Can we distinguish energy loss from hadron absorption?

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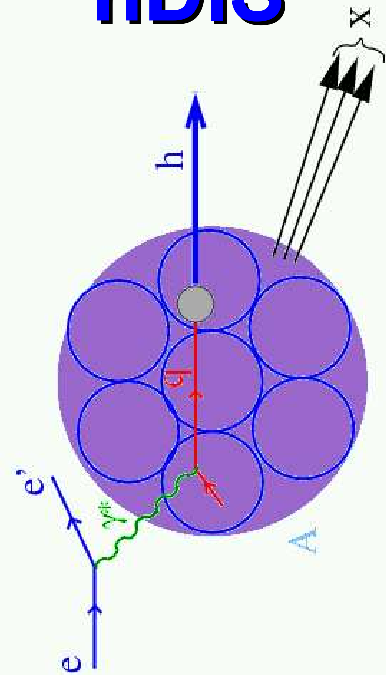
"Parton Propagation through Strongly Interacting Systems"
Trento, Sep. 27th - Oct 7th, 2005

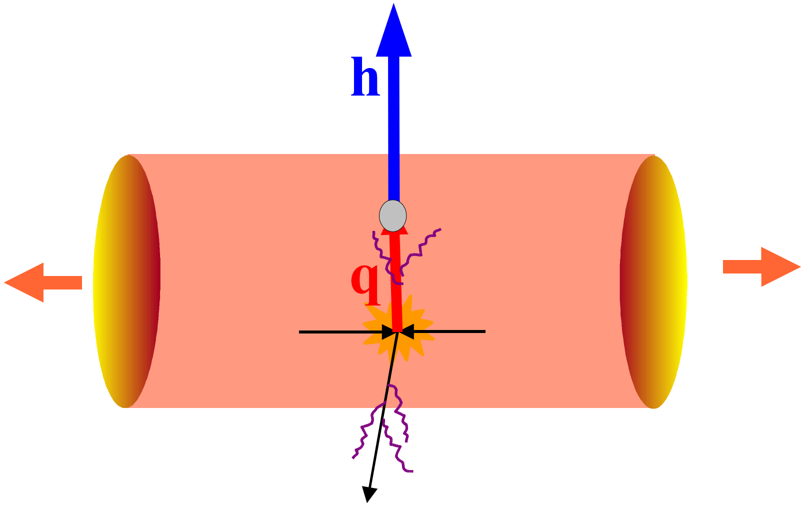
- **Intro: bridging 2 languages**
  - nDIS vs. h+A and A+A collisions
  - a few similarities and differences
- **Hadron attenuation in nDIS - R_M**
  - hadron absorption model
  - energy loss model
- **Energy loss vs. absorption**
  - The "$A^{2/3}$ power law"
  - cA^{α} fits - power law breaking
- **Conclusions**

with many thanks to
D.Gruenewald

I. Bridging 2 languages

nDIS vs. A+A collisions





- ☆ nDIS is a clean environment for
  (1) space-time evolution of fragmentation
    - ➔ nucleons as micro-detectors

  (2) Cold nuclear matter effects
    - ➔ quark energy loss
    - ➔ nuclear modifications of FF

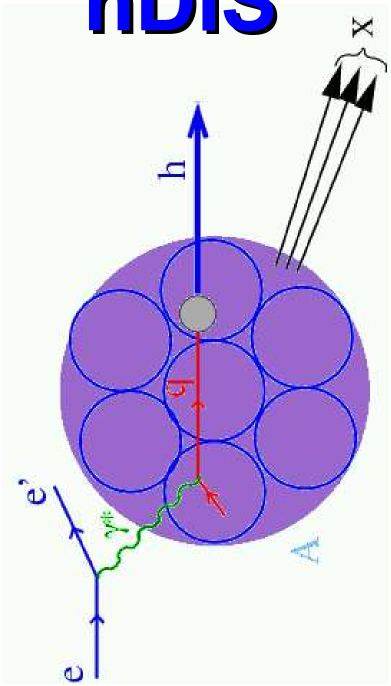
Jet-quenching in A+A

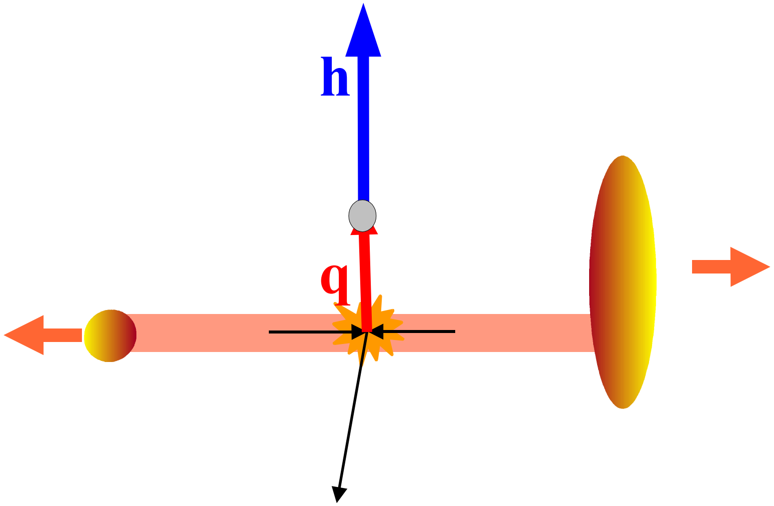
⇓

properties of
hot nuclear matter

☆ Aim of this talk: can (1) and (2) be disentangled?
is one or the other dominant? when?

nDIS vs. h+A collisions

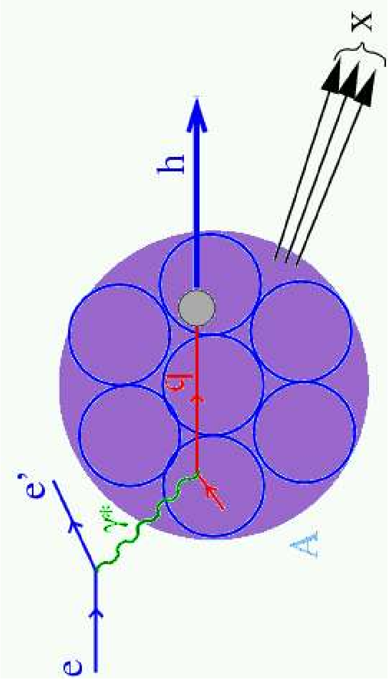


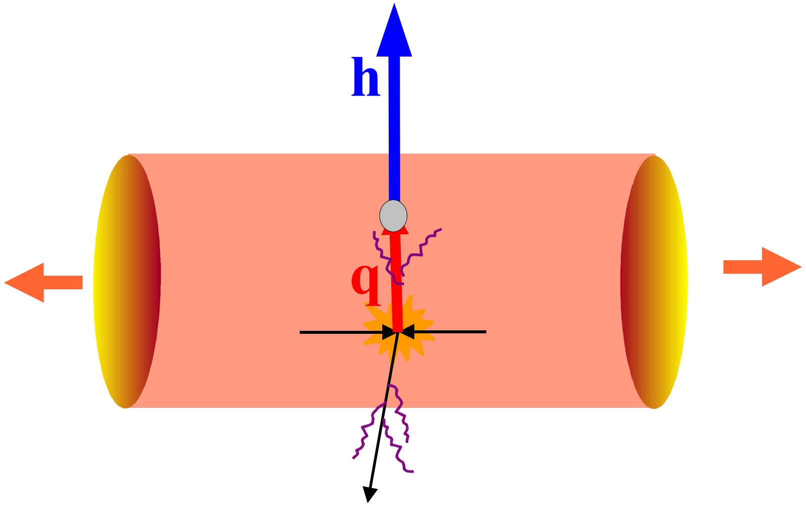


- in h+A collisions:
  - no hot matter, very thin "medium"
  - **exposes initial state nuclear effects**

