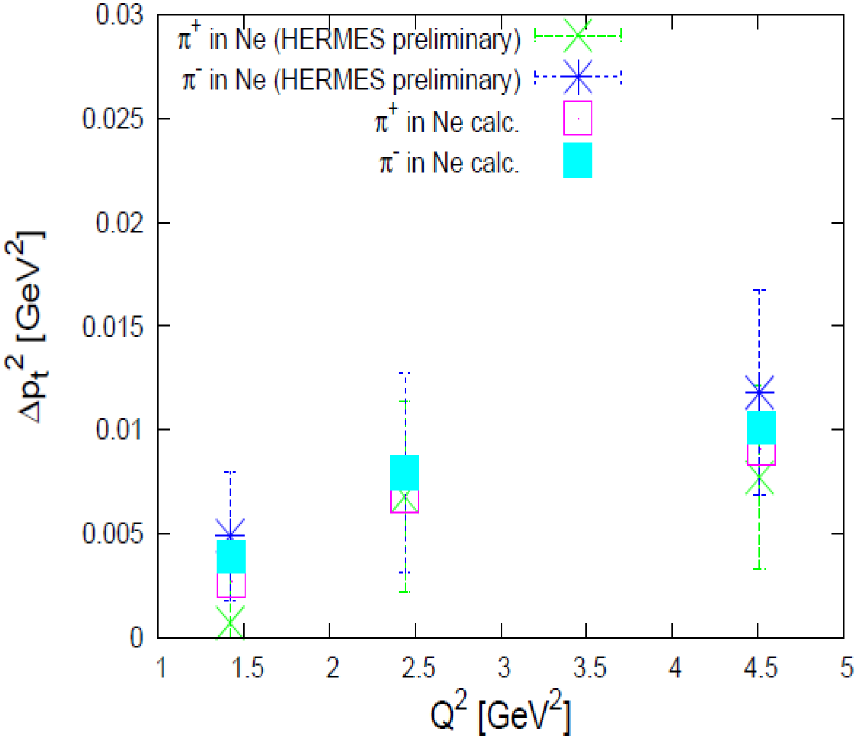
Evolution of Δp_t^2 as a function of Q^2

$$(\Delta p_\perp^2)_h(Q^2) = (\Delta p_\perp^2)_h(\bar{Q}^2) + z_h^2\, \nu\, \rho_0 \,\langle \sigma q_\perp^2 \rangle \left(\frac{1}{\bar{Q}^2} - \frac{1}{Q^2} \right)$$

- The Q^2 dependence comes as an additional contribution to the multiple scattering contribution
- It comes from the scattering term in an evolution equation with transverse momentum

Experimental data support this hypothesis

- Hermes data show an increase with Q^2 over a small interval 1 $GeV^2 < Q^2 < 5$ GeV^2
- Compatible with the theoretical calculation



Resume 3:

- Parton evolution in cold matter can be described at low Q by a string model. There is little leverage for shower evolution at Hermes (1 GeV<Q<2.2 GeV)
- Prehadron formation can explain the observed suppression
- The mean broadening of the hadrons is very small at Hermes , but is not inconsistent with the calculated z dependence for prehadron formation
- There is a weak evidence for Q-evolution
- The energy loss parameter q at Hermes is about 1/15 smaller than in the plasma at T=0.3 GeV, but q would be 3 times larger at EIC, also pt-broadening at EIC would increase.

Numbers

- Hermes (Ecm=5 GeV)
- QsN^2=0.07 GeV^2

- qhat=0.035 GeV^2/fm
- Sigmapt^2=4.6

- EIC (Ecm=100 GeV)
- QsN^2=0.39 GeV^2
- QsAu^2=0.84 GeV^2

  For L=R_A

- qhat=0.12 GeV^2/fm
- Sigmapt^2=18.7

RHIC: q hat=0.5 GeV^2/fm at 300 MeV