Space-time evolution of hadronization

Alberto Accardi (Iowa State U.)

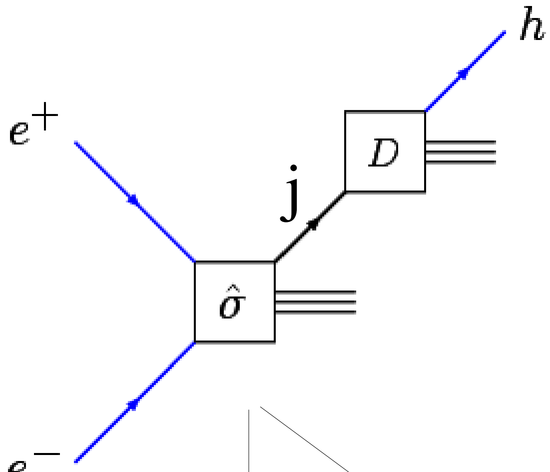
XLIV International Winter Meeting on nuclear physics
Bormio (ITA), 29 Jan – 5 Feb, 2006

- **Hadronization in nuclear matter**
  - small systems: $e^+ + e^-$, e+p, p+p
  - nuclear targets: nDIS vs. Heavy-Ion Collisions
- **Hadron formation time**
  - prehadron vs. hadron – energy loss vs. absorption
  - hadron attenuation in nDIS
- **Can we distinguish energy loss from absorption?**
  - The "$A^{2/3}$ power law"
  - cA^{α} fits - power law breaking
- **Conclusions and perspectives**

Based in part on work in collaboration with D.Gruenewald, V.Muccifora, H.J.Pirner

I. Hadronization in nuclear matter

Hadronization in elementary collisions



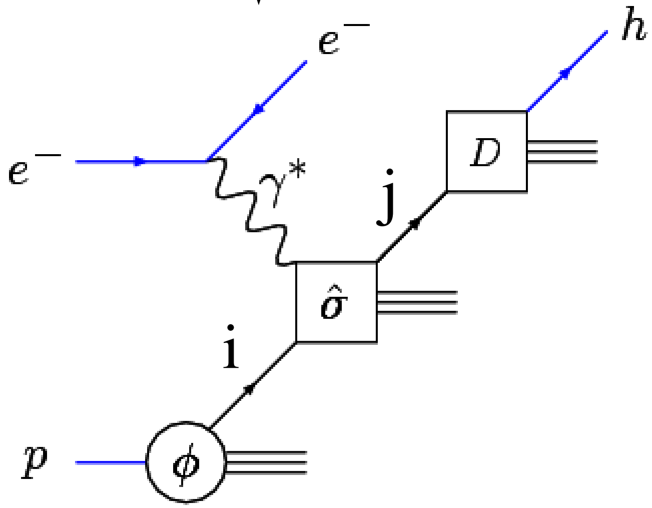
- **pQCD factorization**
  of short and long distance physics

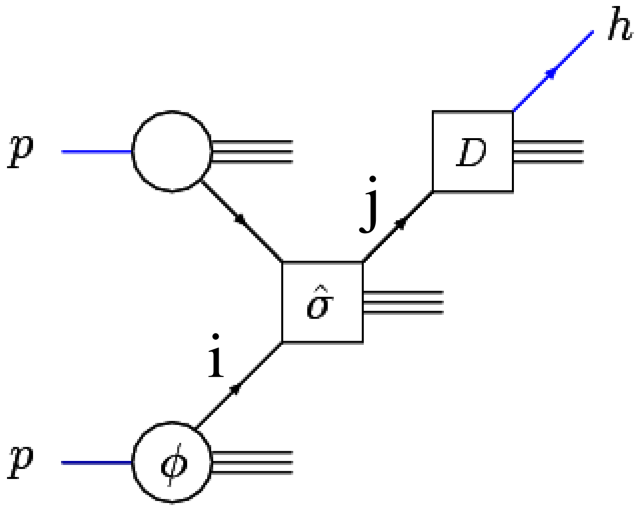
$$d\sigma_{hadronic} = \Pi_i \ \phi_i \otimes \hat{\sigma}^{j}_{partonic} \otimes D_{j|h}$$

Parton Distribution Fns
(from inclusive DIS)

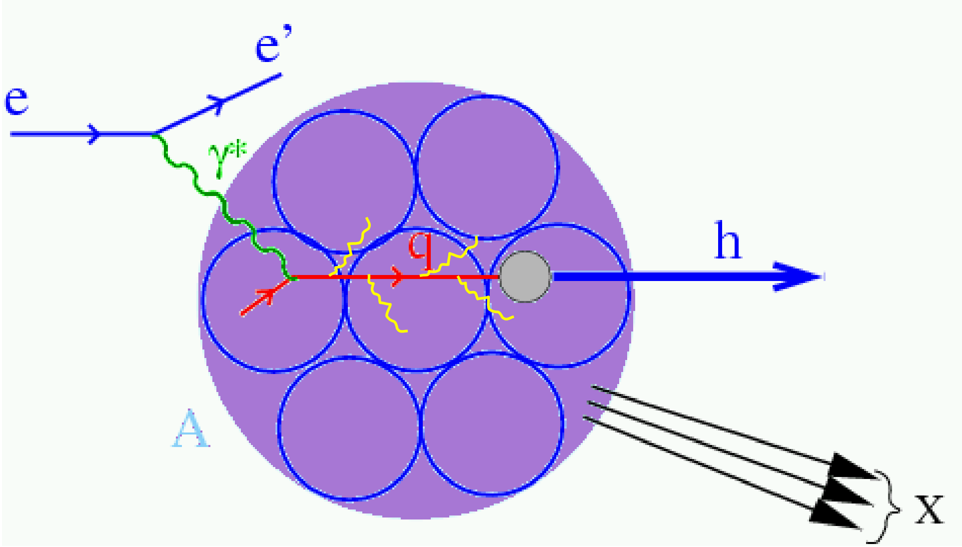
Fragmentation Fns
(from $e^+ + e^- \rightarrow h+X$)

- **Universality**: Fragm. Fns. from $e^+ + e^- \rightarrow h+X$ describe hadronization in DIS and $p+p \rightarrow h+X$

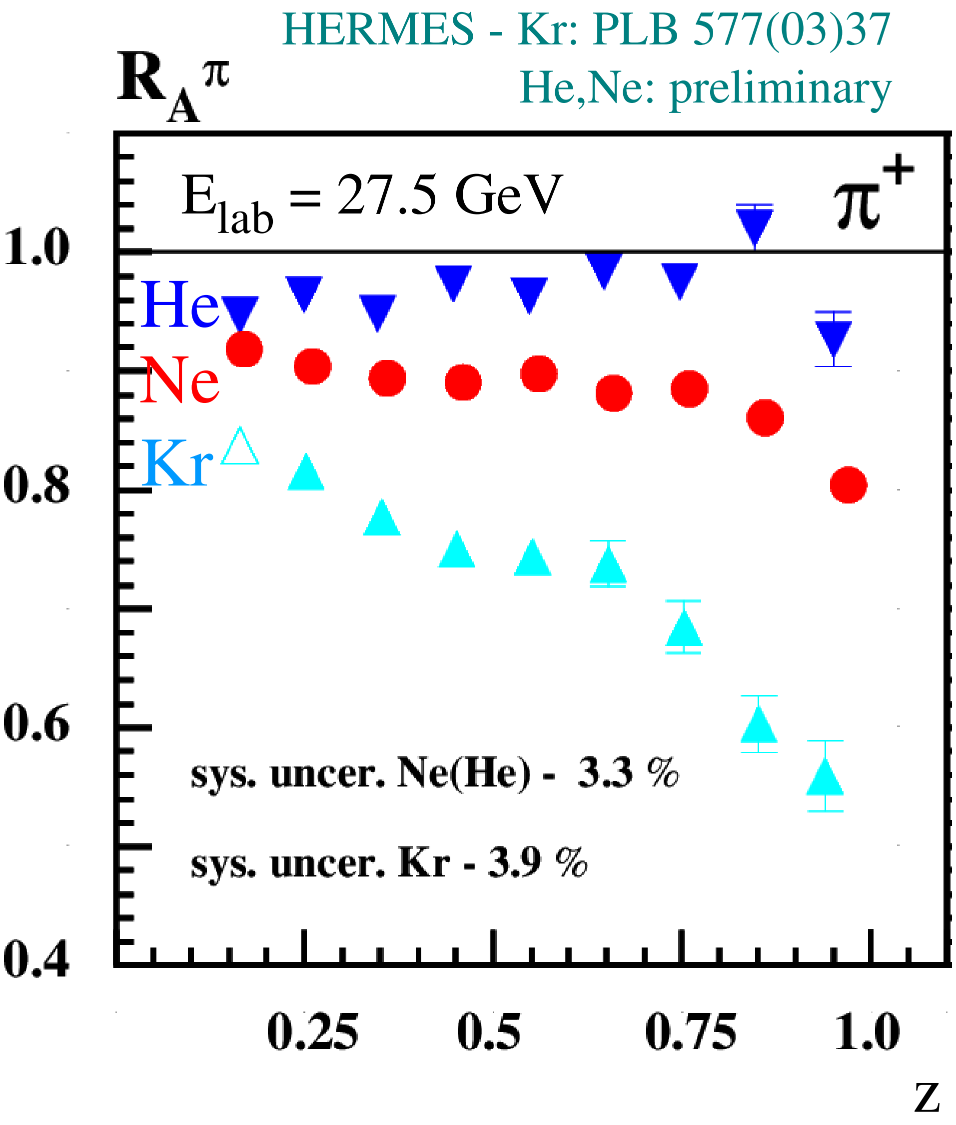




Nuclear collisions 1 – nuclear DIS



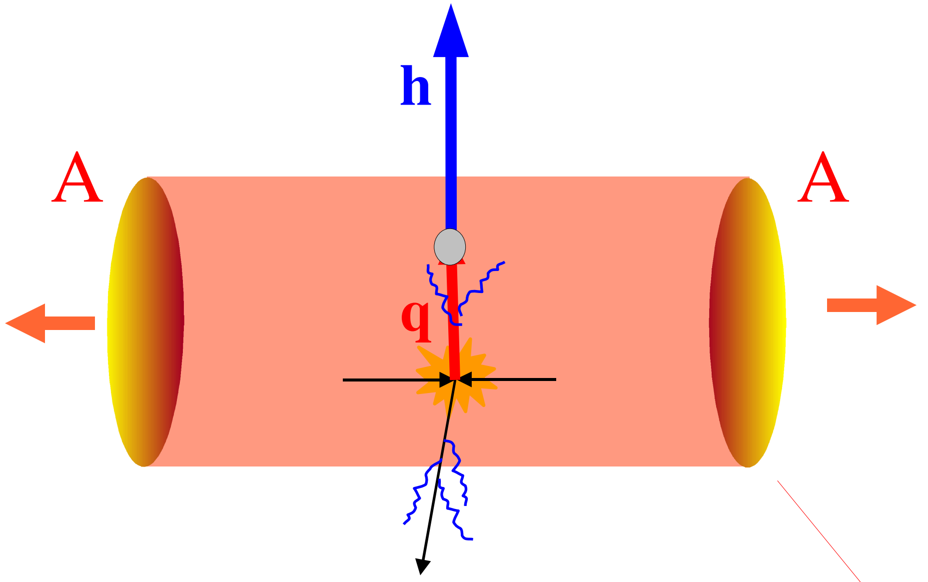
$$R^h_M(z) = \frac{\frac{1}{N_A^{DIS}}\frac{dN_A^h(z)}{dz}}{\frac{1}{N_D^{DIS}}\frac{dN_D^h(z)}{dz}}$$

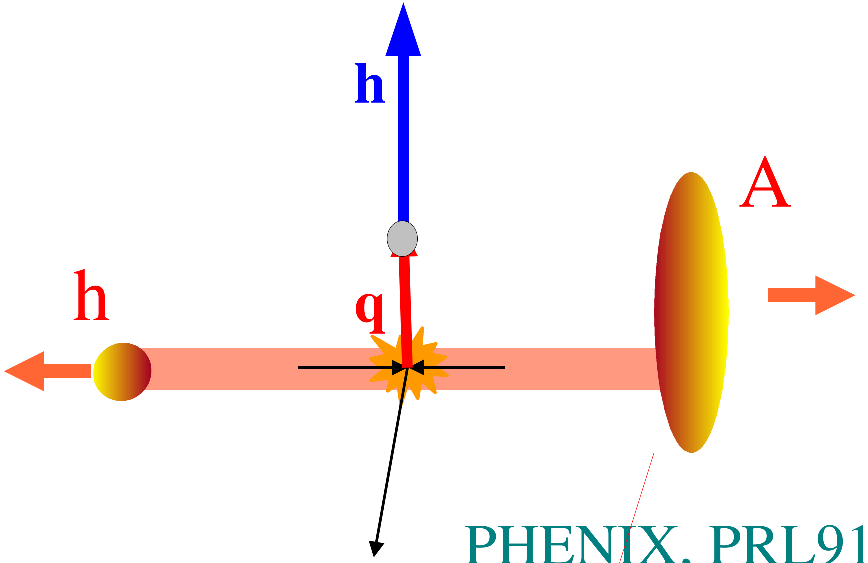

HERMES - Kr: PLB 577(03)37
He,Ne: preliminary

- Nuclear effects on PDF cancel in ratios
- Exposes modifications of hadronization

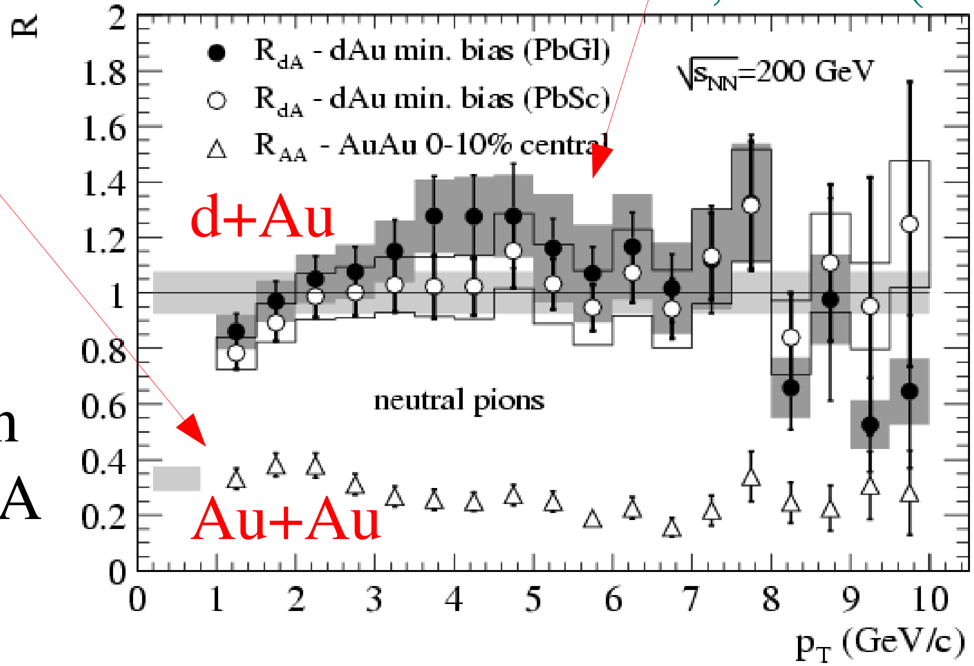
$R_M < 1 \Rightarrow$ hadron attenuation in cold nuclear matter

Nuclear collisions 2 – Heavy Ion Collisions





PHENIX, PRL91(02)



$$R_{AB} = \frac{(dN^h/d^2p_T)_{A+B}}{T_{BA}(b)\ (d\sigma^h/d^2p_T)_{p+p}}$$

- Medium modifications of hadronization isolated by comparison of h+A and A+A

$R_{AuAu}<1$ & $R_{dAu}>1 \Rightarrow$ hadron attenuation in hot nuclear matter

Breaking of universality on nuclei

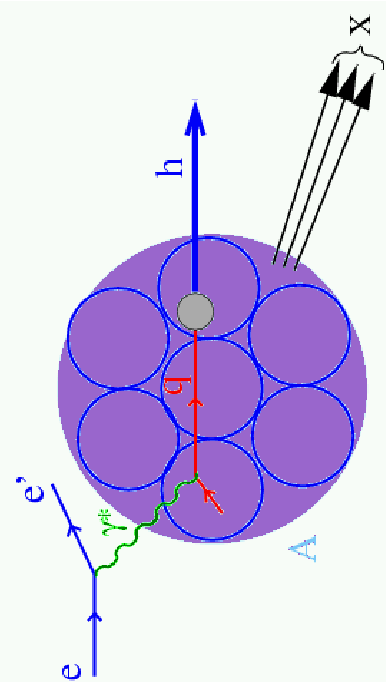
- Hadron attenuation data show a remarkable breaking of universality (hadronization is no more process-independent)

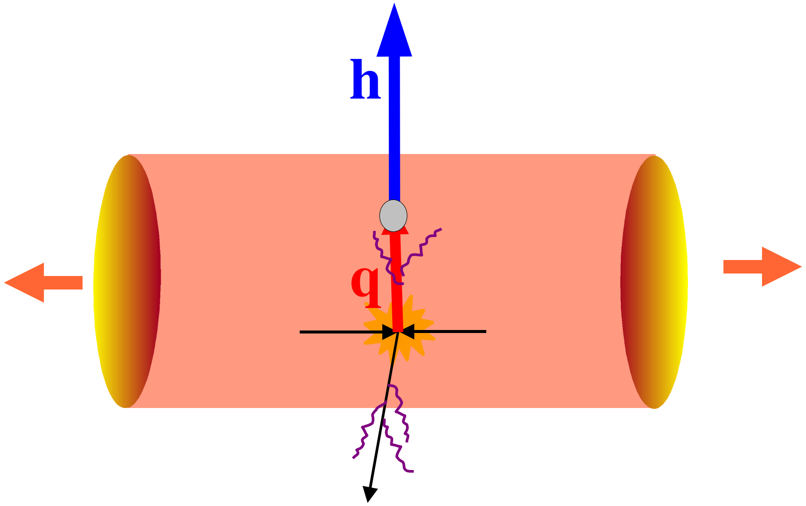
- Among possible causes:
  - struck quark interactions with the medium
  - (pre)hadron interactions with the medium
  - (other medium nuclear, e.g., partial deconfinement [Dias de Deus '87])
  - in-medium modifications of parton showers [Borghini, Wiedemann '05]
  - breakdown of factorization [for nuclear PDF, see Qiu, Sterman '02]

This talk: space-time evolution of hadroniz.