- **Interplay of nDIS and h+A collisions needed to extract hot nuclear matter effects**

Similarities and differences





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

on average

$E_h = z\,\nu \approx$ **2 - 20 GeV**

$E_q = p_T / z$

$E_h = p_T \approx$ **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

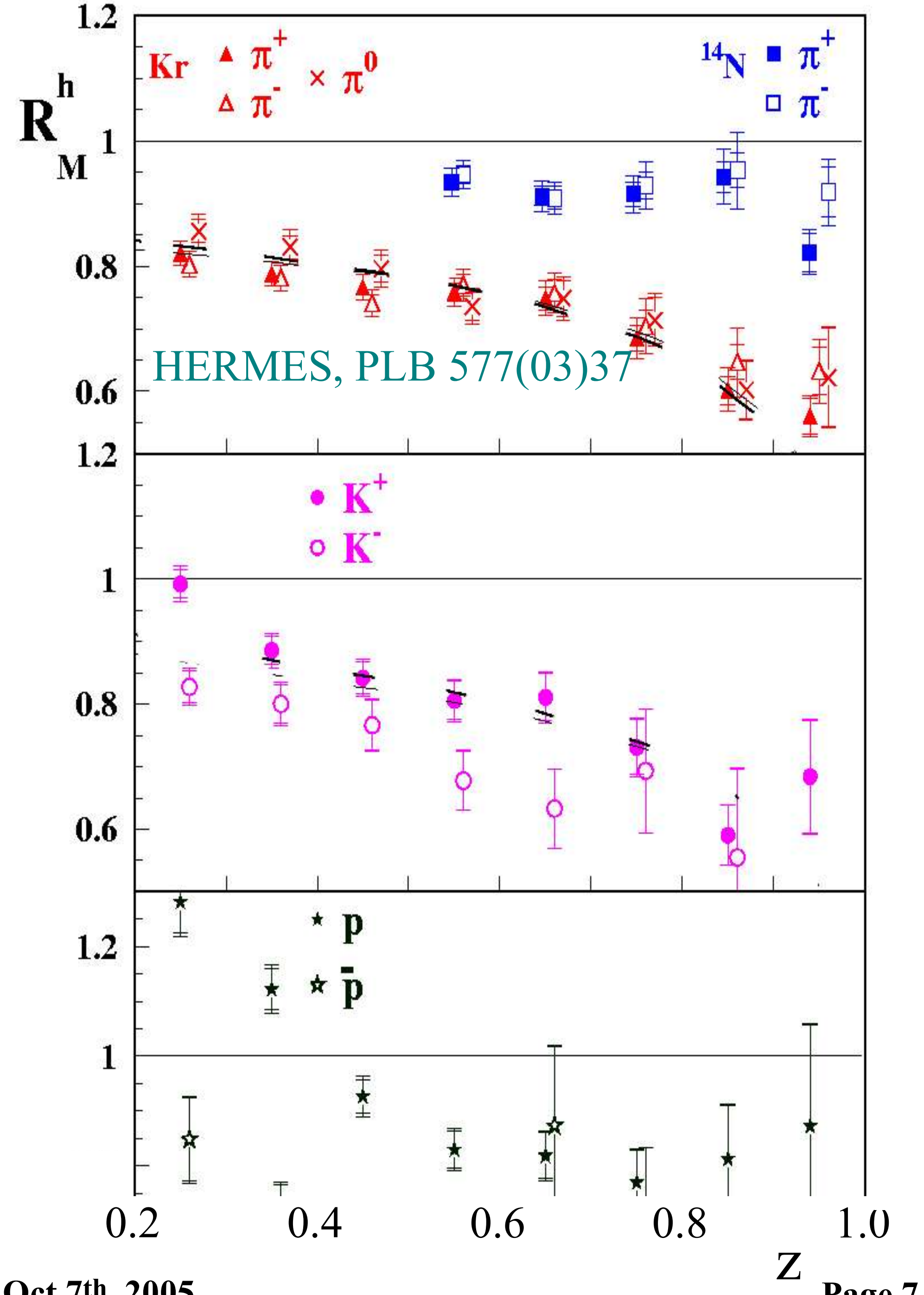
rapidity can change

II. Hadron attenuation in nDIS

The hadron attenuation ratio

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

- HERMES
  - Kr and N data are final
  - preliminary He, Ne are available
  - Xe soon to come
- JLAB
  - Statistics greatly enhanced
  - 4π detector
  - many targets up to Pb possible
  - poorer PID



2 frameworks

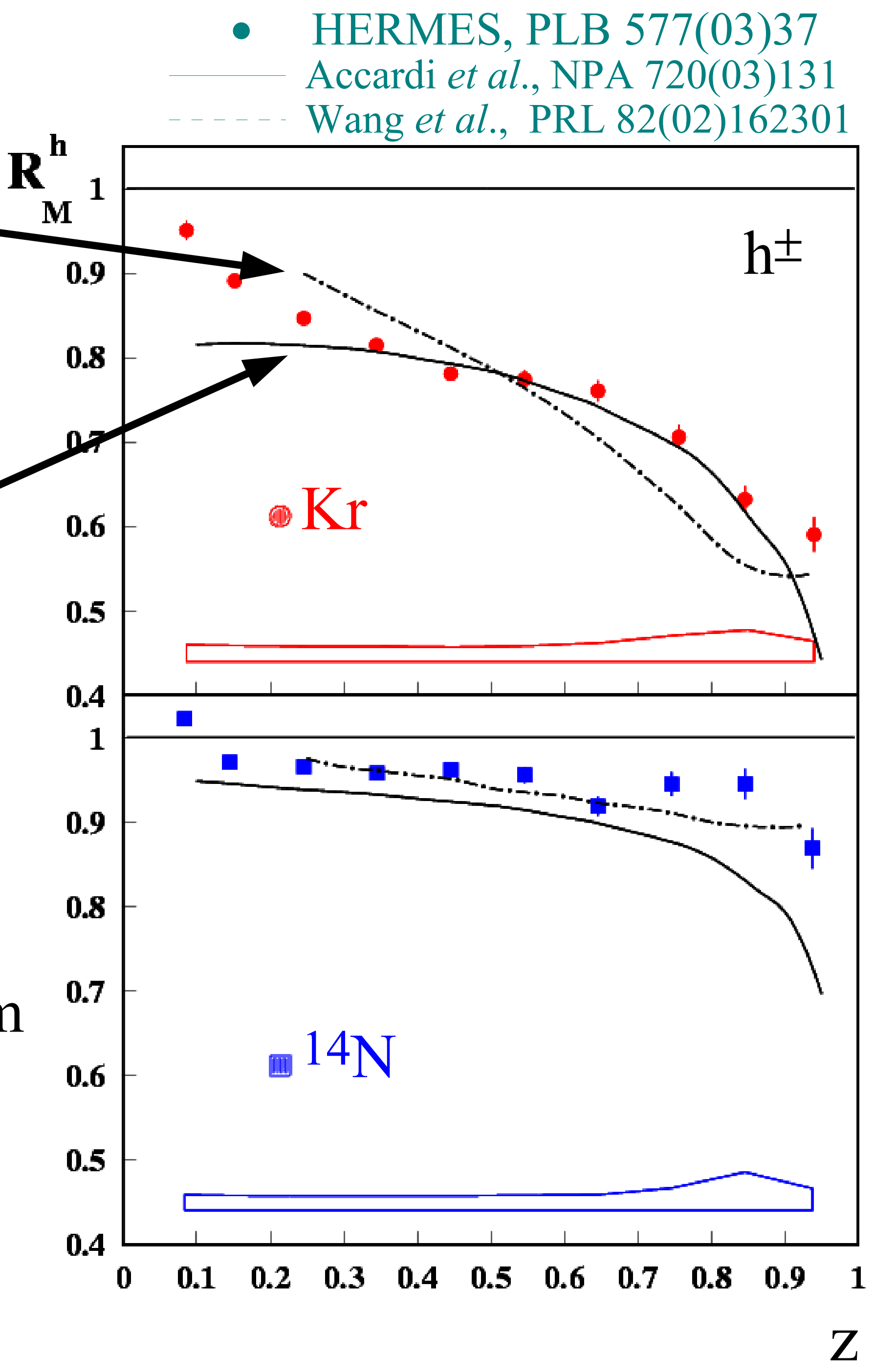
- **Energy loss (gluon brehmsstrahlung)**