- **space-time evolution of hadronization is necessary for correct interpretation of attenuation data**

nDIS vs. A+A collisions





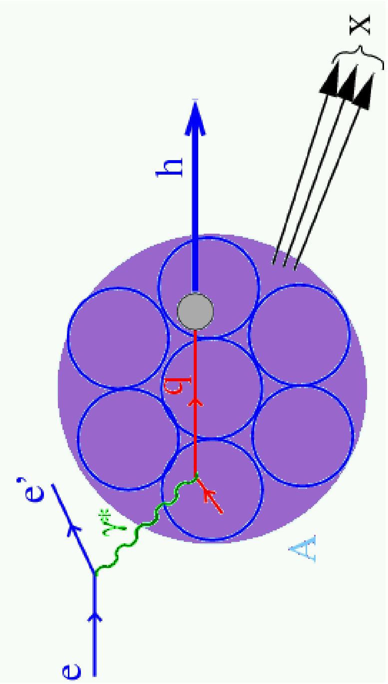
- ☆ nDIS is a clean environment for
  - **(1) space-time evolution of fragmentation**
    - nucleons as micro-detectors
    - medium rather well known
  - **(2) Cold nuclear matter effects**
    - quark energy loss
    - nuclear modifications of FF

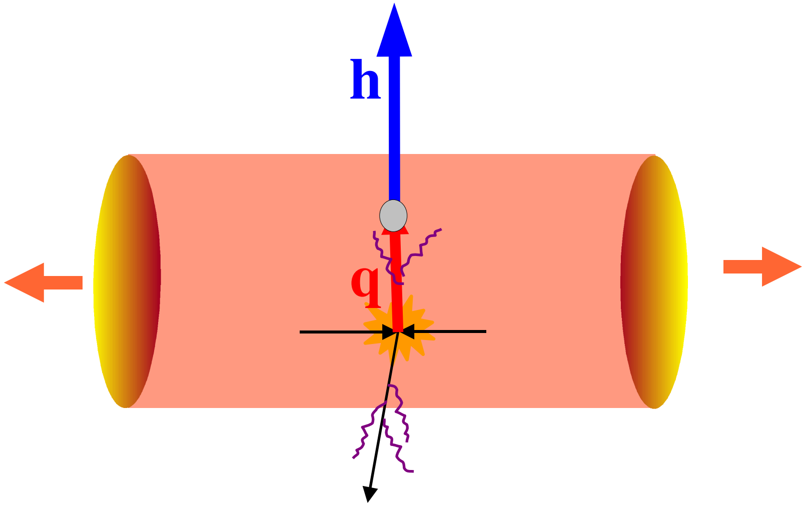
Jet-quenching in A+A

$\Downarrow$

properties of
hot nuclear matter

Similarities and differences





$E_q = \nu = E_e - E_{e'} \approx$ 2-25 GeV at HERMES

$E_h = z\,\nu$ **≈ 2 - 20 GeV**

$E_q = p_T / z$

$E_h = p_T$ **≈ 2 - 20 GeV**

✯ HERMES kinematics is relevant to RHIC mid-rapidity

...but beware the virtuality...

$Q^2 = -\,q^2$ is measured

$Q^2 \equiv E_q^2 \propto (p_T/z)^2$

...and the rapidity...

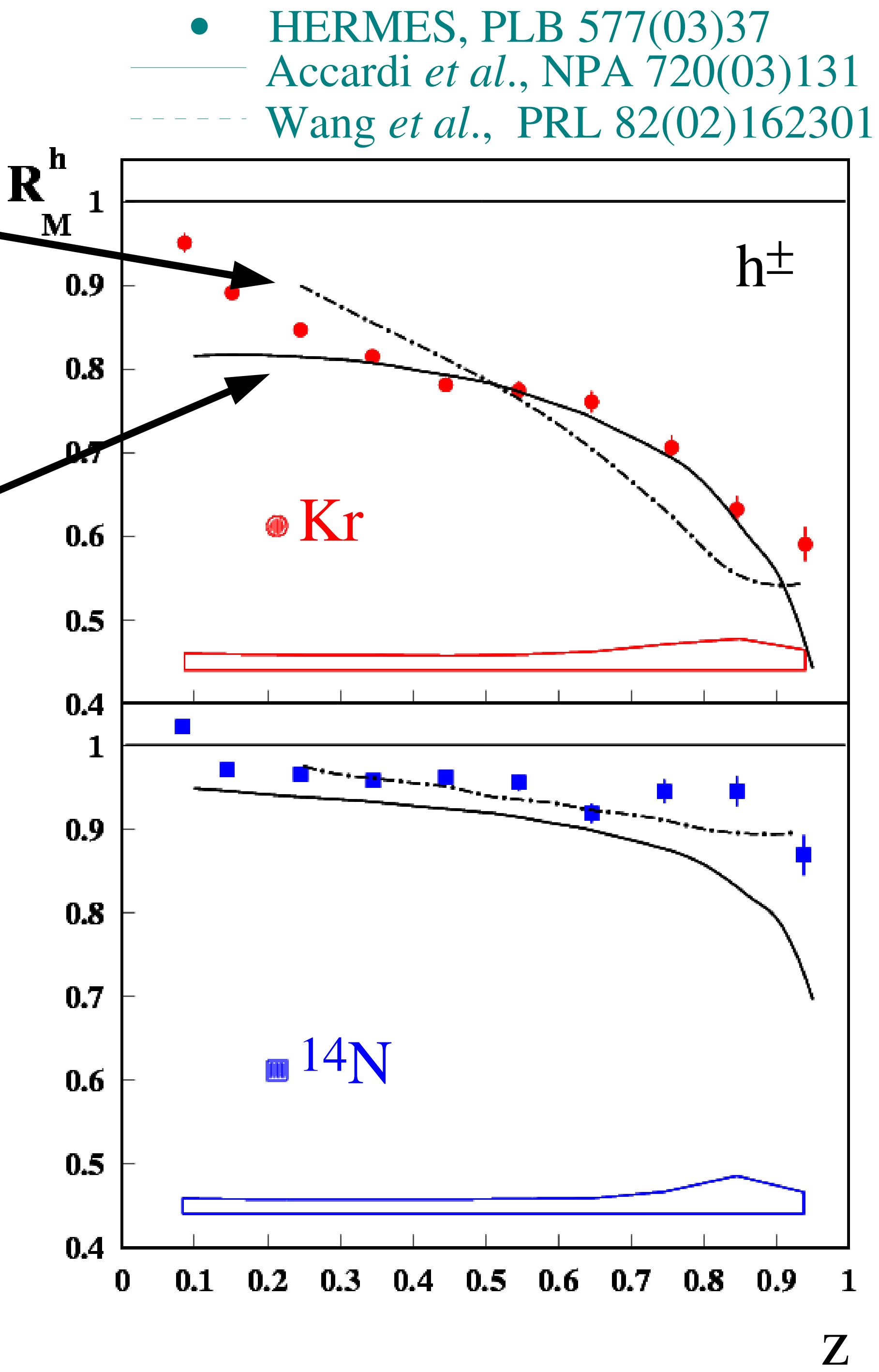
always forward rapidity

rapidity can change

Hadron attenuation – 2 frameworks

- **Energy loss (gluon brehmsstrahlung)**
  (Arleo;
  Wang *et al.*)
  - hadronization outside the medium
  - gluon bremsstrahlung off struck quark
  - "parton attenuation"

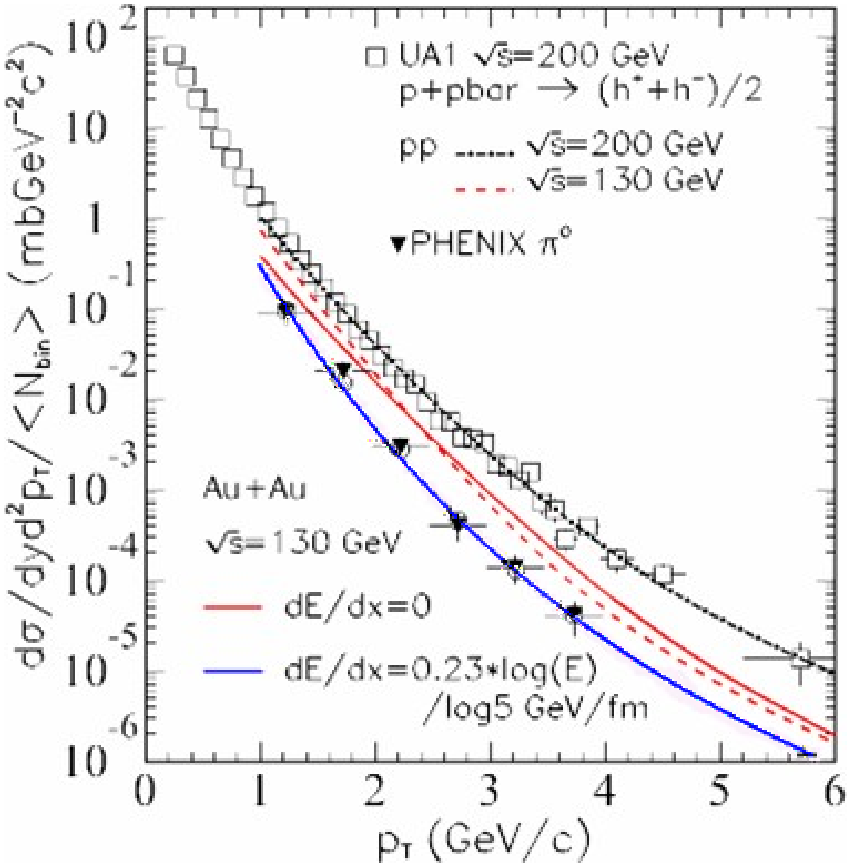
- **Hadron absorption**
  (Accardi *et al.;*
  Falter *et al.*; includes also en.loss
  Kopeliovich, *et al.*)
  - color neutralization inside the medium
  - prehadron-nucleon scatterings
  - hadron attenuation



Interplay of nDIS and A+A : an example

animation: P. Di Nezza

- Consider energy loss model of
  Wang *et al.*, PRL 82(02)162301
  - fit HERMES $e^+ + N \rightarrow h^\pm + X$
    $(dE/dx)_{\mathrm{cold}} = 0.5$ GeV/fm
  - fit PHENIX $Au + Au \rightarrow h^\pm + X$
    $(dE/dx)_{\mathrm{medium}} = 7.3$ GeV/fm



- Convert to medium temperature [Vitev '04]

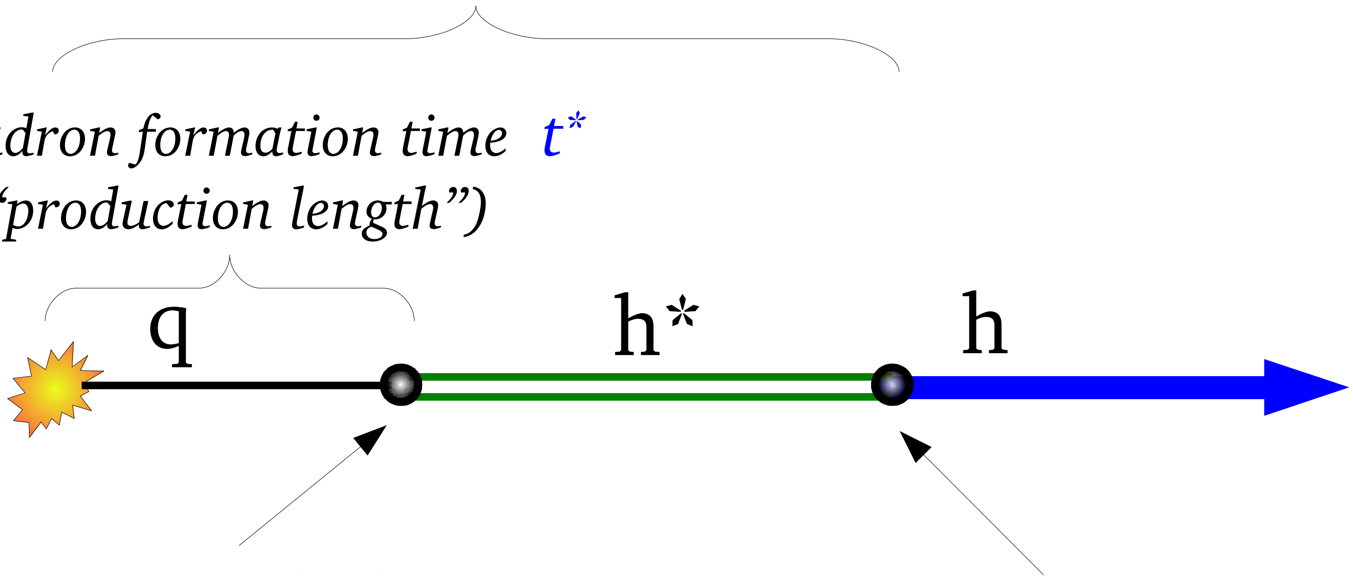
$$T_{\mathrm{medium}} \approx 400 \text{ MeV} \gg T_{\mathrm{crit}} \approx 170 \text{ MeV}$$

- **But** remember the **assumption**:
  partons travel through all medium and hadronize well outside
  - **is it correct?**

II. Hadron formation time

Space-time evolution of hadronization

- A non perturbative process ⇒ (many) models
- General features:



hadron formation time t^h

prehadron formation time t^*
(“production length”)

Color neutralization
⇒ “prehadron” h*

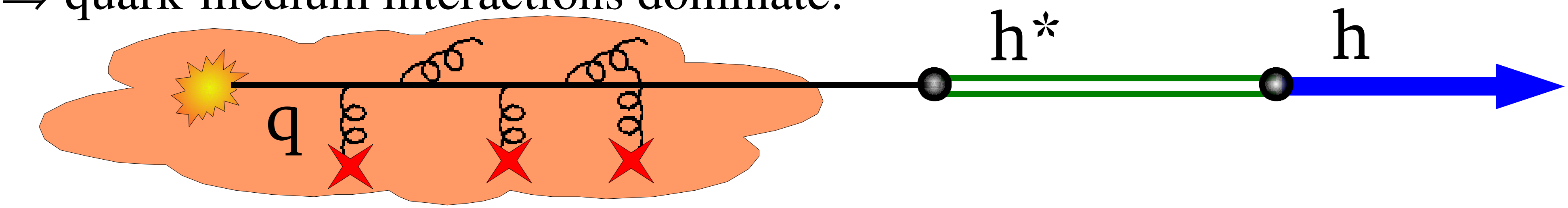
prehadron collapses on
hadron's h wavefunction

- *NOTE:*
  - It's tricky to rigorously define t^*, t^h: consider them as working tools
  - factorization theorems with nuclear targets are not guaranteed [Sterman, Qiu '02]