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

- **Hadron absorption**

  (Accardi, Gruenewald *et al.;*
  Grigoryan *et al.;*
  Falter *et al.*;
  Kopeliovich, Nemchik, Hayashigaki *et al.*)

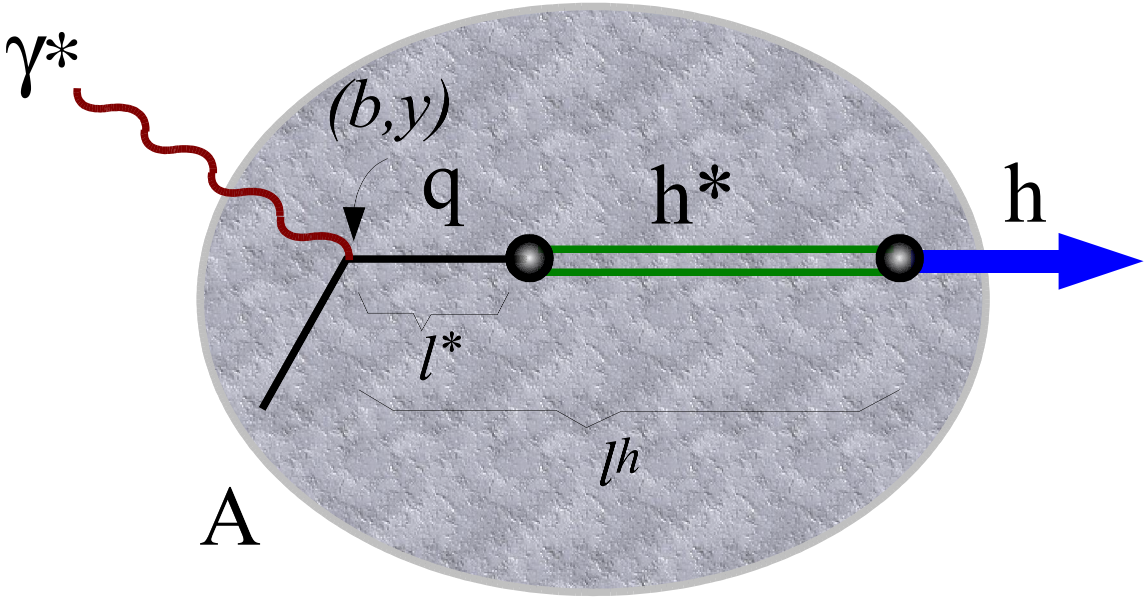
  includes also en.loss
  - colour neutralization inside the medium
  - (pre)hadron-nucleon scatterings



II.1 Hadron absorption model

Hadron absorption model

(A.A. et al., hep-ph/0502072, NPA in press) see D.Gruenewald's talk



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

- Average formation lengths $<l^*>(z,\nu)$, $<l^h>(z,\nu)$ from Lund model

Hadron absorption model - 2

(A.A. et al., hep-ph/0502072, NPA in press) see D.Gruenewald's talk

- (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'