Space-time evolution of hadronization

- **If parton is long lived**, with $t^* >> L_{medium}$

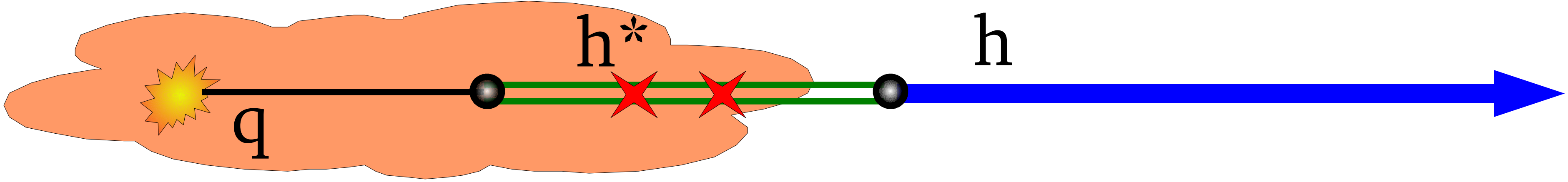
  ⇒ quark-medium interactions dominate:



  - quark multiscattering – Cronin effect
  - gluon bremsstrahlung – parton energy loss

- **If color neutralization is inside the medium**, $t^* < L_{medium}$

  ⇒ (pre)hadron-medium interactions must be taken into account



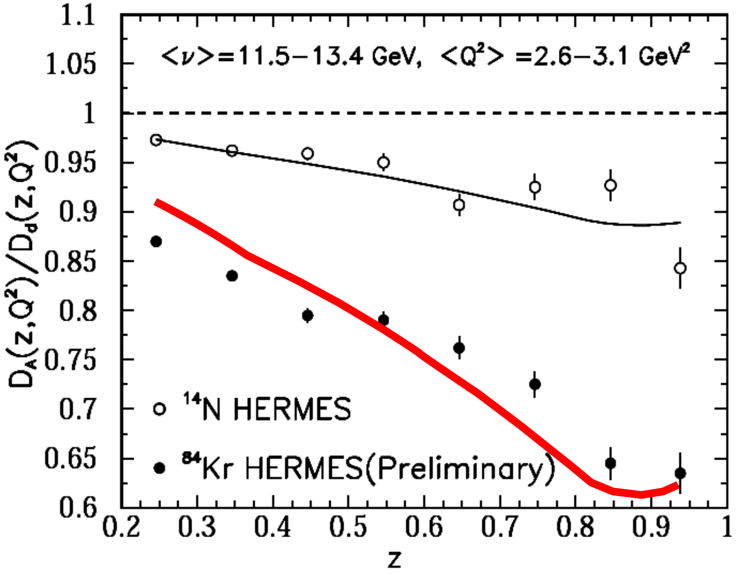
  - gluon bremsstrahlung stops (small color neutral object)
  - inelastic scatterings – prehadron is destroyed (dominant)
  - elastic scatterings – elastic energy loss
  - “missed hadronization” in deconfined medium

Formation time estimates 1

- Hadron formation time = time for partons to build up a color field and develop hadron wave function
  - hadron's rest frame: $\tau^h \sim R_h$
  - lab frame: $t^h \sim R_h \frac{E_h}{m_h}$ (in DIS $t^h \sim R_h \frac{z\nu}{m_h}$)

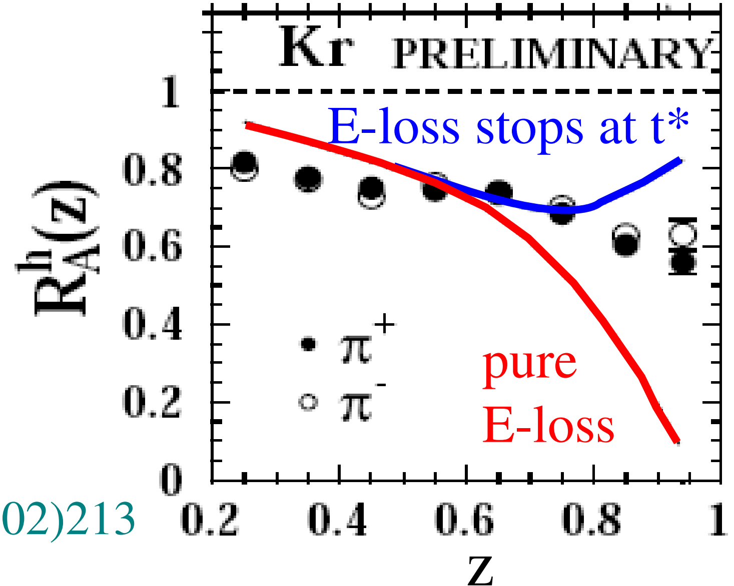
boost factor

- For a 10 GeV pion at Hermes $t^h \sim 45$ fm $\gg R_A$
- This is used in energy loss models to justify the assumptions, but **neglects interactions of the forming color field with the medium**



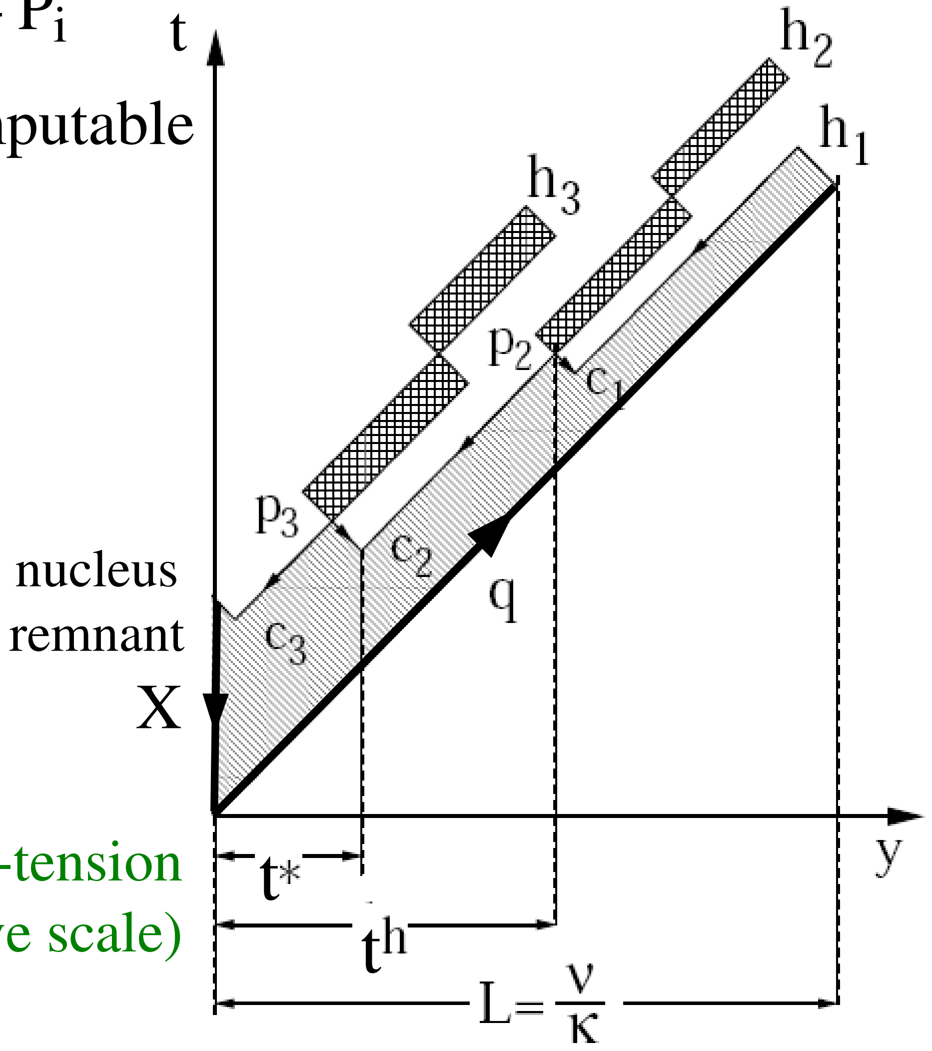
Wang et al.
PRL 82(02)162301

Arleo,
EPJ C30(02)213



Formation time estimates 2 – Lund model

- Prehadrons and hadrons are identified as follows [Bialas-Gyulassy '87]
  - Prehadron formed at $q\bar{q}$ creation (string breaking) – C_i
  - Hadron h_i formed when q and q meet – P_i
- Average formation times analytically computable
  - At large $z \to 1$
    $E_h \to \nu \;\Rightarrow$ string breaks early to leave
    all energy to the hadron: $t^* \to 0$
  - At small $z \to 0$
    hadron created at high rank after
    many string breakings: $t^* \to 0$



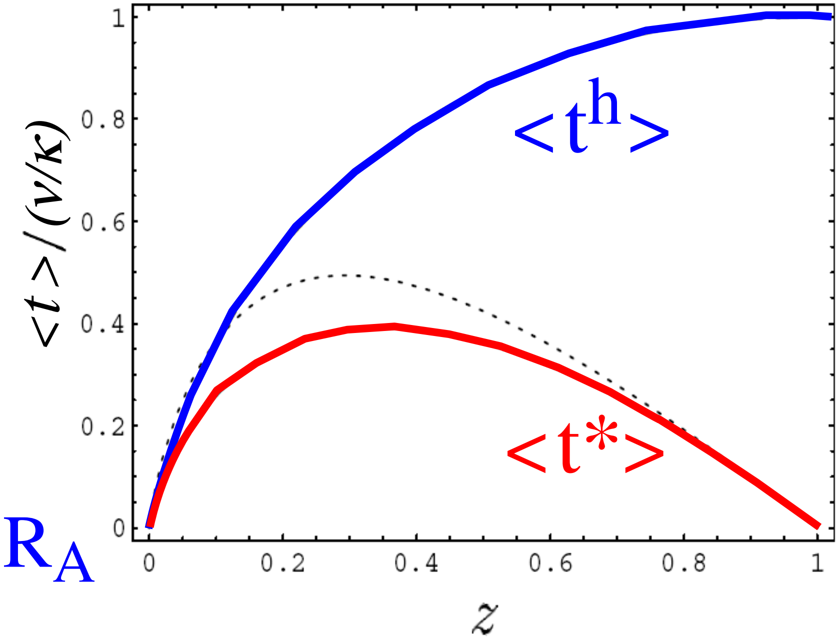
$$\begin{cases} \langle t^* \rangle = f(z)\,(1-z)\,\dfrac{z\nu}{\kappa} \\ \langle t^h \rangle = \langle t^* \rangle + \dfrac{z\nu}{\kappa} \end{cases}$$

string-tension
(non perturbative scale)

energy
conservation

Formation time estimates 2 – Lund model

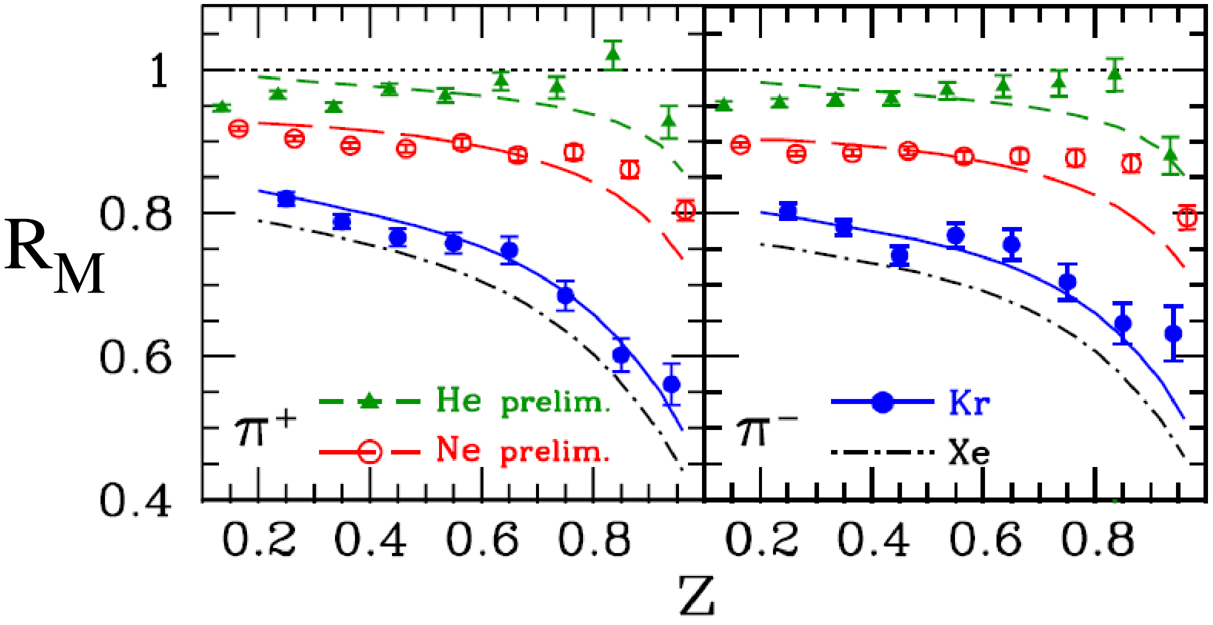
$$\begin{cases} \langle t^* \rangle = f(z)\,(1-z)\,\dfrac{z\nu}{\kappa} \\[2ex] \langle t^h \rangle = t^* + \dfrac{z\nu}{\kappa} \end{cases}$$



- For a 10 GeV pion at Hermes

  $t^* < 4$ fm ~ $O(R_A)$ $t^h = 6\text{-}10$ fm $> R_A$

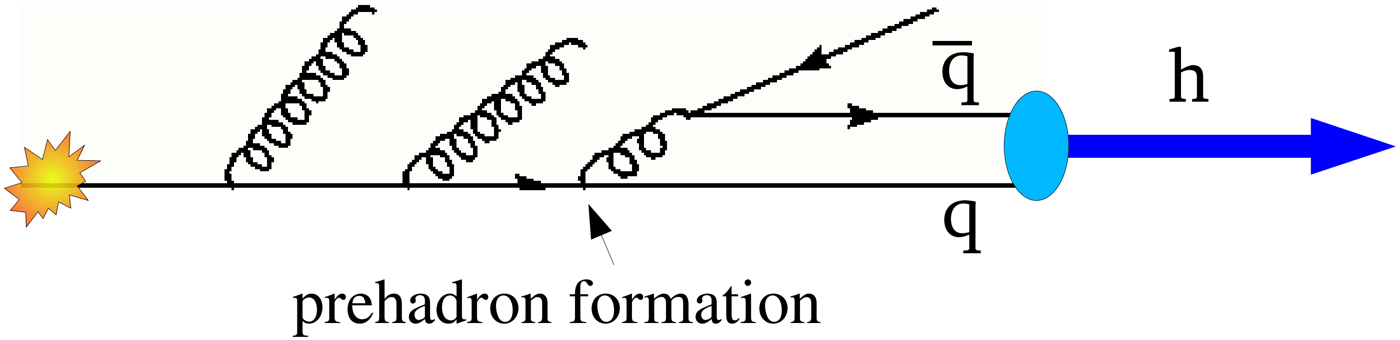
- Prehadron absorption with this estimate [A.A. et al., NPA 761(05)67]



see also:
Falter, Gallmeister, nucl-th/0512104
for similar ideas in a transport model

Formation time estimates 3 – Dipole model

- Leading hadron formation ($z > 0.5$) [Kopeliovich et al., NPA 740(04)211]



- Prehadron formation time t^* = time necessary to radiate $\Delta E = \nu - E_{q\bar{q}}$
  - At large $z \to 1$

    $E_h \to \nu \;\Rightarrow$ quark must be short-lived

    (it can radiate only a few soft gluons)

$$\langle t^* \rangle \propto (1-z)\,\frac{z\,\nu}{Q^2}$$

boost

energy conservation

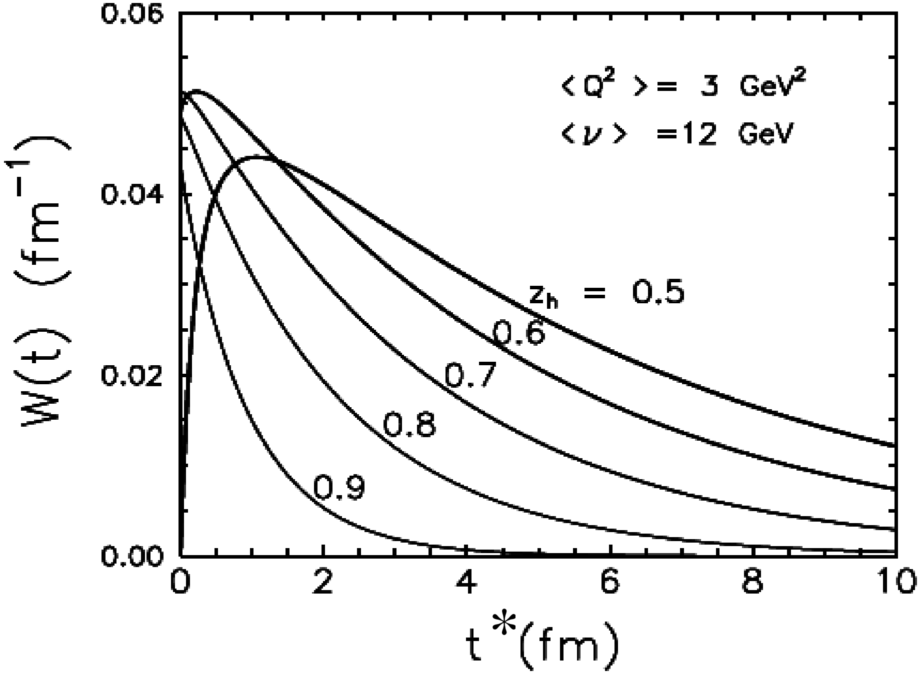
virtuality
(perturbative scale)

- Evolution into hadron by path-integral formalism
  - usually $\quad \langle t^h \rangle \gg R_A$

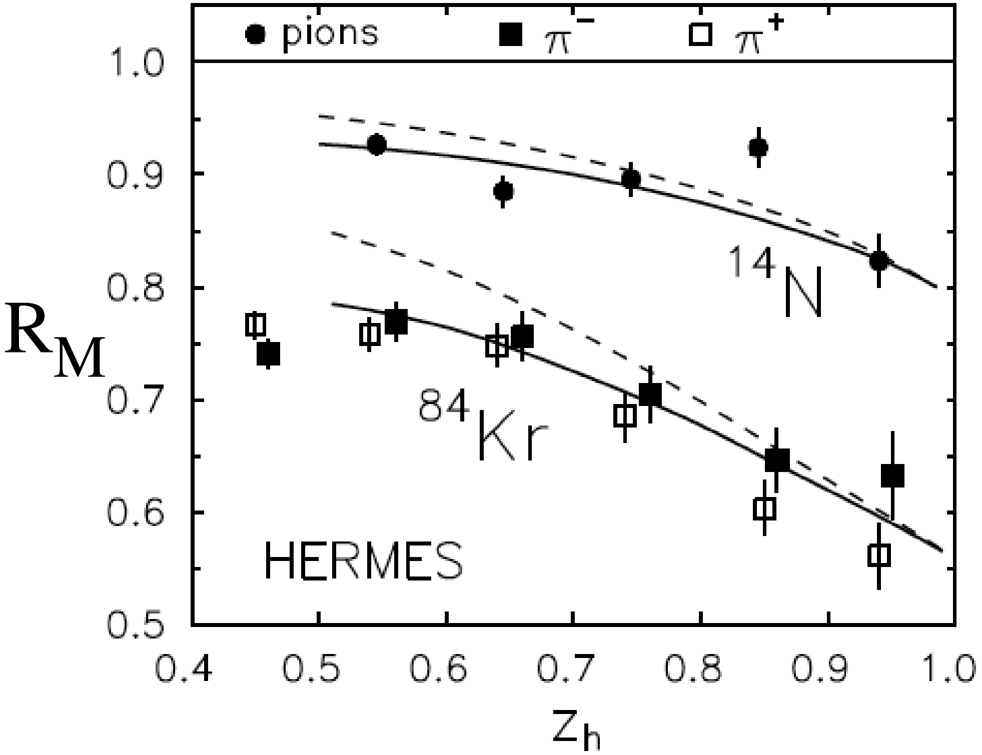
Formation time estimates 3 – Dipole model

probabilty distribution in t*

[Kopeliovich et al., NPA 740(04)211]



[Kopeliovich et al., NPA 740(04)211]



$$\langle t^* \rangle \propto (1-z)\frac{z\nu}{Q^2} < 5 \text{ fm} \quad (\text{at } z<0.5)$$

Note: computation of R_M includes: 1) prehadron absorption (dominant effect)

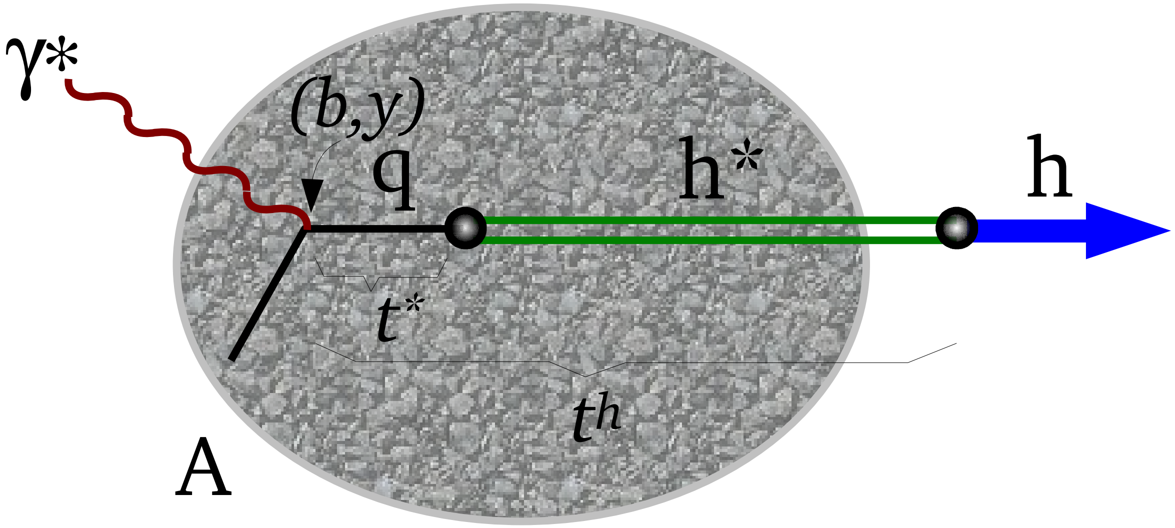
2) quark energy loss (subdominant)

III. Can we distinguish energy loss from prehadron absorption?

III.1 Hadron absorption model

Hadron absorption model

A.A. et al., NPA 761(05)67

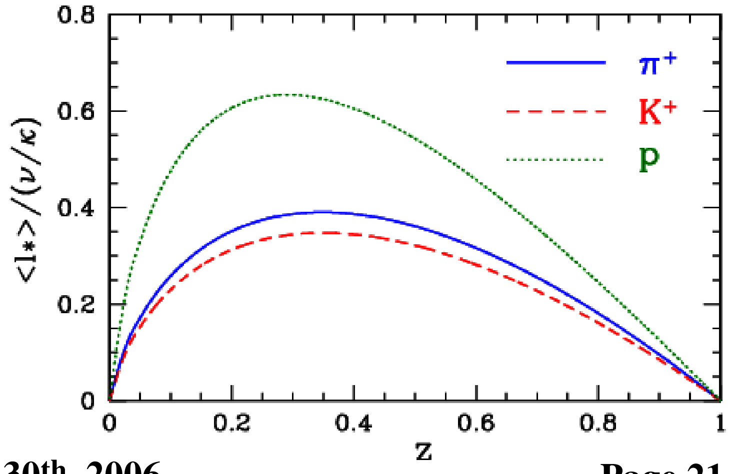


- Two-step hadronization inside the nucleus:
  1) quark *q* neutralizes color ⇒ **prehadron** h^*
  2) **hadron** *h*'s wavefunction fully develops

- Average formation lengths

  $\langle t^*\rangle(z,\nu)$, $\langle t^h\rangle(z,\nu)$ from Lund model

"production length" "formation length"



Hadron absorption model - 2

A.A. et al., NPA 761(05)67

- (Pre)hadron survival probability S_A by transport diff. eqns.
- (Pre)hadron-nucleon cross sections:

$\sigma_* = 2/3\, \sigma_h$ - fitted to $e^+ + \mathrm{Kr} \to \pi^+ + X$

σ_h - from Particle Data Group

$$S^A_{f,h} = \int d^2b\, dy\, \rho_A(b,y) \int_y^\infty dx' \int_y^{x'} dx \frac{e^{-\frac{x-y}{\langle l^* \rangle}}}{\langle l^* \rangle} e^{-\sigma_* \int_x^{x'} ds A \rho_A(b,s)} \frac{e^{-\frac{x'-x}{\langle \Delta l \rangle}}}{\langle \Delta l \rangle} e^{-\sigma_h \int_{x'}^{\infty} ds A \rho_A(b,s)}$$

prob. that h^* is formed at x

absorption of h^* up to x'

prob. that h is formed at x'

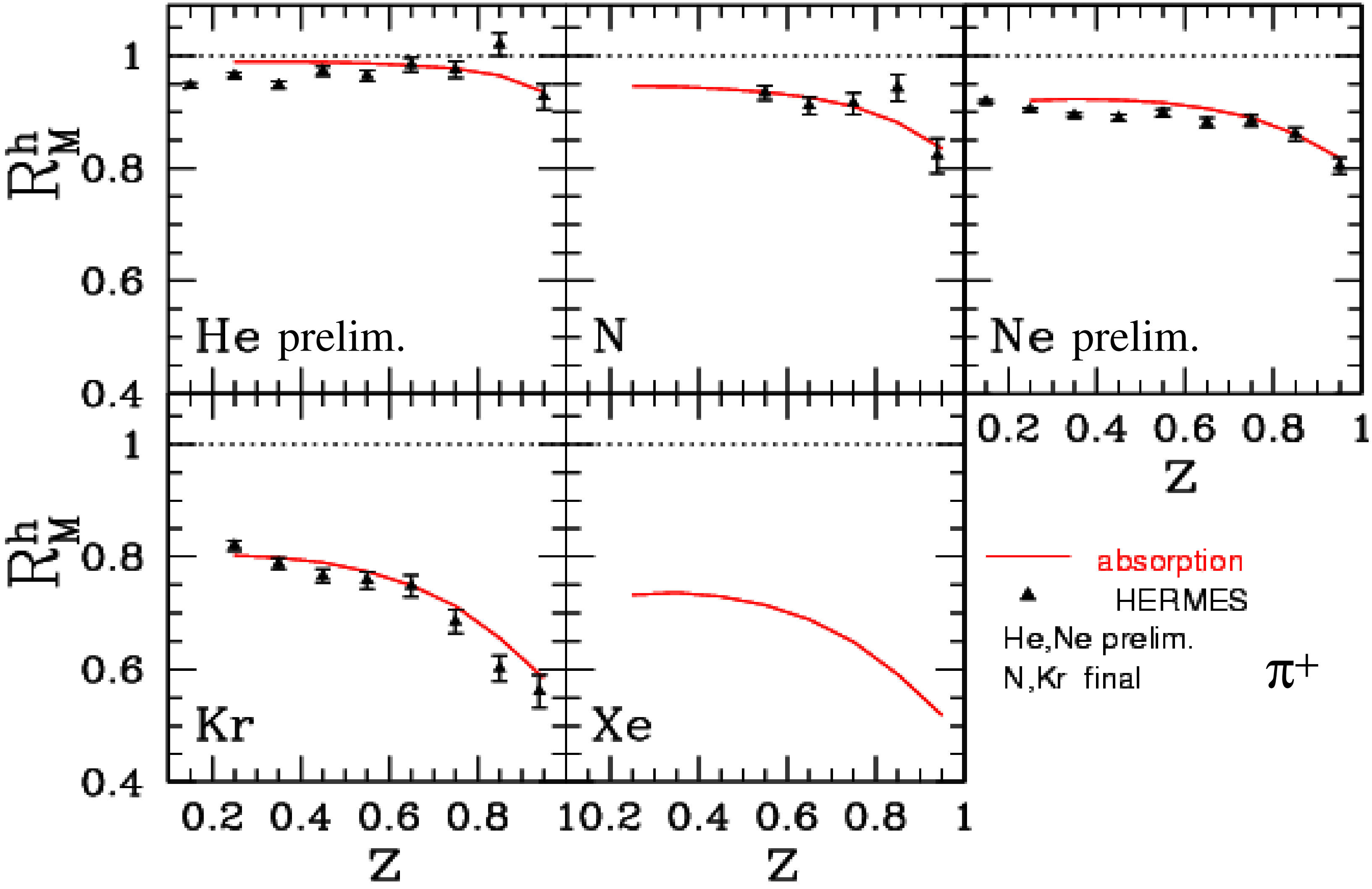
absorption of h from x' to ∞

- Full integration over $\gamma * q$ interaction point (b,y)

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

Hadron absorption model - results

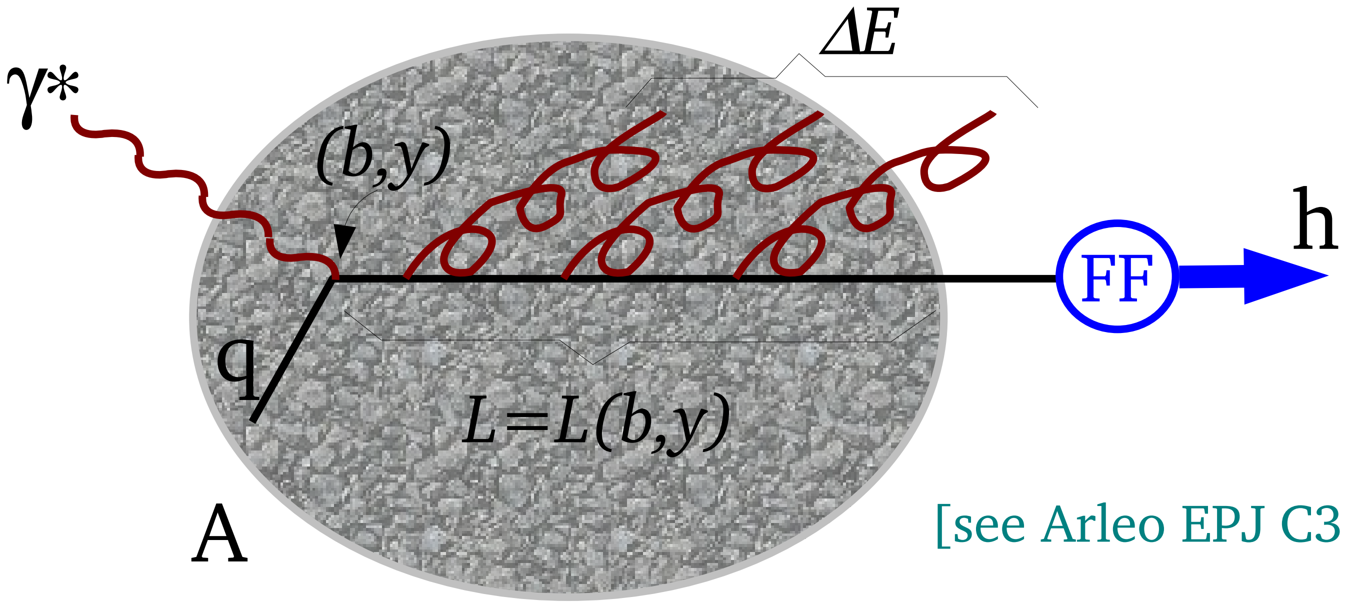
A.A. et al., NPA 761(05)67



Note: in ref. above, curves differ by inclusion of Q^2-rescaling due to additional hypothesis of partial deconfinement in nuclei

III.2 Energy loss model

Energy loss model



[see Arleo EPJ C30(02)213]

- The quark hadronizes outside the nucleus
- Gluon bremsstrahlung ⇒ ΔE ⇒ modified fragment. funct.

$$D_q^h(z,Q^2) \longrightarrow \frac{1}{1-\Delta z}\, D_q^h\left(\frac{z}{1-\Delta z},Q^2\right) \quad ; \quad \Delta z = \Delta E/\nu$$

- *New*: use quenching weights $P(\Delta z, L)$ with corrections for finite in-medium path $L=L(b,y)$ [Salgado-Wiedemann,PRD68(03)162301]

$$\tilde{D}_f^h(z,Q^2;L) = \int_0^{(1-z)} d\Delta z\, \mathcal{P}(\Delta z\,;\hat{q},L)\frac{1}{1-\Delta z} D_f^h\left(\frac{z}{1-\Delta z},Q^2\right) + p_0(\hat{q},L)\, D_f^h(z,Q^2)$$

prob. of radiating Δz

prob. of radiating no gluons

Energy loss model - realistic geometry

- *New:* Full integration over $\gamma^* q$ interaction point (b,y)

$$\frac{1}{N_A^{DIS}}\frac{dN_A^h(z)}{dz} = \frac{1}{\sigma^{lA}}\int d^2b\,dy\,\rho_A(b,y)\int_{\text{exp. cuts}} dx\,d\nu \sum_f e_f^2 q_f(x,Q^2)\frac{d\sigma^{lq}}{dx\,d\nu}\tilde{D}_f^h(z,Q^2;L(b,y))$$