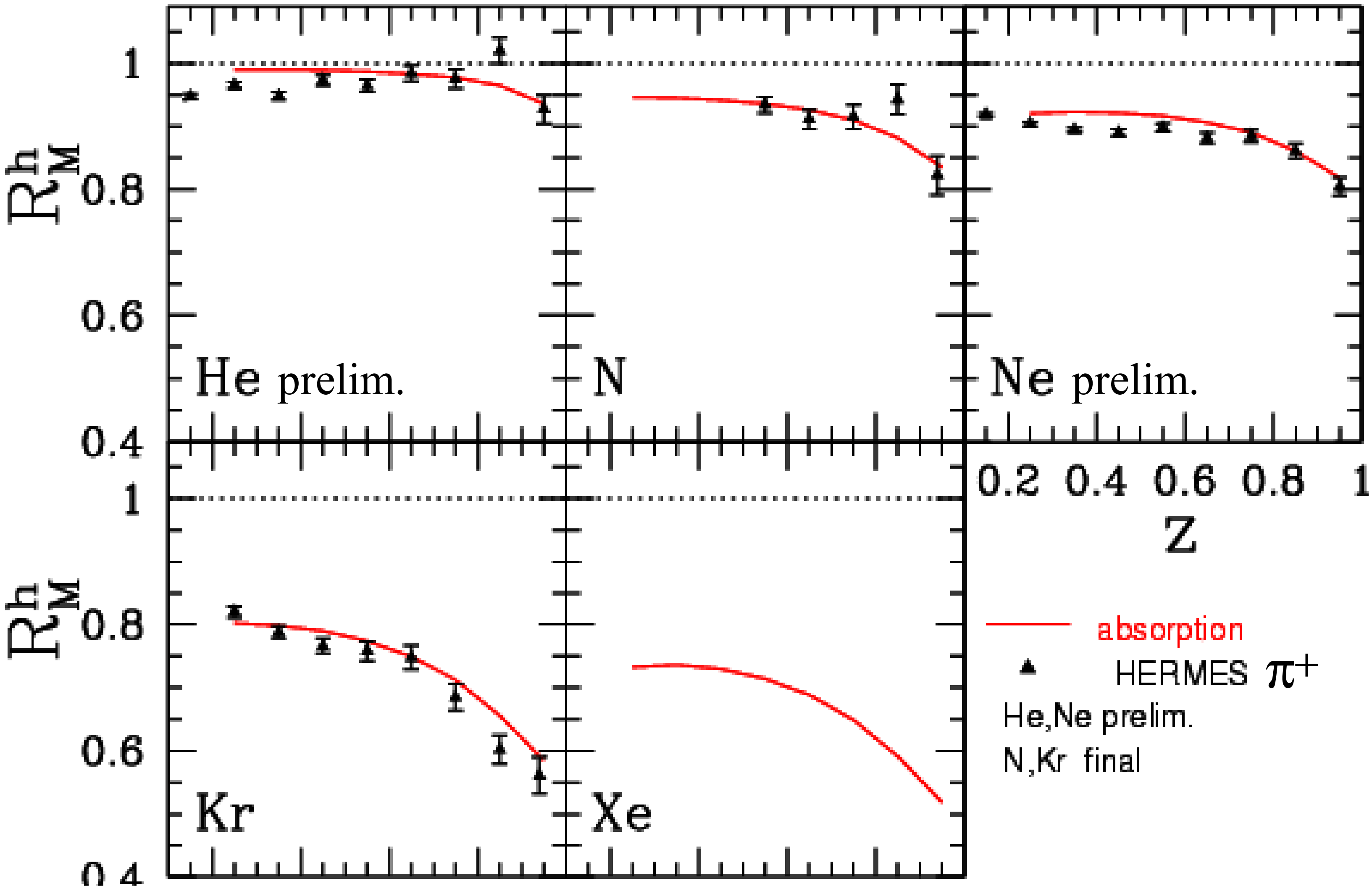
absorption of h from x' to ∞

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

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

Hadron absorption model - results

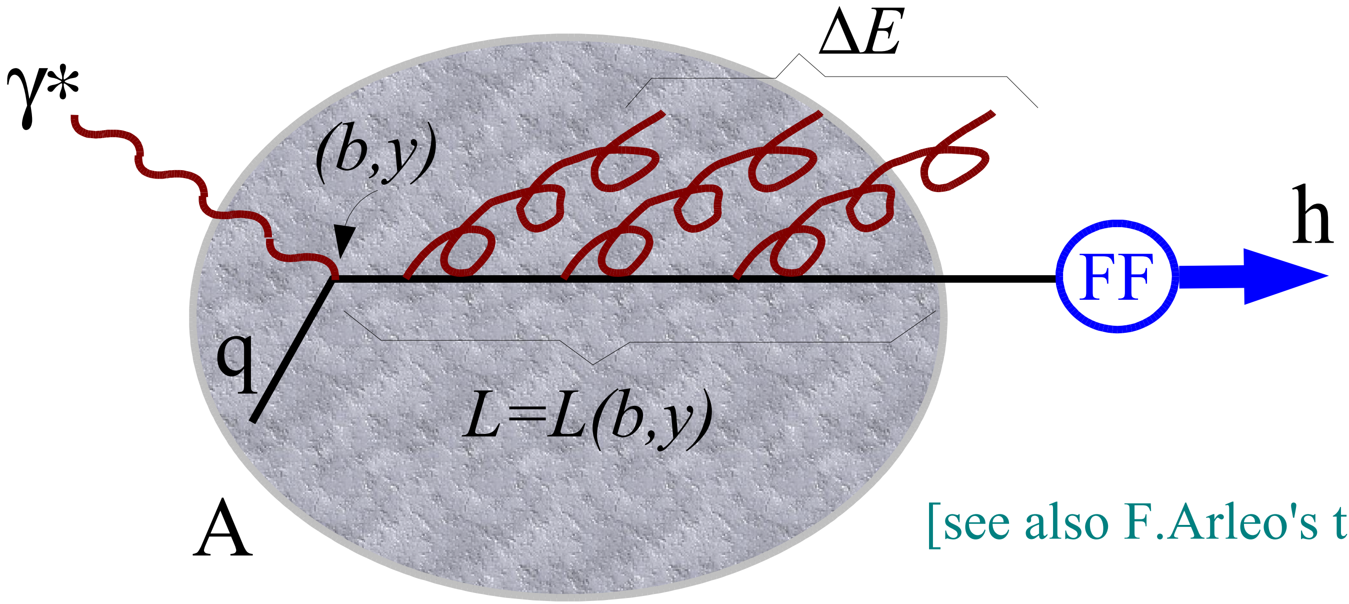
(A.A. et al., hep-ph/0502072, NPA in press) see D.Gruenewald's talk



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

II.1 Energy loss model

Energy loss model



[see also F.Arleo's talk]

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

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

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

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

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

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

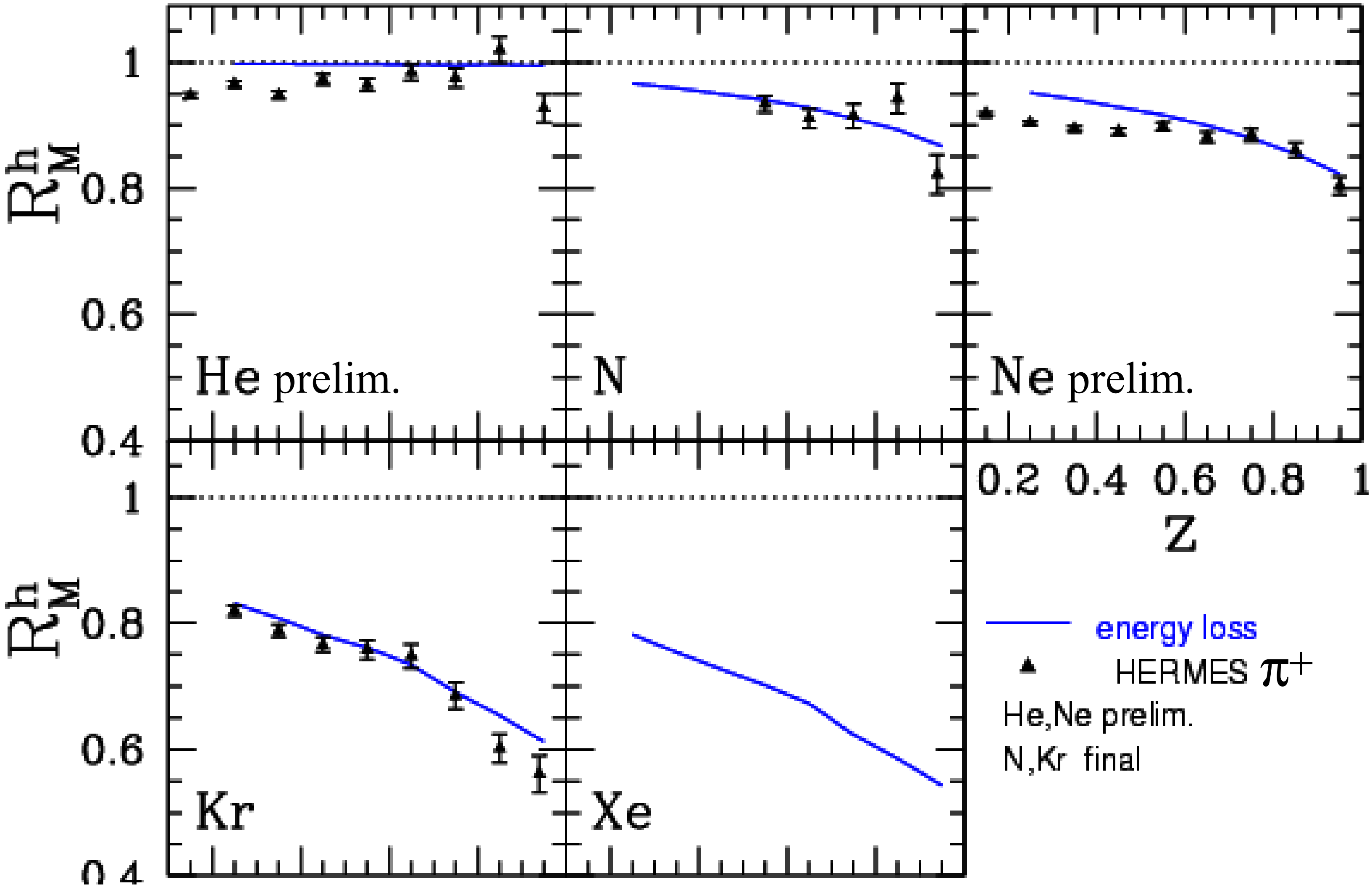
$$\langle\rho\rangle(b,y) = \int_y^\infty dz\,\rho(b,z) \Big/ L(b,y) \quad = \rho_{HS} \quad \text{for Hard-Sphere}$$