- Realistic nuclear density: Woods-Saxon parametrization for A>2
  Reid's soft-core for ^{2}D

$$L(b,y) = 2\int_y^\infty dz\,(z-y)\rho(b,z) \Big/ \int_y^\infty dz\,\rho(b,z) \quad (= R(b) - y \quad \text{for Hard-Sphere})$$

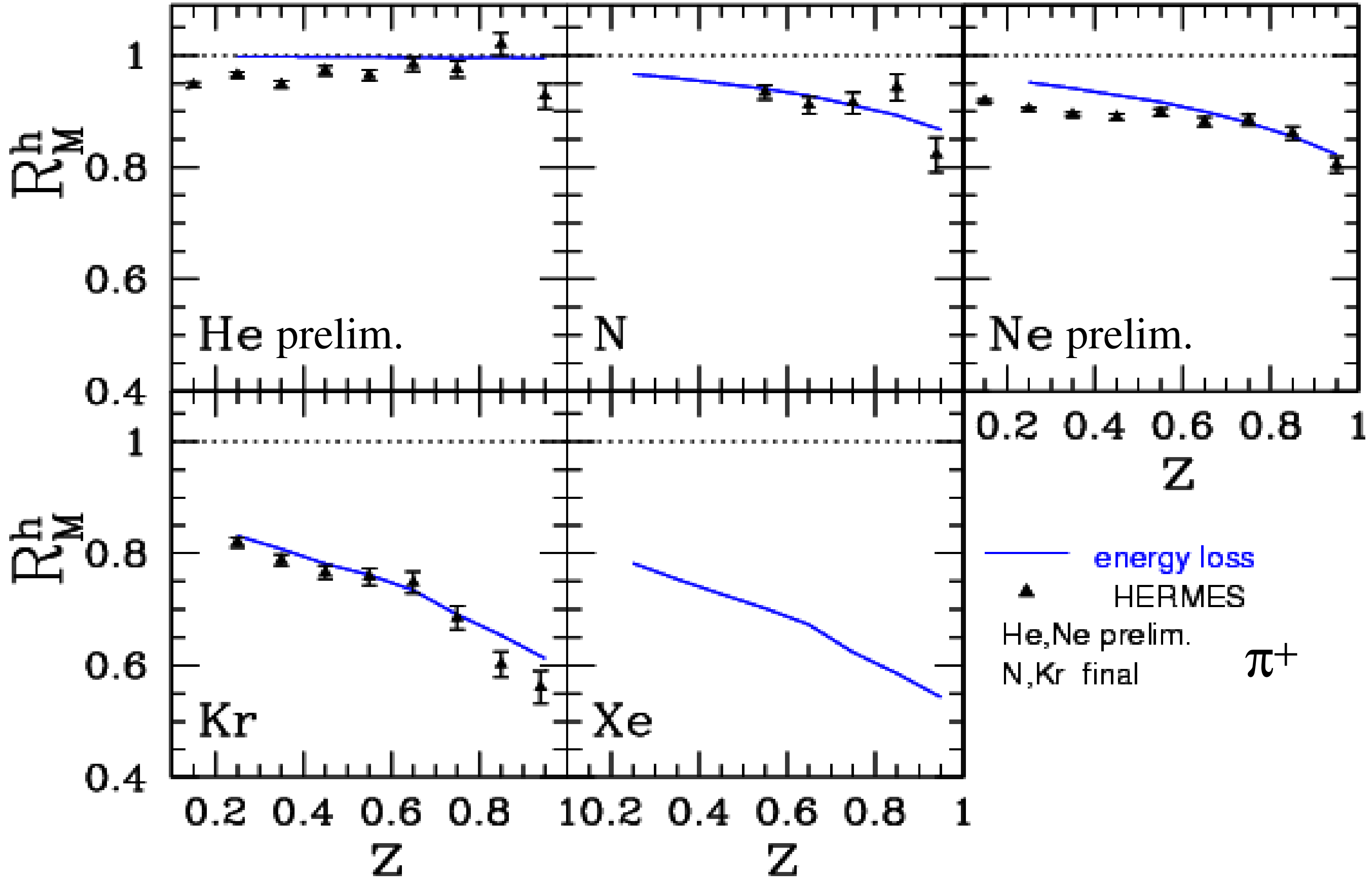
$$\langle\rho\rangle(b,y) = \int_y^\infty dz\,\rho(b,z) \Big/ L(b,y) \quad (= \rho_{HS} \quad \text{for Hard-Sphere})$$

- Transport coefficient

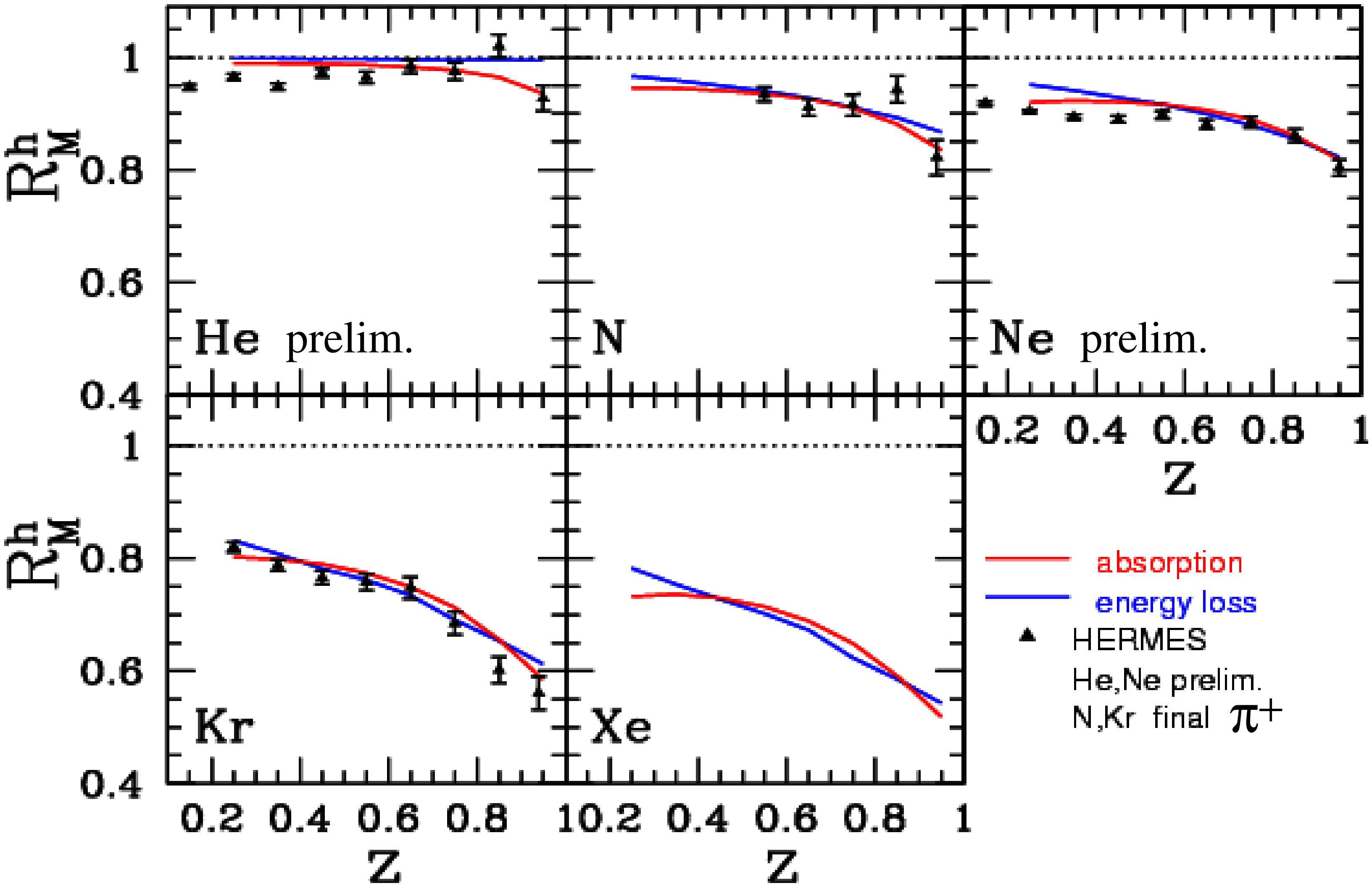
$$\langle\hat{q}\rangle(b,y) = \hat{q}_0\,\frac{\langle\rho\rangle(b,y)}{\rho(0,0)} \qquad \text{where} \quad \hat{q}_0 = \langle\hat{q}\rangle(0,0)$$

with $\hat{q}_0 = 0.5$ GeV^2/fm - fitted to $e^+ + \mathrm{Kr} \to \pi^+ + X$

Energy loss model - results



Energy loss vs. absorption



- Both models account well for HERMES R_M data
- Surprisingly similar up to heavy nuclei

III.3 The "$A^{2/3}$ power law"

A-dependence - naïve argument

At first order – i.e., for light nuclei:

a) Energy loss (LPM effect):

$$1-R_M \sim \langle \Delta z \rangle \sim L^2 \sim A^{2/3}$$

very naive,
incorrect,
but not too wrong…

b) Hadron absorption:

$1-R_M \sim$ ~~$< \textit{no. of rescatterings} > \sim L \sim A^{1/3}$~~

WRONG!

⇒ ~~a simple fit of $1-R_M$ to A^α should discriminate the 2 models~~

Let's really expand in powers of $A^{1/3}$

- Approximations for analytic formulae:
  - hard-sphere nuclei ($R_A = r_0 A^{1/3}$)
  - neglect nuclear effects on ^{2}H

- **Energy loss model**
  - neglect finite size corrections
  - large ν ⇒ neglect boundary in $\int_0^{1-z} d\Delta z$ - no energy conservation!

$$1 - R_M^{\text{en.loss}} = \underbrace{\frac{C_F \alpha_s r_0^2}{5}\,\frac{\hat{q}}{\nu}\left[-1 - z\frac{\partial_z D(z)}{D(z)}\right]}_{\substack{\text{coefficient is } z\text{-dependent} \\ \Rightarrow\ \text{fragmentation dynamics}}} A^{2/3} + \text{h.o.t.}$$

Energy loss yields $A^{2/3}$ as expected at leading order

where do h.o.t. begin to break $A^{2/3}$?

Let's really expand in powers of $A^{1/3}$

- **Hadron absorption model**
  - prehadron formed inside A, hadron outside (it's a good approximation, see A.A. et al. NPA720(03)13)

$$1 - R_M^{\text{abs.}} = \underbrace{\frac{2\rho_0 r_0^2}{5}\,\frac{\sigma_*}{\langle l^*\rangle(z)}}_{\text{fragmentation dynamics}} \overset{!!}{\boxed{A^{2/3}}} + \text{h.o.t.}$$

Hadron absorption follows $A^{2/3}$ law, as well!

- to distuinguish energy loss and absorption:
  1) **check breaking of $A^{2/3}$ law**
  2) **don't forget the coefficient: it contains dynamics**

Why $A^{2/3}$ also for absorption?

- Absorption can, quite generally, be approximated in terms of

$$1 - R_M \approx \frac{\pi\rho_0}{A} \int_0^{R^2} db^2 \int_{-R(b)}^{R(b)} dy \int_y^\infty dx\, \underbrace{\mathcal{P}_*(x-y)}_{\substack{\text{prob. distrib. for h*} \\ \text{production length}}} \left[1 - e^{-\rho_0 \sigma_* \int_x^\infty ds\, \Theta(R(b)-|s|)} \right]$$

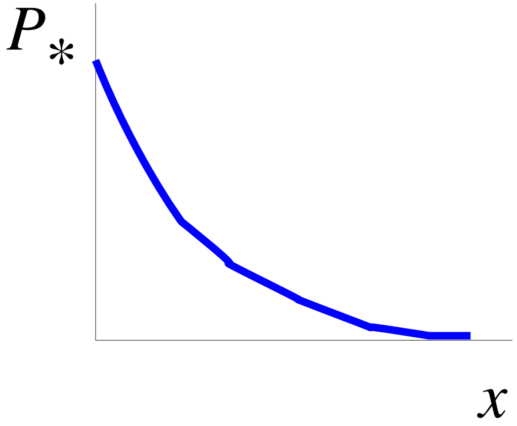
- If $\mathcal{P}_*(x-y) = \delta(x-y) \Rightarrow 1 - R_M = c\, A^{1/3}$ (e.g. Falter's et al. leading h_*)
- If not, we have a dimensionful scale $\langle l_* \rangle = \int_0^\infty dx\, x\, \mathcal{P}_*(x)$
- After all integrations we obtain an extra power of A: $\left(\frac{R_A}{\langle l_* \rangle} \right)^n \propto A^{n/3}$
- Theorem: if $\mathcal{P}_*$ is normalizable $\Rightarrow$ $n>0$

Why $A^{2/3}$ also for absorption?

- **Special cases**

1) $$\lim_{x\to 0} \mathcal{P}_*(x) = k \neq 0 \implies 1 - R_M = c\,A^{2/3} + \text{h.o.t.}$$

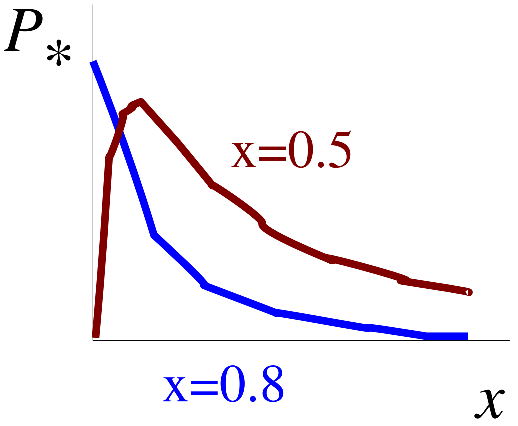
[e.g., the absorption model
A.A. et al. NPA '05]



2) $$\lim_{x\to 0} \mathcal{P}_*(x) = 0 \implies 1 - R_M = c\,A^{\alpha} + \text{h.o.t.}$$

[e.g., Kopeliovich et al. NPA...]

Not too different from case 1)

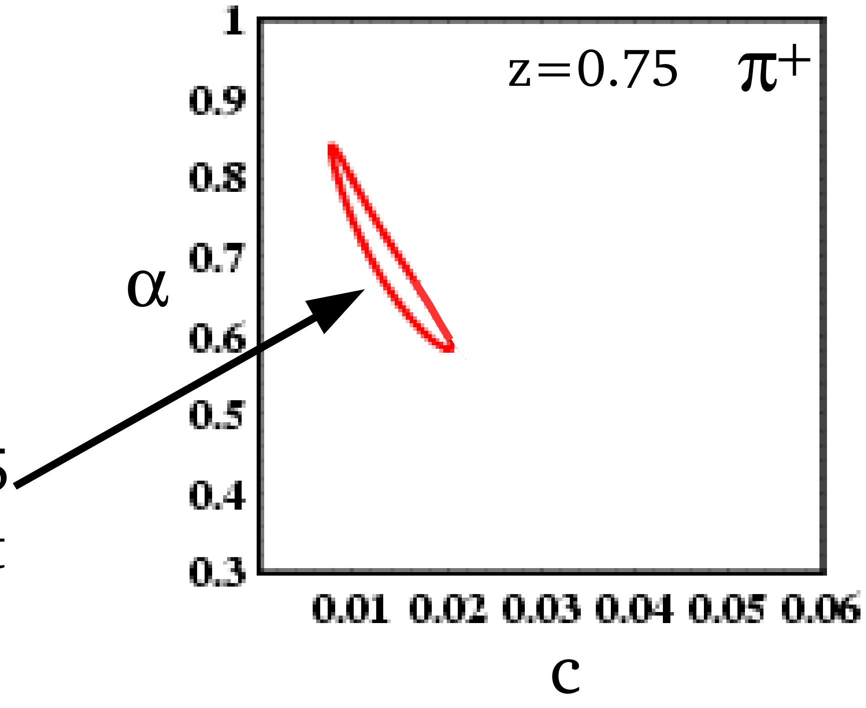


III.4 cA^{α} fits

cA^{α} fits

- to distuinguish energy loss and absorption:
  1) **check breaking of $A^{2/3}$ law**
  2) **don't forget the coefficient: it contains dynamics**

- the simplest option:
  - i) choose a set of nuclei $\{A_1, A_1, \ldots, A_N\}$
  - ii) fit $1 - R_M(z) = c(z)\, A^{\alpha(z)}$ as a function of A
    - at fixed z (or ν or Q^2)
    - with c and α as free parameters
  - iii) draw a 2σ confidence contour in the (c,α) plane



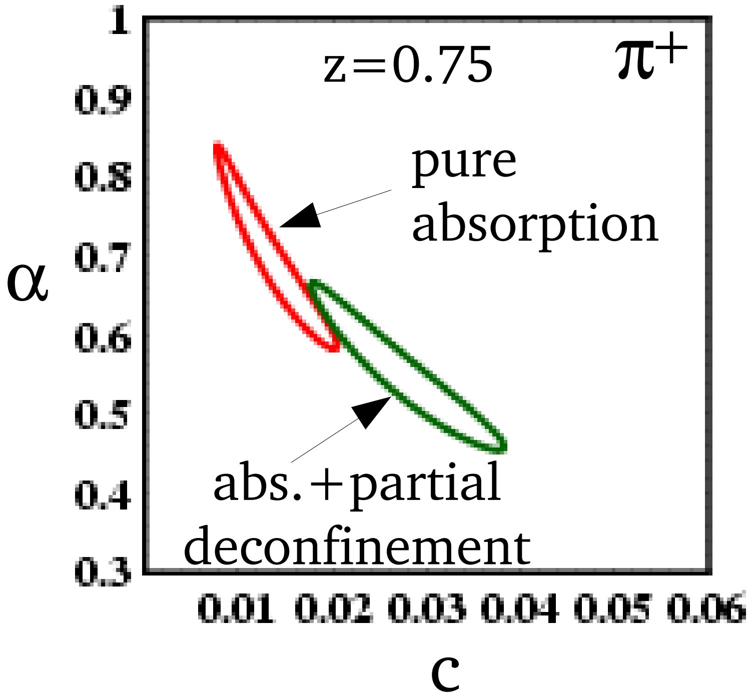
- Example: absorption model at $z = 0.75$ with {He, N, Ne, Kr} included in the fit

The power of cA^{α} fits

- **sensitive to model assumptions**

  E.g., pure absorption vs. absorption plus partial quark deconfinement:

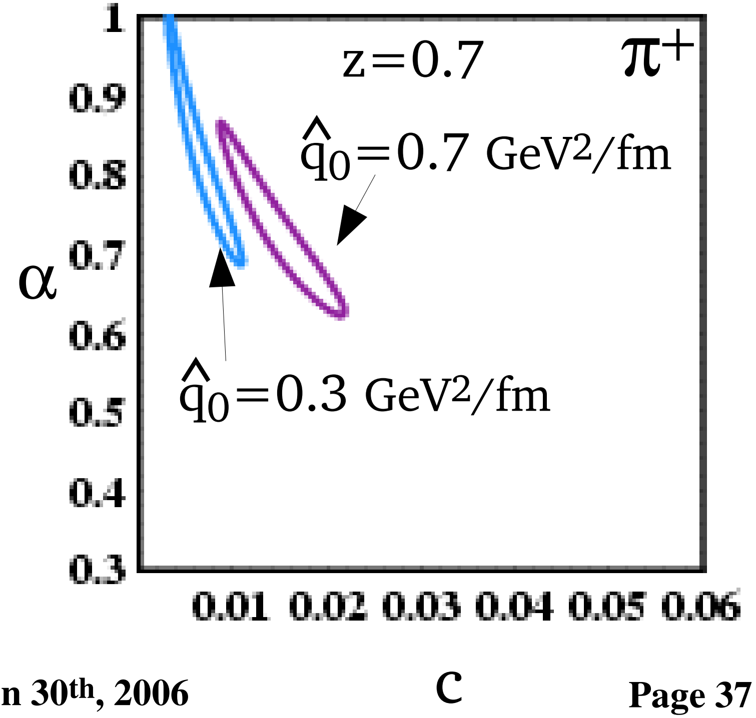
  $Q^2 \rightarrow \xi(A,Q^2) \times Q^2$



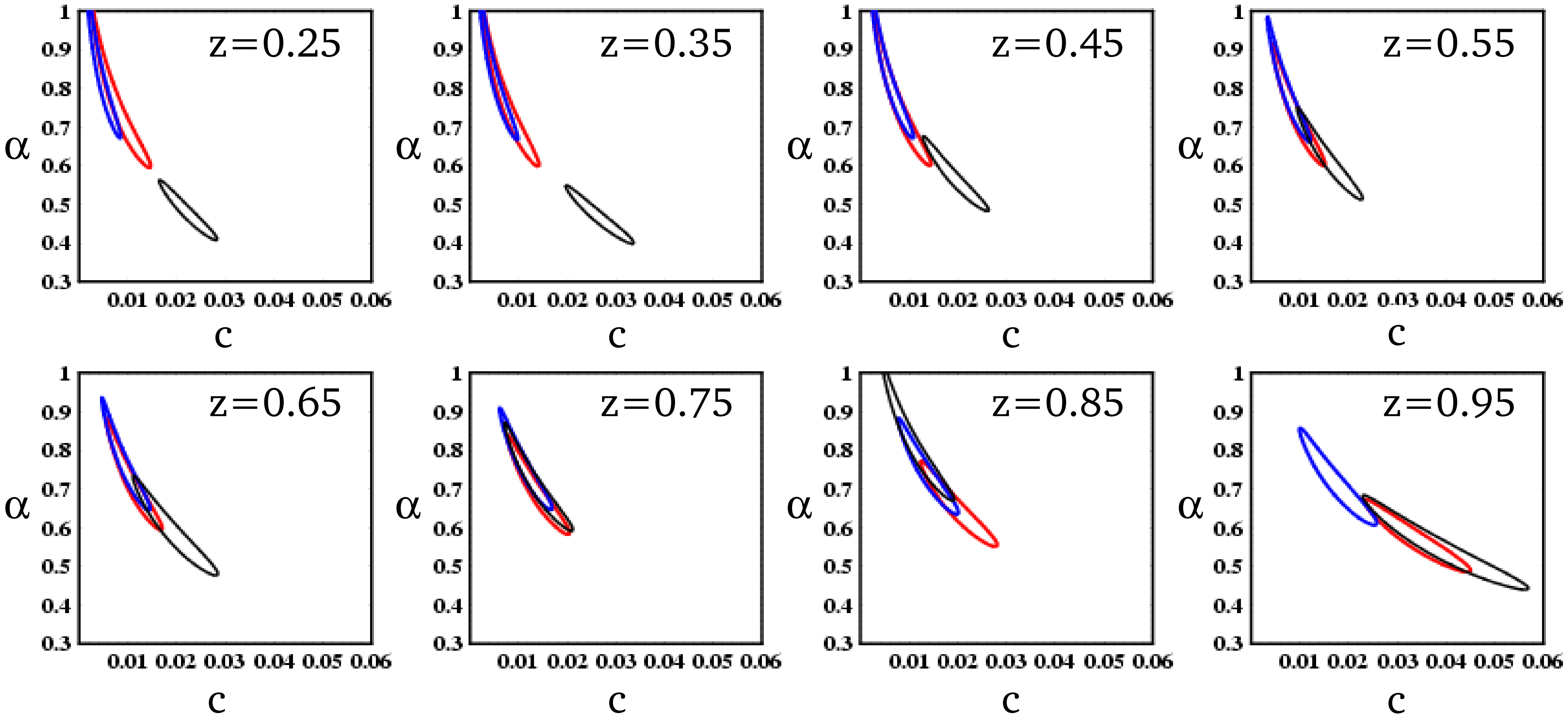
- **sensitive to model parameters**

  E.g., energy loss with

  $\hat{q}_0=0.3$ GeV^2/fm vs. $\hat{q}_0=0.7$ GeV^2/fm



HERMES vs. theory - π^+



Nuclei included in the fit: He, N, Ne, Kr

🟥 absorption model - $\sigma_* = 2/3\ \sigma_h$

🟦 energy loss model - $\hat{q} = 0.5\ \mathrm{GeV}^2/\mathrm{fm}$

⬛ HERMES data

HERMES vs. theory - π^+

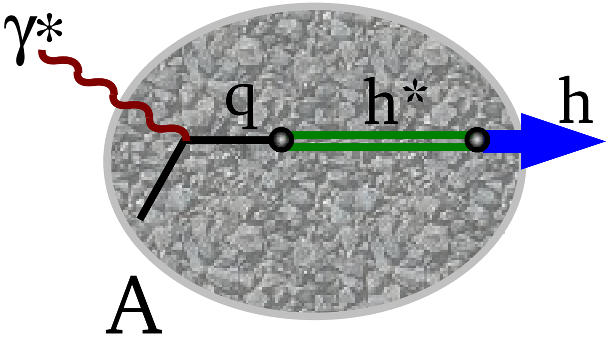
- **Data and absorption are consistent with $A^{2/3}$ - en.loss only partially**
- **Absorption and struck quark en.loss mimick each other**
  - not possible to distinguish (separate) the 2 mechanisms even using heavy nuclei
- **cA^{α} fits are powerful: may distinguish other models**
  - other implementations of energy loss
  - additional effects (e.g. Q^2 rescaling and partial deconfinement)

A-dependence of RM cannot be conclusively used to test dominance of partonic or prehadronic physics

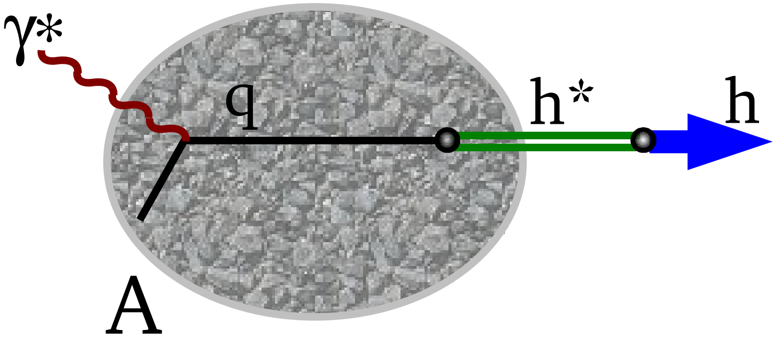
Need for more exclusive observables and data on different hadron flavors

III.5 More exclusive observables

More exclusive observables



high-z

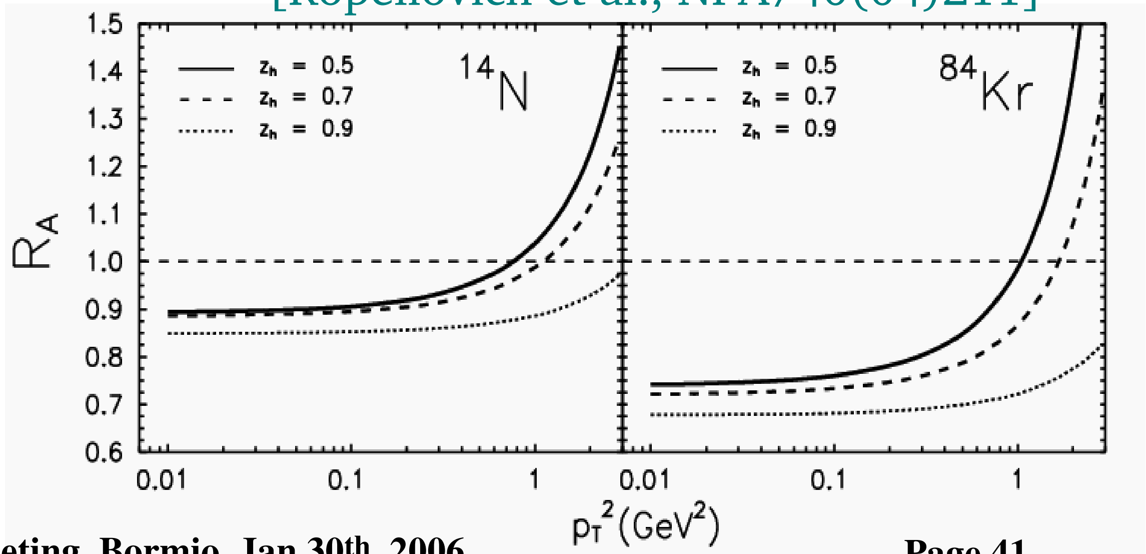


low *z*

- **$\langle p_T^2 \rangle$ broadening**
  1) Directly proportional to quark's in-medium path
  2) Can measure production time t_p
  3) Detect hadronization inside or outside the nucleus

- **p_T distributions - Cronin effect**
  1) z-, ν-, Q^2-dependence of Cronin effect

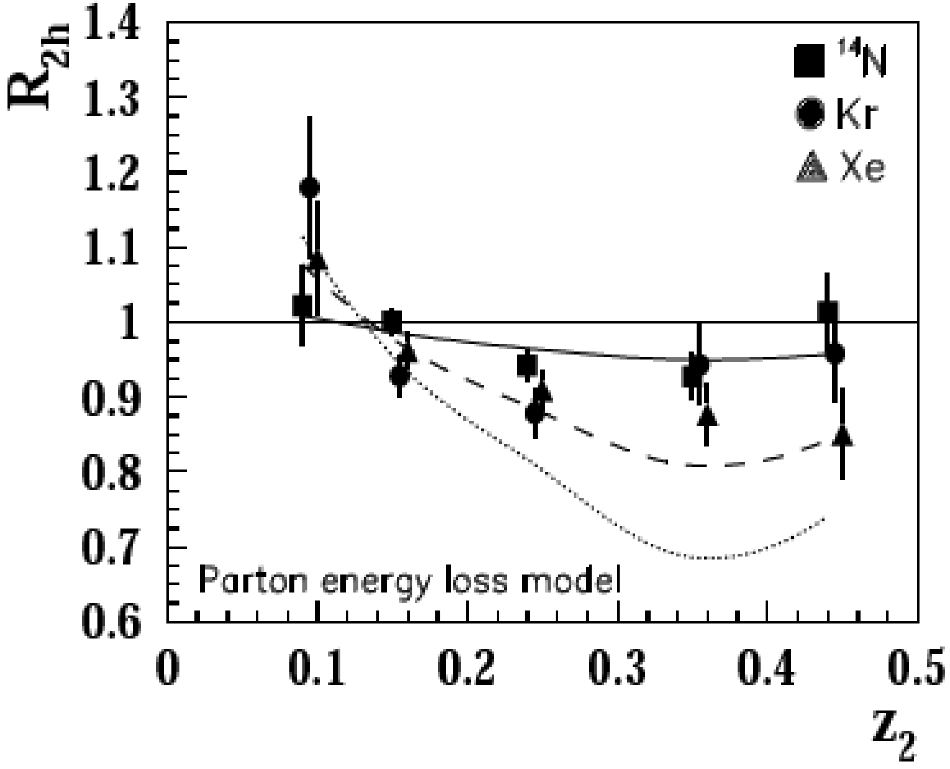
[Kopeliovich et al., NPA740(04)211]