- Transport coefficient

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

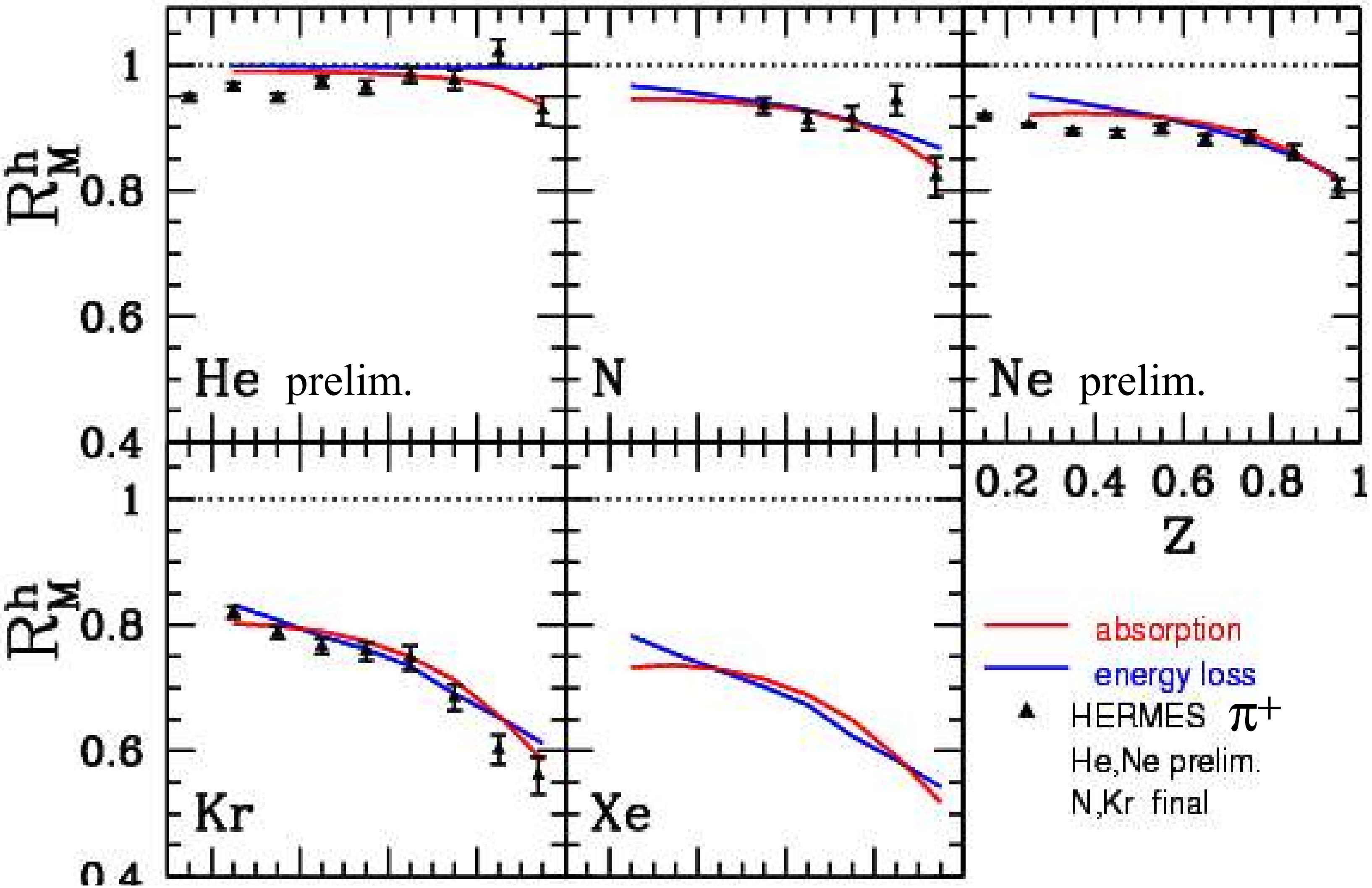
with $\hat{q}_0 = 0.5\ \text{GeV}^2/\text{fm}$ - fitted to $e^+ + \text{Kr} \rightarrow \pi^+ + X$

Energy loss model - results



III. Energy loss vs. absorption

Energy loss vs. absorption



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

III.1 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:

$$\xcancel{1-R_M \sim \langle \textit{no. of rescatterings} \rangle \sim L \sim A^{1/3}}$$

WRONG!

$\Rightarrow$ 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!

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

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

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

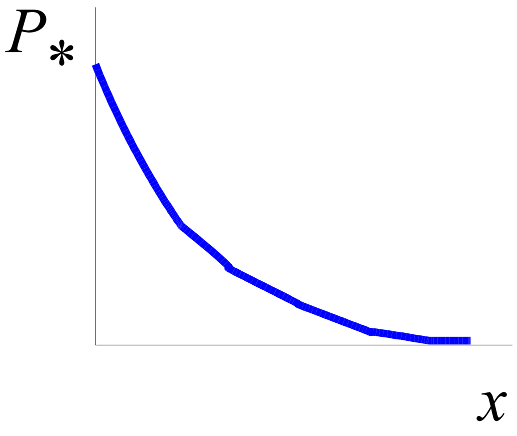
- If $\mathcal{P}_*(x-y) = \delta(x-y)$ ⇒ $1 - R_M = c\, A^{1/3}$ (e.g. Falter's et al. leading h_*)
- If not, we have a dimensionful $\langle l_* \rangle = \int_0^{\infty} dx\, x\, \mathcal{P}_*(x)$
- After all integrations we obtain an extra power of A: $\left(\frac{R_A}{\langle l_* \rangle} \right)^n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

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

- **Special cases**

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

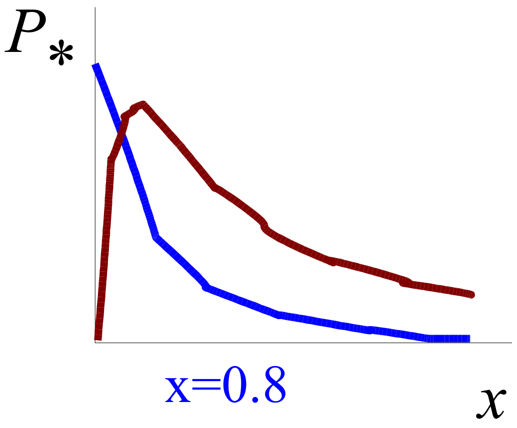
[e.g., the presented model
A.A. et al. hep-ph/0502072, NPA]



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...
see Nemchik's talk]

Not too different from case 1)