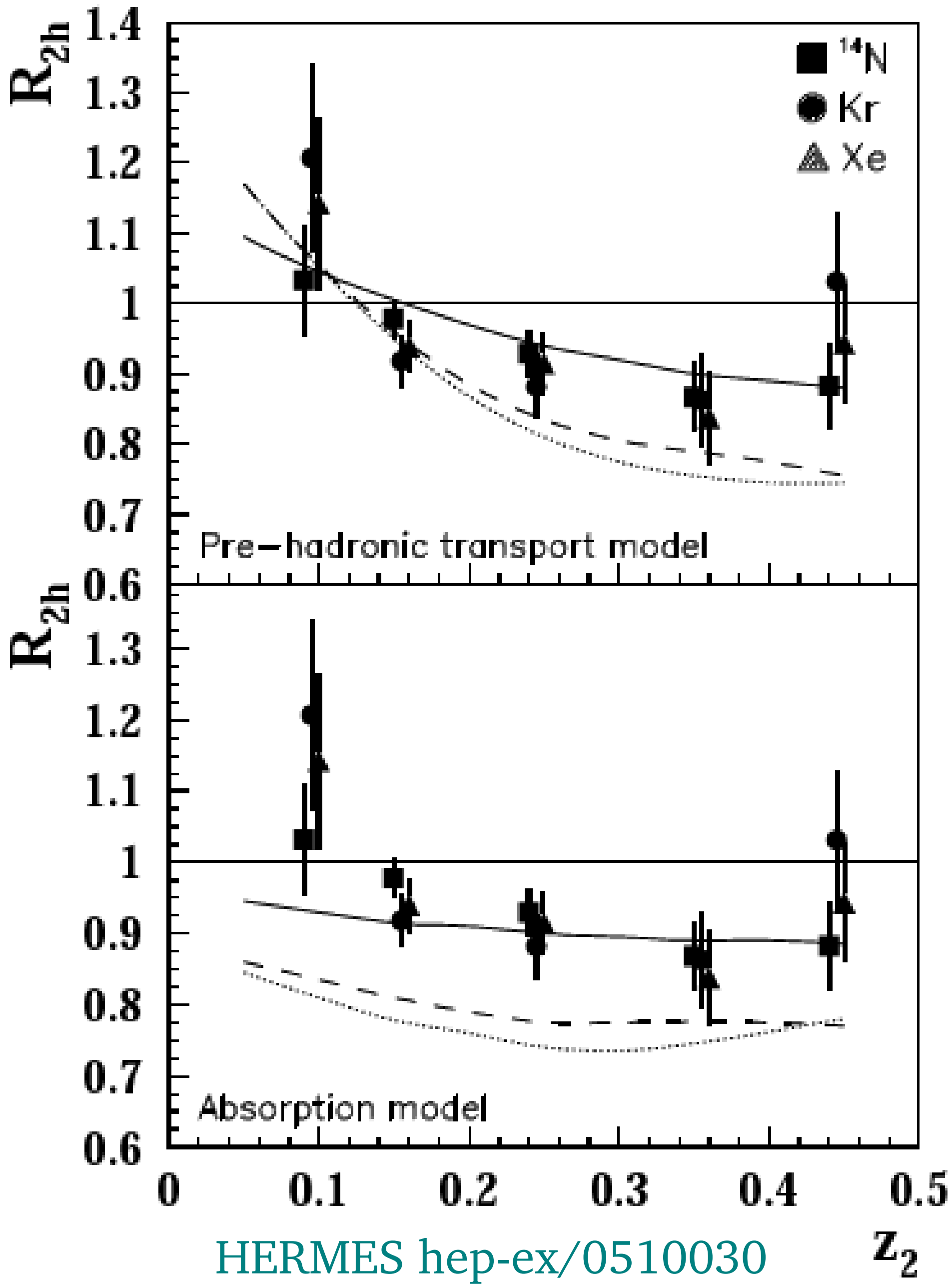


More exclusive observables

- double hadron attenuation

$$R_2(z_2) = \frac{\left.\frac{N_2(z_2)}{N_1}\right|_A}{\left.\frac{N_2(z_2)}{N_1}\right|_D}$$





HERMES hep-ex/0510030

Conclusions

- **It's not easy to separate absorption from energy loss effects, even in DIS**
  - Hadron absorption predicts $R_M \sim A^{2/3}$ as well
  - Very important for accurately measuring QGP properties
- **cA^{α} fits are powerful - A-dependence of R_M but will not solve the issue**
  - meaningful test of theory models – allows to study $\alpha=\alpha(A)$
- **For future experiments [JLAB, a few runs at HERMES]**
  - Use a few more targets to complete the light-to-heavy scan and allow precise cA^{α} fits
  - Concentrate resources on collecting high statistics to access
    1) more exclusive observables (pT-broadening, Cronin vs. z , 2PC)
    2) heavy unflavored mesons (ϕ,η,ω)
    3) other baryons (Λ) → light on baryon anomaly
    4) charmed mesons (D) → help for charm/bottom puzzle at RHIC
- **On the theory side, need of studying**
  - in-medium modifications of DGLAP – breakdown of factorization at small t* -- NLO contributions (~ ½ of the cross-section)

Backup Slides

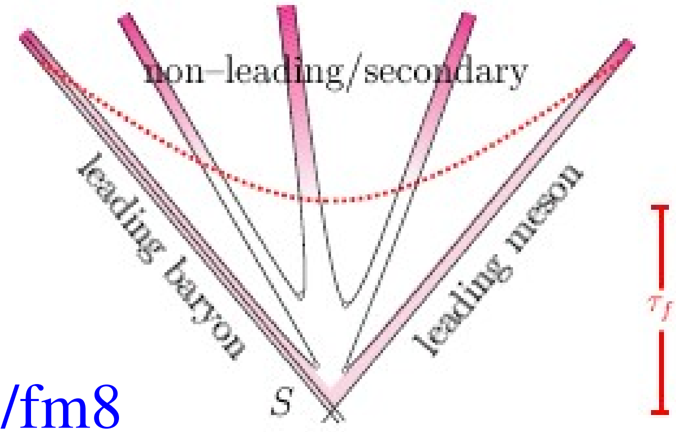
An absorption+transport model for Au+Au

Falter et al., PRC 70(04)054609 – Greiner et al., NPA 735(04)277

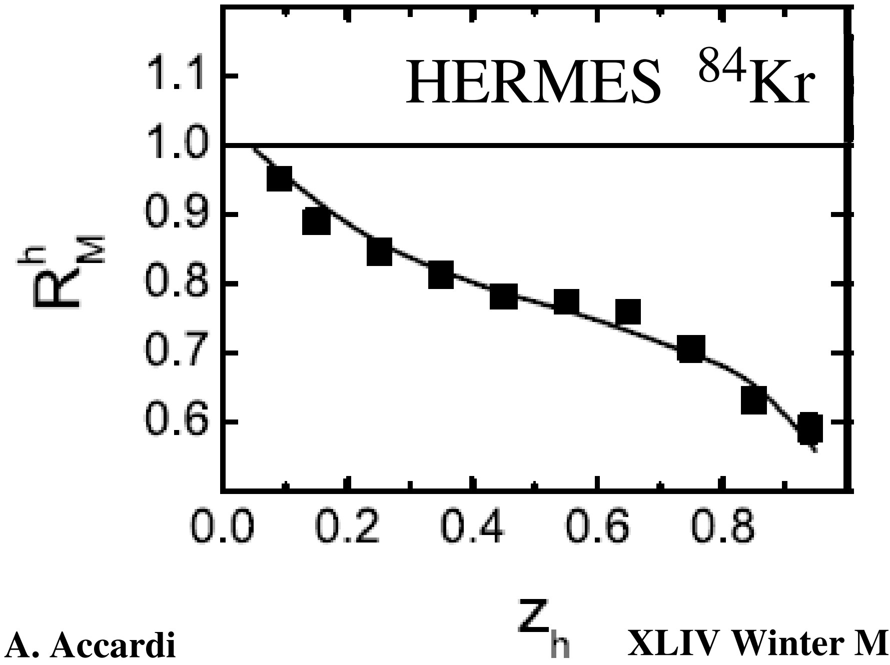
- Formation times: $t_* = 0$ fm and $t_h = (E_h/m_h)\,\tau_F$ with $\tau_F = 0.5$ fm

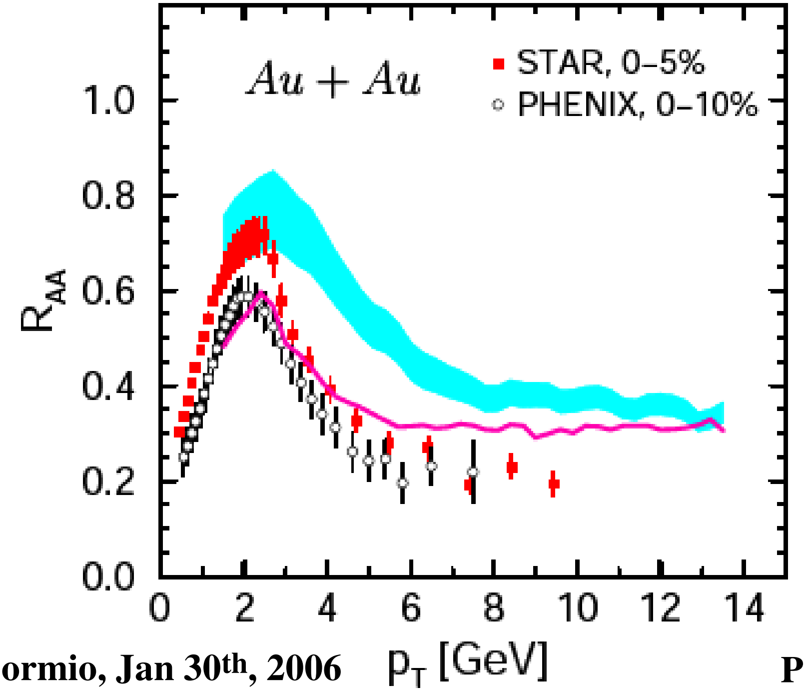
  Cross sections: leading h: $\sigma_* = 1/2\,\sigma_h$ (mesons) $1/3\,\sigma_h$ (barions)

  subleading h: $\sigma_* = 0$ mbarn



- Final state X
  - by PYTHIA and FRITJOF
  - Fermi motion, Pauli blocking, shadowing
  - evolved by BUU transport equations
- In A+A: no hadron formation above $\varepsilon_{crit} = 1$ GeV/fm8



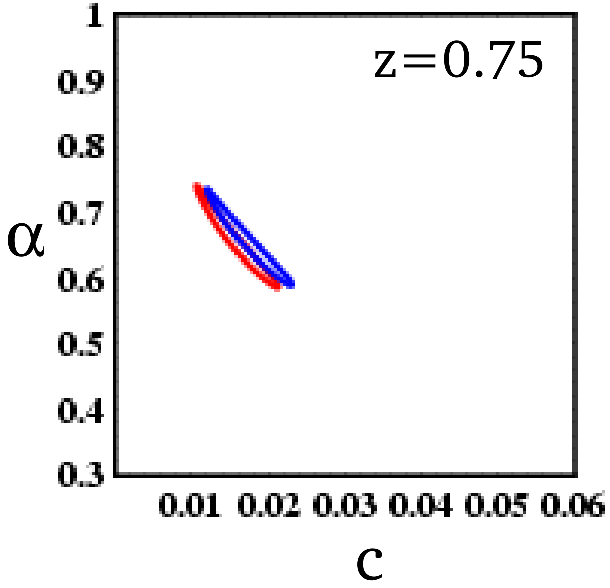


IV. Perspectives

The future: HERMES + JLAB

- **Let's imagine to have many more targets:**
  - **N,Ne,Kr,Xe** from HERMES
  - **C,Fe,SnW,Au,Pb** from JLAB

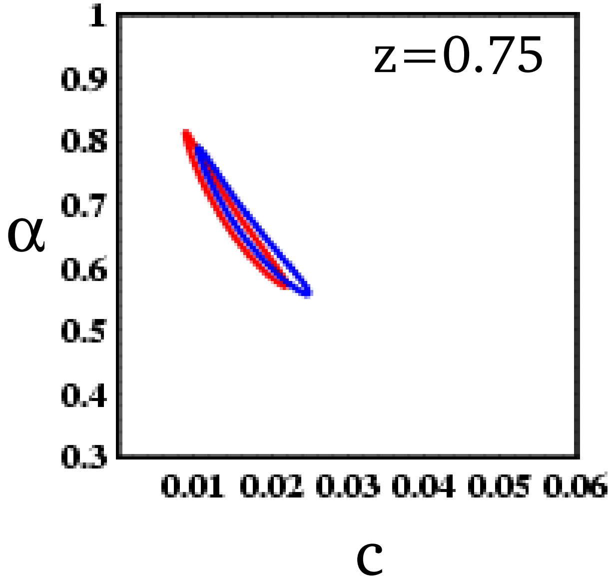
- **Full set of targets**
  - shrinks contours
  - constant α is good



(C,N,Ne,Fe,Kr,Sn,Xe,W,Au,Pb)

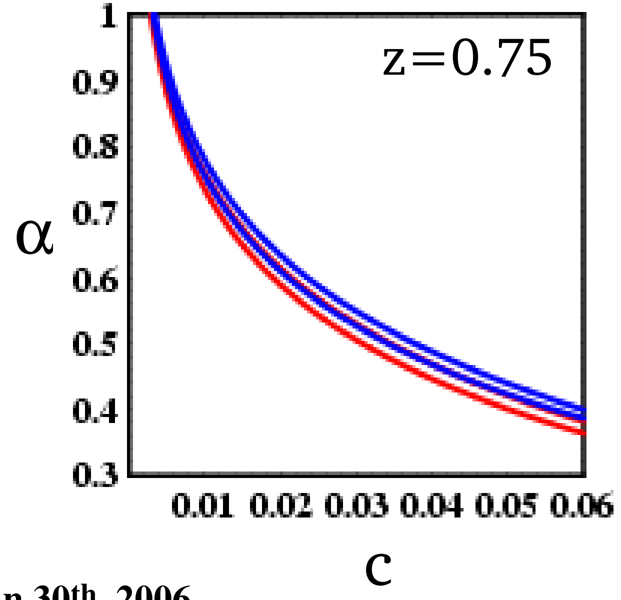
The future: HERMES + JLAB

- **Only light nuclei**
  - contours bigger than full set; comparable to HERMES alone
  - constant α is a good assumption


(C,N,Ne,Fe,Kr)

- **Only heavy nuclei**
  - elongated contours
  - signal of α=α(*A*)

Evidence for a running α=α(*A*) at large A


(Kr,Sn,Xe,W,Au,Pb)

What about ω, η, ϕ ?

- What about heavier mesons - ω, η, ϕ ?

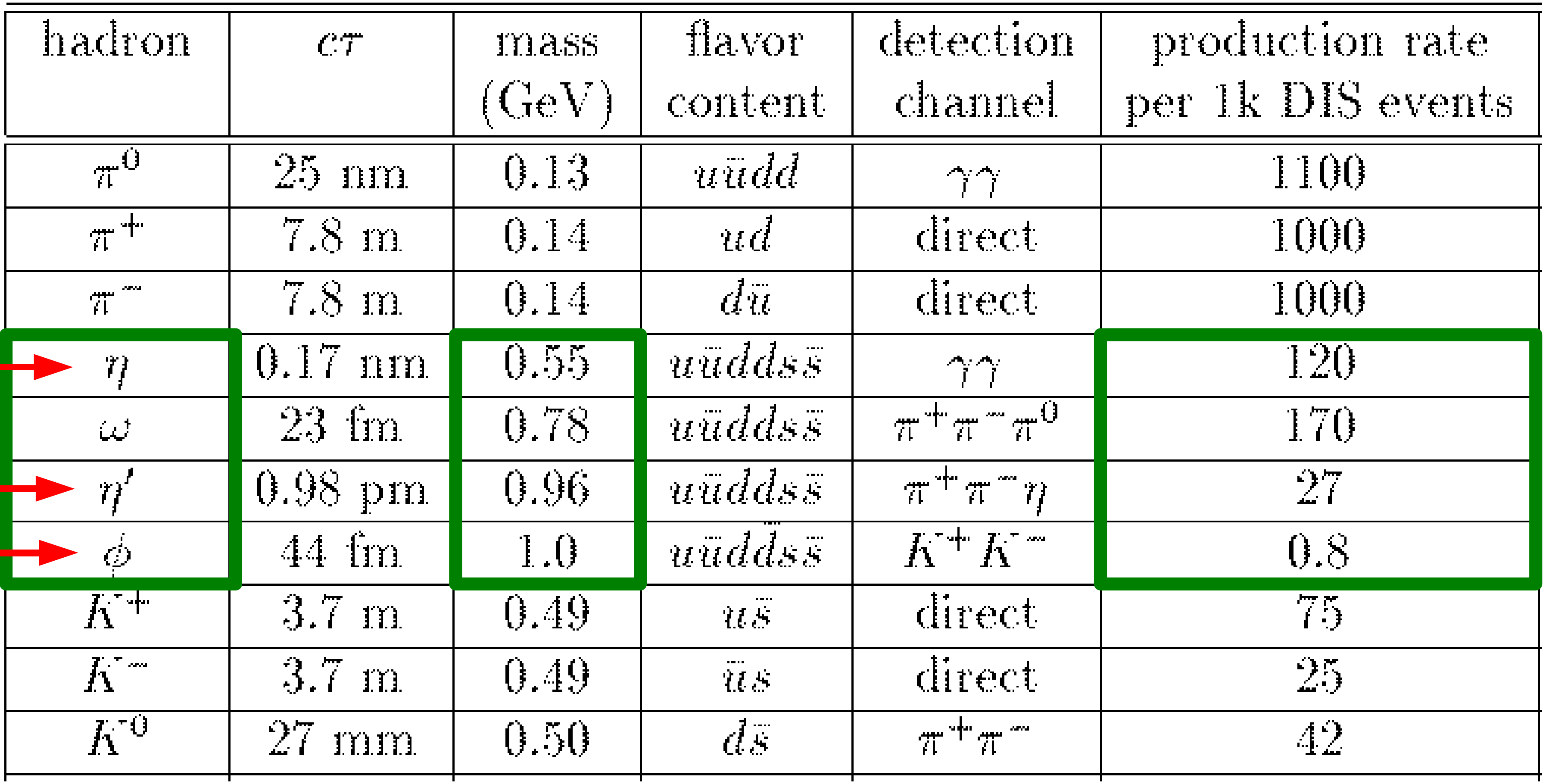
- **Energy loss with hadronization outside**
  1) similar quark content as π: $\omega, \eta, \phi = c_1(u\bar{u}+d\bar{d})+c_2(s\bar{s})$
  2) s quark is subdominant in HERMES and JLAB kinematics
  3) ⇒ similar attenuation to π (but beware the fragm. fn.)