III.2 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**

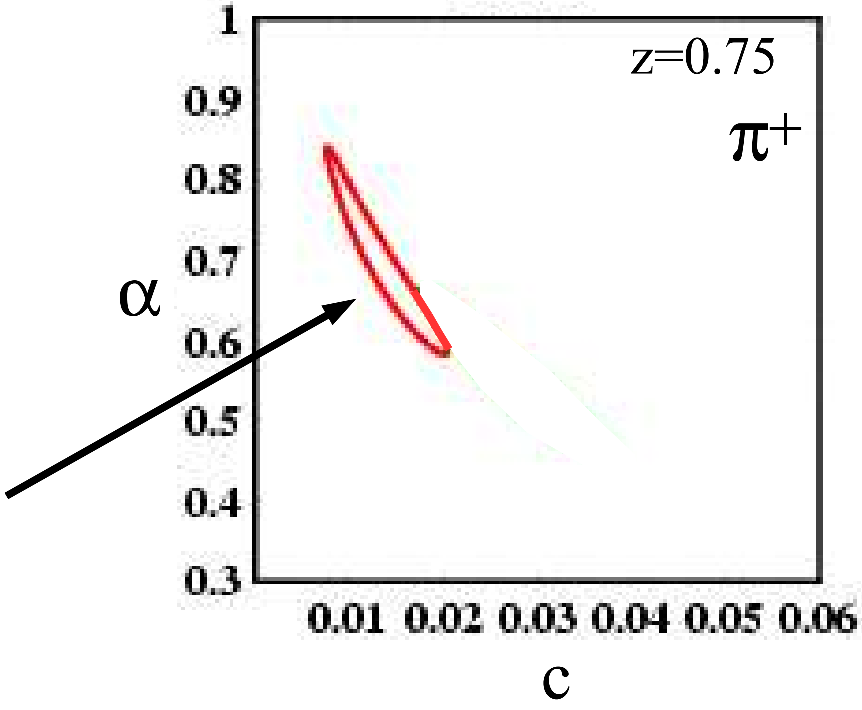
- the simplest option:

  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

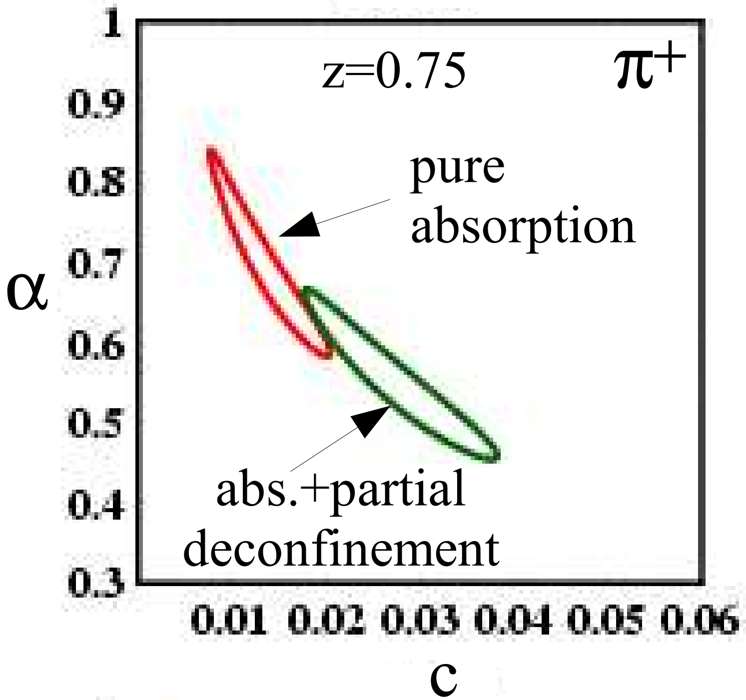


The power of cA^{α} fits

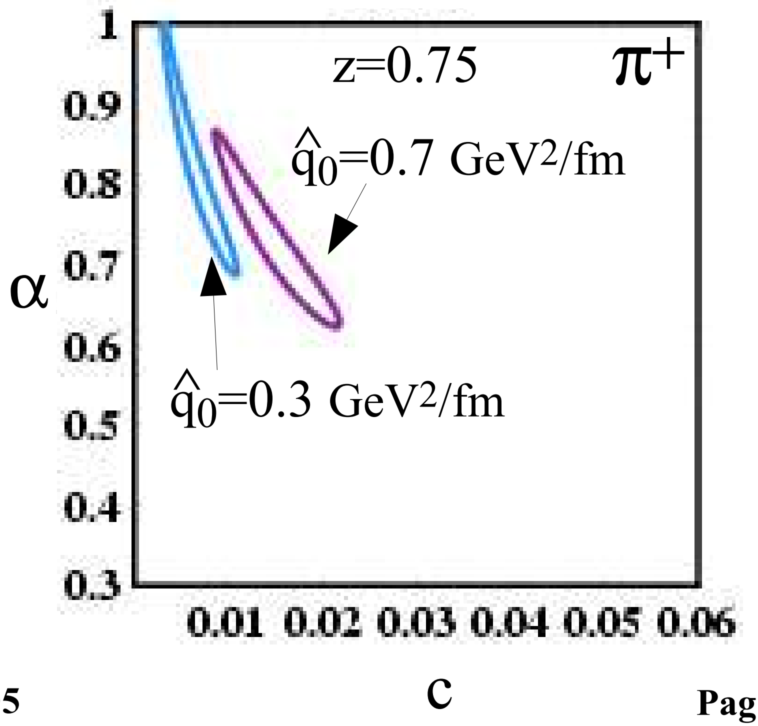
- **sensitive to model assumptions**
  E.g., pure absorption vs. absorption plus partial quark deconfinement:

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

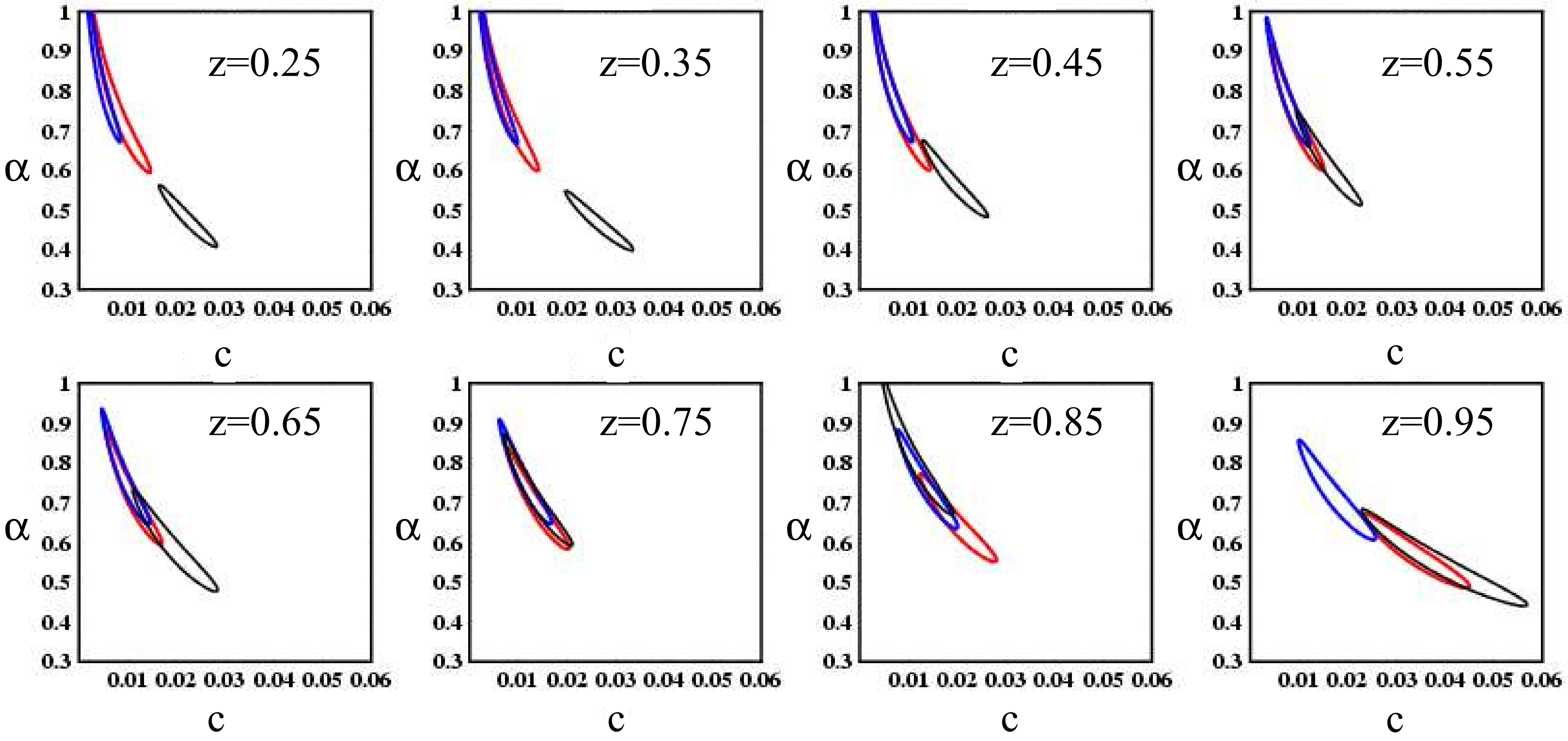
  - rescaling similar to Kopeliovich's but different physical justification



- **sensitive to model parameters**
  E.g., energy loss with
  $\hat{q}_0$=0.3 GeV^2/fm vs. $q_0\triangleq$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 - $q = 0.5\ \mathrm{GeV}^2/\mathrm{fm}$

⬛ HERMES data

HERMES vs. theory - π^+

- **Data and absorption are consistent with $A^{2/3}$ - en.loss not really**

- **Absorption and *z*-shifted en.loss mimick each other**
  - not possible to distinguish (separate) the 2 mechanisms

- **Absorption and Q^2-shifted energy loss seem different**
  - cA^α fits may test in which proportion they contribute

cA^a fits are a meaningful test of theory models

When correct physics is established
they will help in cross-checking it
and its model implementation

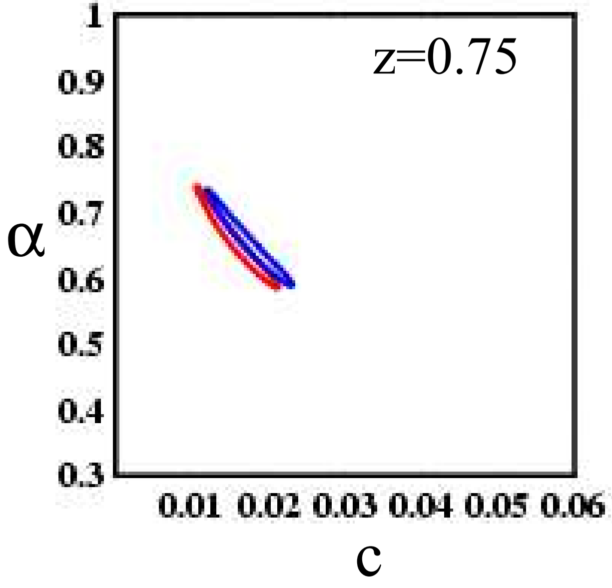
Need for more exclusive observables
and data on different hadron flavours

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 a is good

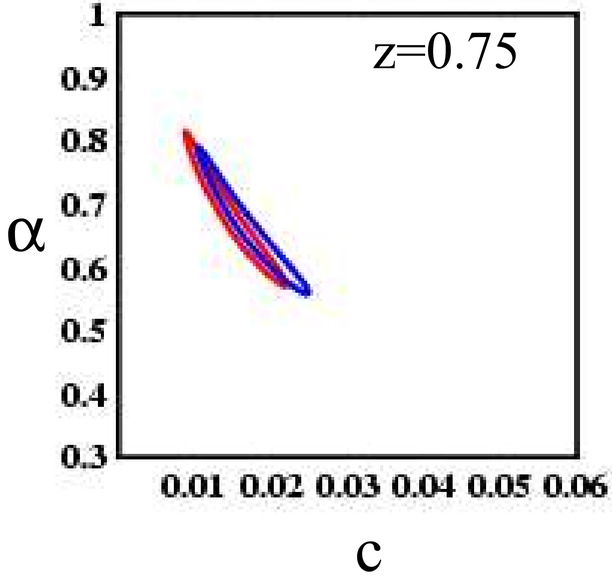
(C,N,Ne,Fe,Kr,Sn,Xe,W,Au,Pb)



The future: HERMES + JLAB

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

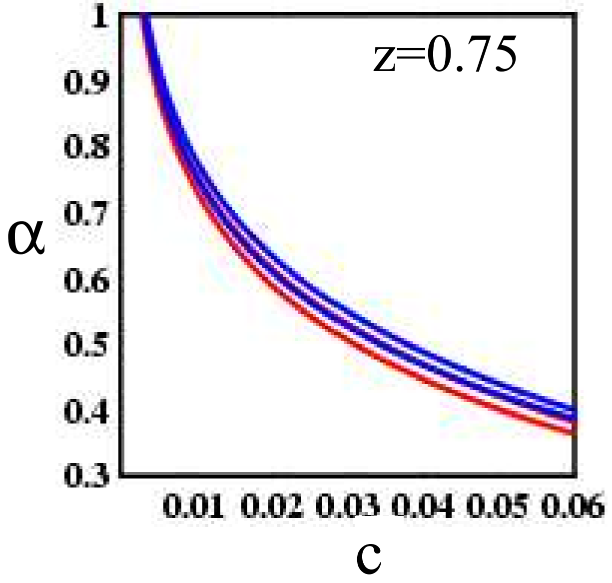
(C,N,Ne,Fe,Kr)



- **Only heavy nuclei**
  - elongated contours
  - signal of $\alpha=\alpha(A)$

Evidence for a running $\alpha=\alpha(A)$ at large A

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



IV. Perspectives and conclusions

What about ω, η, ϕ ?