- **Absorption point of view:**
  1) heavy ⇒ produced earlier than π ⇒ longer in-medium path
  2) earlier breakdown of $A^{2/3}$ (extreme: $<l^*>=0 \Rightarrow A^{1/3}$)
  3) However... ϕ has small hadronic cross-sections
     ⇒ smaller attenuation, compensates for 1) and 2)

What about ω, η, ϕ ?

- Can ω, η, ϕ be measured at JLAB?

CLAS++ detector [W.Brooks, FizikaB13(04)321]

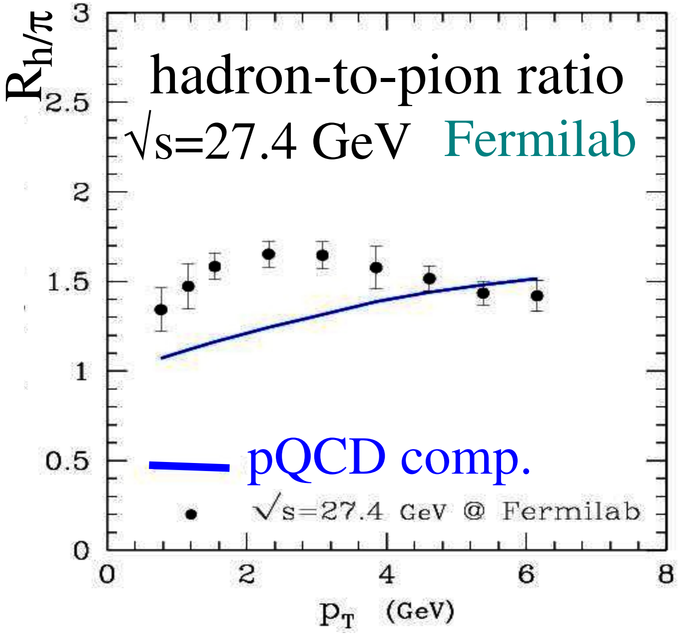


hadron	$c\tau$	mass (GeV)	flavor content	detection channel	production rate per 1k DIS events
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$	$\gamma\gamma$	1100
π^+	7.8 m	0.14	$u\bar{d}$	direct	1000
π^-	7.8 m	0.14	$d\bar{u}$	direct	1000
η	0.17 nm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	$\gamma\gamma$	120
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$	$\pi^+\pi^-\pi^0$	170
? η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$	$\pi^+\pi^-\eta$	27
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$	K^+K^-	0.8
K^+	3.7 m	0.49	$u\bar{s}$	direct	75
K^-	3.7 m	0.49	$\bar{u}s$	direct	25
K^0	27 mm	0.50	$d\bar{s}$	$\pi^+\pi^-$	42

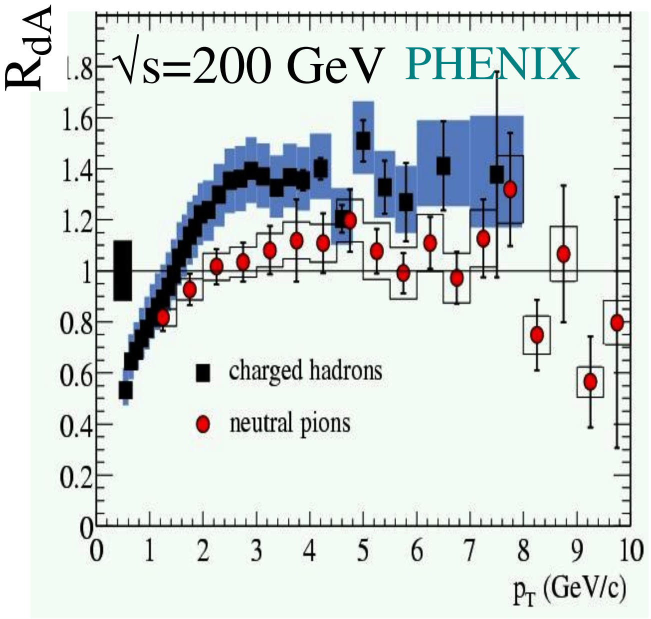
Baryon sector

"Baryon anomaly" = difference between mesons and baryons production not understood in conventional models (e.g., pQCD)

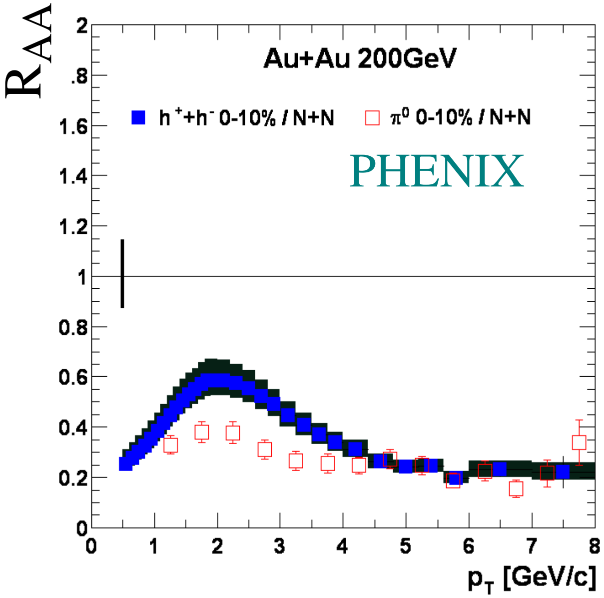
in p+p



in h+A



in A+A



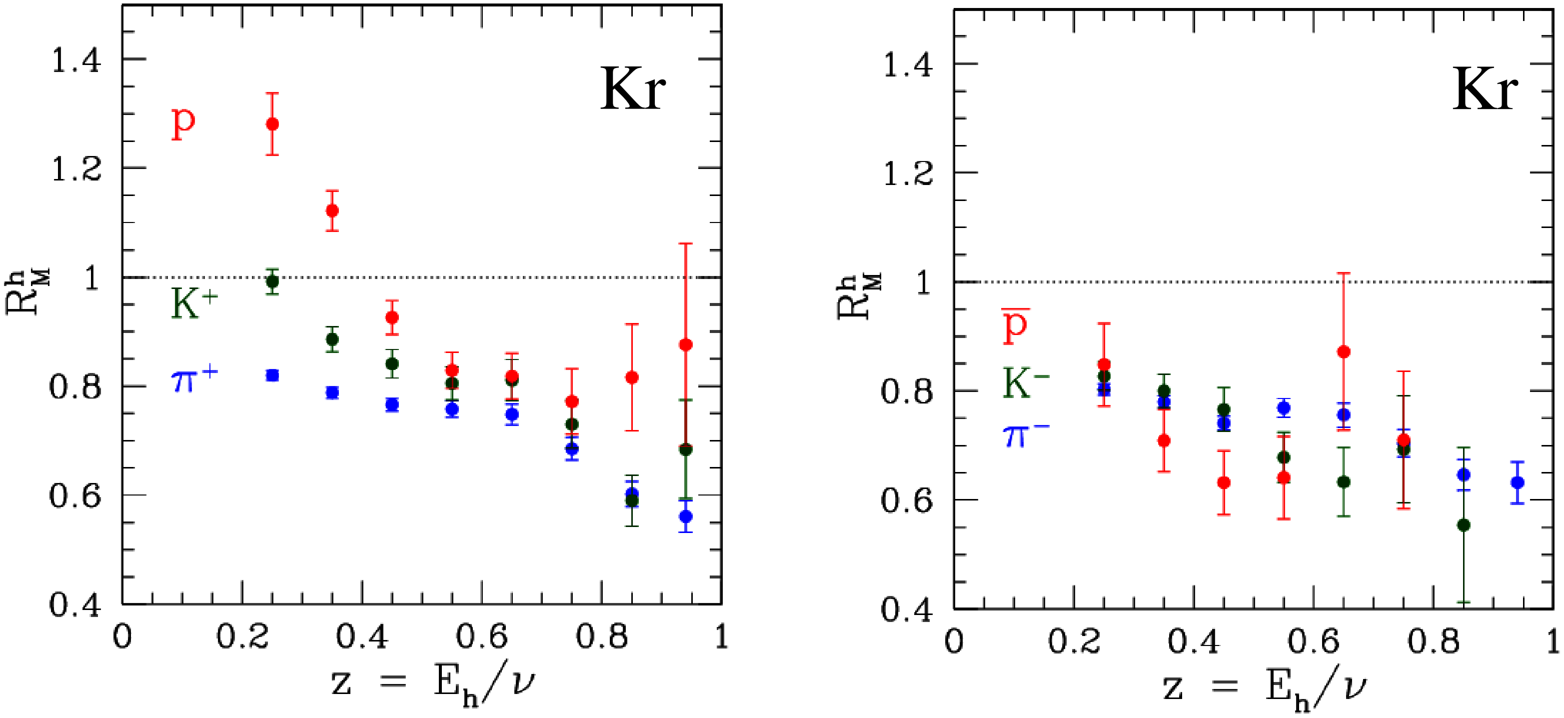
$$R_{h/\pi} = \frac{dN^h/d^2p_T}{dN^\pi/d^2p_T}$$

$$R_{BA} = \frac{1}{T_{BA}(b)} \frac{(dN^h/d^2p_T)_{d+A}}{(d\sigma^h/d^2p_T)_{p+p}}$$

Baryon sector

- Almost no model is able to reproduce the proton's rise at low-*z*
  ⇒ **baryon anomaly also in nDIS!** (what about antibaryons?)

HERMES E_{lab}=27 GeV - Phys.Lett.B577(03)37



- **What is nDIS teaching us about the baryon anomaly?**
  - same mechanism in nDIS and h(A)+A ?

(Baryon stopping? - String flip?)

Baryon sector

- Baryon vs. antibaryons

- Is the baryon anomaly in nDIS only for protons? ⇒ measure Λ!
(at RHIC R_{dAu} and R_{AuAu} similar for p and Λ)

- Λ is accessible at HERMES - what about JLAB?

CLAS++ detector [W.Brooks, FizikaB13(04)321]

?

hadron	$c\tau$	mass (GeV)	flavor content	detection channel	production rate per 1k DIS events
p	stable	0.94	ud	direct	1100
$\bar{p}$	stable	0.94	$\bar{u}\bar{d}$	direct	3
Λ	79 mm	1.1	uds	$p\pi^-$	72
$\Lambda(1520)$	13 fm	1.5	uds	$p\pi^-$	–
Σ^+	24 mm	1.2	us	$p\pi^0$	6
Σ^0	22 pm	1.2	uds	$\Lambda\gamma$	11
Ξ^0	87 mm	1.3	us	$\Lambda\pi^0$	0.6
Ξ^-	49 mm	1.3	ds	$\Lambda\pi^-$	0.9

Heavy flavours ?

- Heavy flavour puzzle at RHIC [QM2005, STAR, Djordjevic, Armesto]
  - single non-photonic e^- as much suppressed as π
  - e^- comes from D and B mesons $\Rightarrow$ c and b-quarks
  - use NLO pQCD rates for c and b + heavy quark energy loss theory

    $\Rightarrow$ ***theory gives half of the observed suppression!***

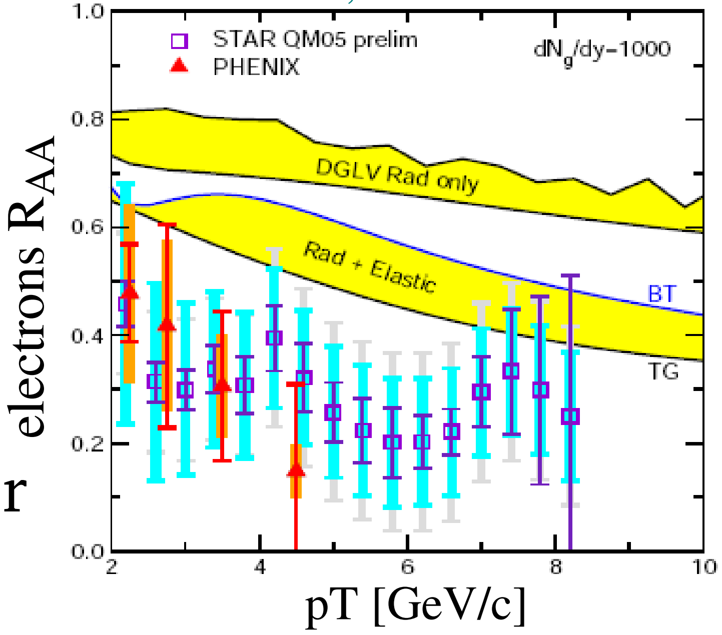
    (but compatible with c-quark suppression only...)

- **"If STAR $R_{AA}(e^-)$ is confirmed, it will be a theoretical challenge to devise novel energy loss mechanisms able to explain these data."**

  M.Djordjevic, QM2005

- Can JLAB measure identified D mesons?
  - study of c-quark attenuation in cold matter
  - help in solving heavy flavour puzzle

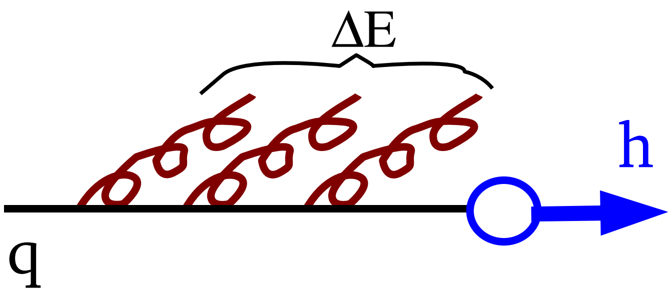
Wicks et al., nucl-th/0512076



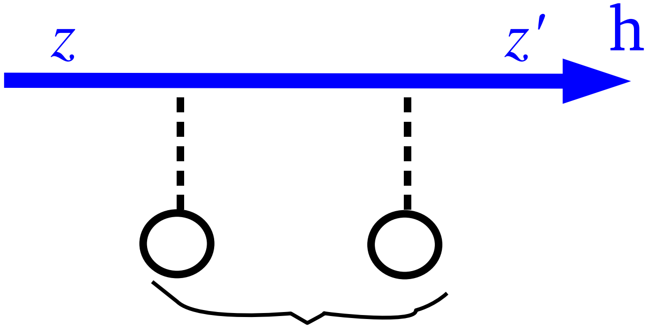
A note on "energy loss"

Many phenomena, the same name,
the same effect (hadron attenuation at high-*z*)

- Gluon bremsstrahlung



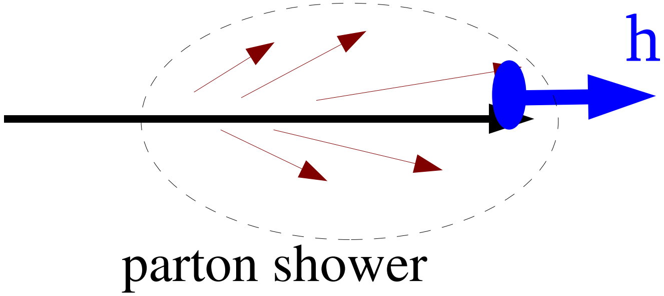
- Hadron-nucleon rescatterings



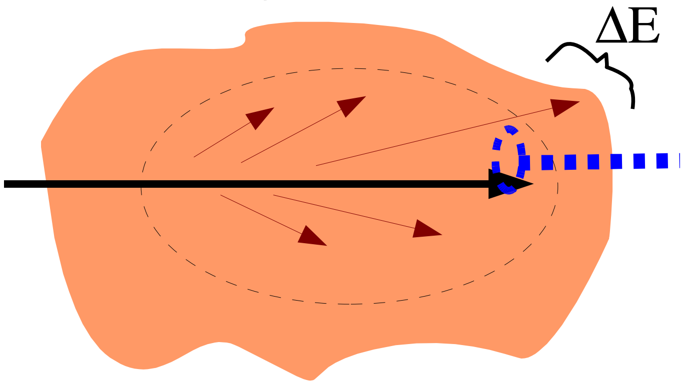
$\Delta E = (z - z')\nu$

- "Missed" hadronization in a colour screening medium

a) vacuum



b) screening medium



The end