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

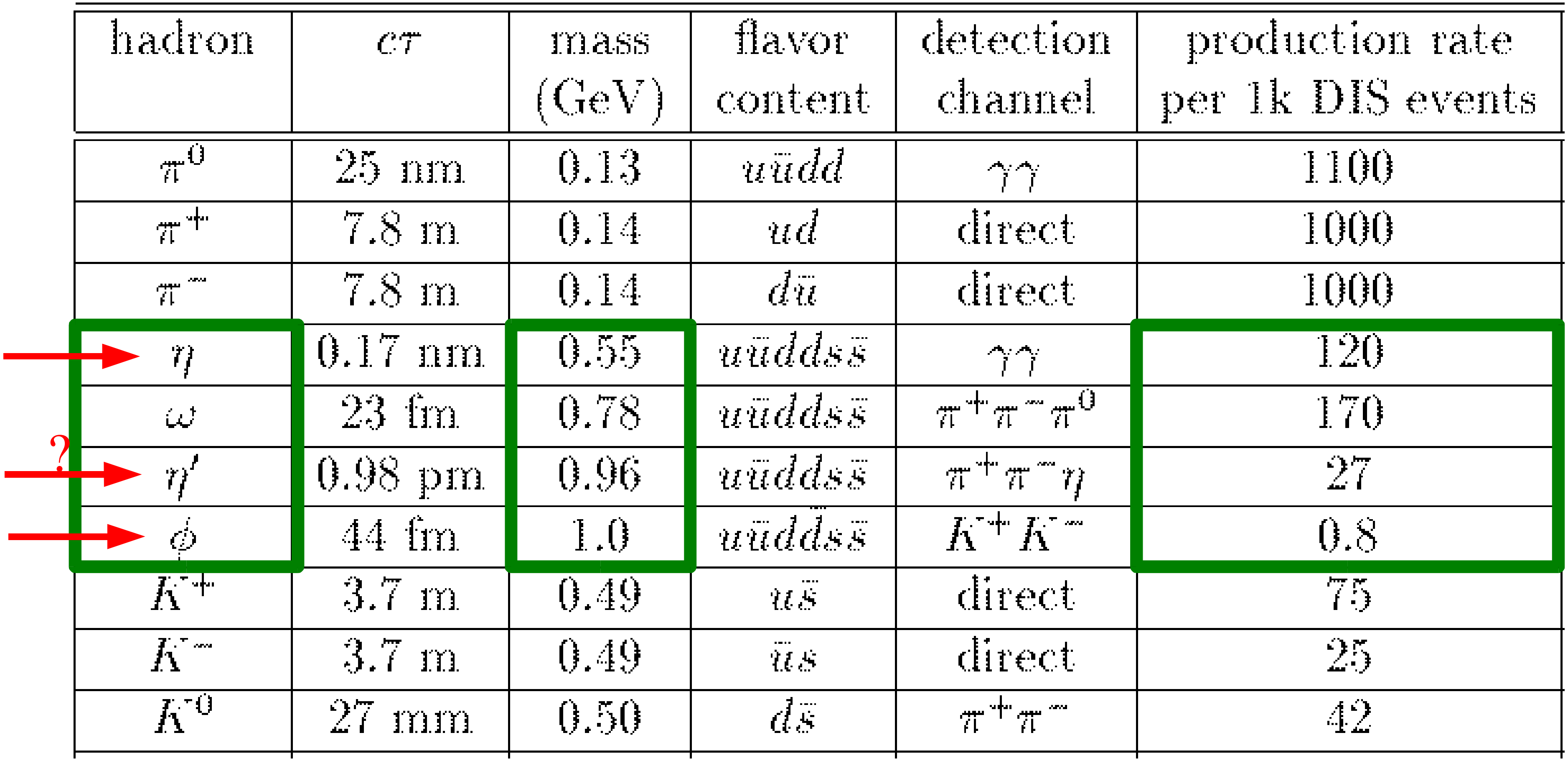
- **Energy loss with hadronization outside**
  1) similar quark content as π: $\omega, \eta, \phi = c_1(u\bar{u}+d\bar{d})+c_2(s\bar{s})$
  2) s quark is subdominant in HERMES and JLAB kinematics
  3) $\Rightarrow$ similar attenuation to π (but beware the fragm. fn.)

- **Absorption point of view:**
  1) heavy $\Rightarrow$ produced earlier than $\pi \Rightarrow$ longer in-medium path
  2) earlier breakdown of $A^{2/3}$ (extreme: $\langle l^* \rangle = 0 \;\Rightarrow\; A^{1/3}$)
  3) However... ϕ has small hadronic cross-sections
  $\Rightarrow$ 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]

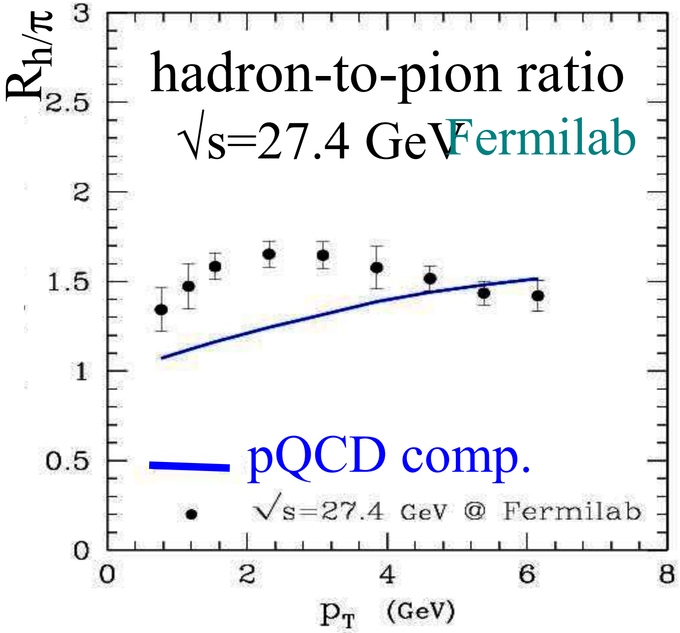


hadron	$c\tau$	mass (GeV)	flavor content	detection channel	production rate per 1k DIS events
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$	$\gamma\gamma$	1100
π^+	7.8 m	0.14	ud	direct	1000
π^-	7.8 m	0.14	$d\bar{u}$	direct	1000
η	0.17 nm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	$\gamma\gamma$	120
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$	$\pi^+\pi^-\pi^0$	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

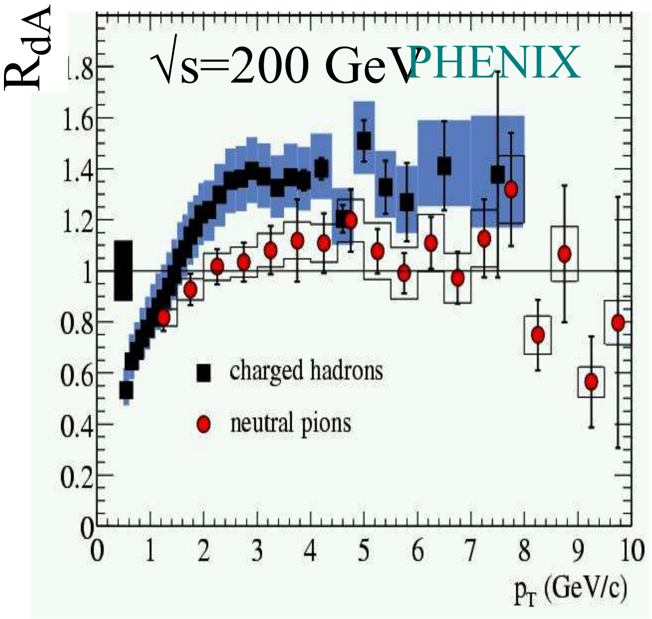
Baryon sector

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

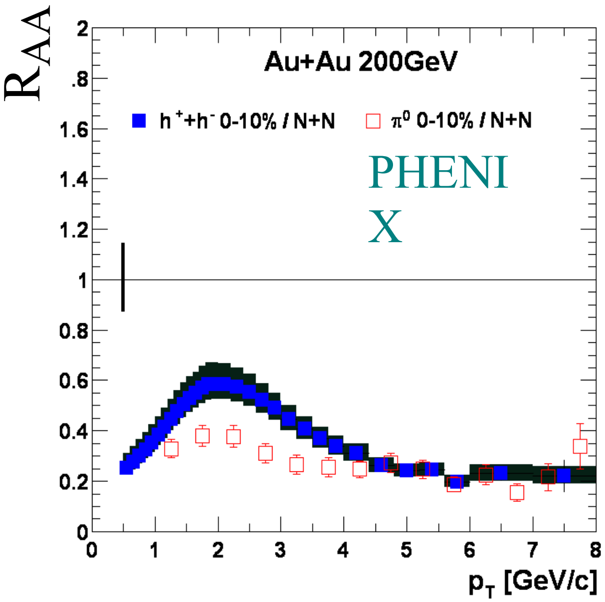
in p+p



in h+A



in A+A



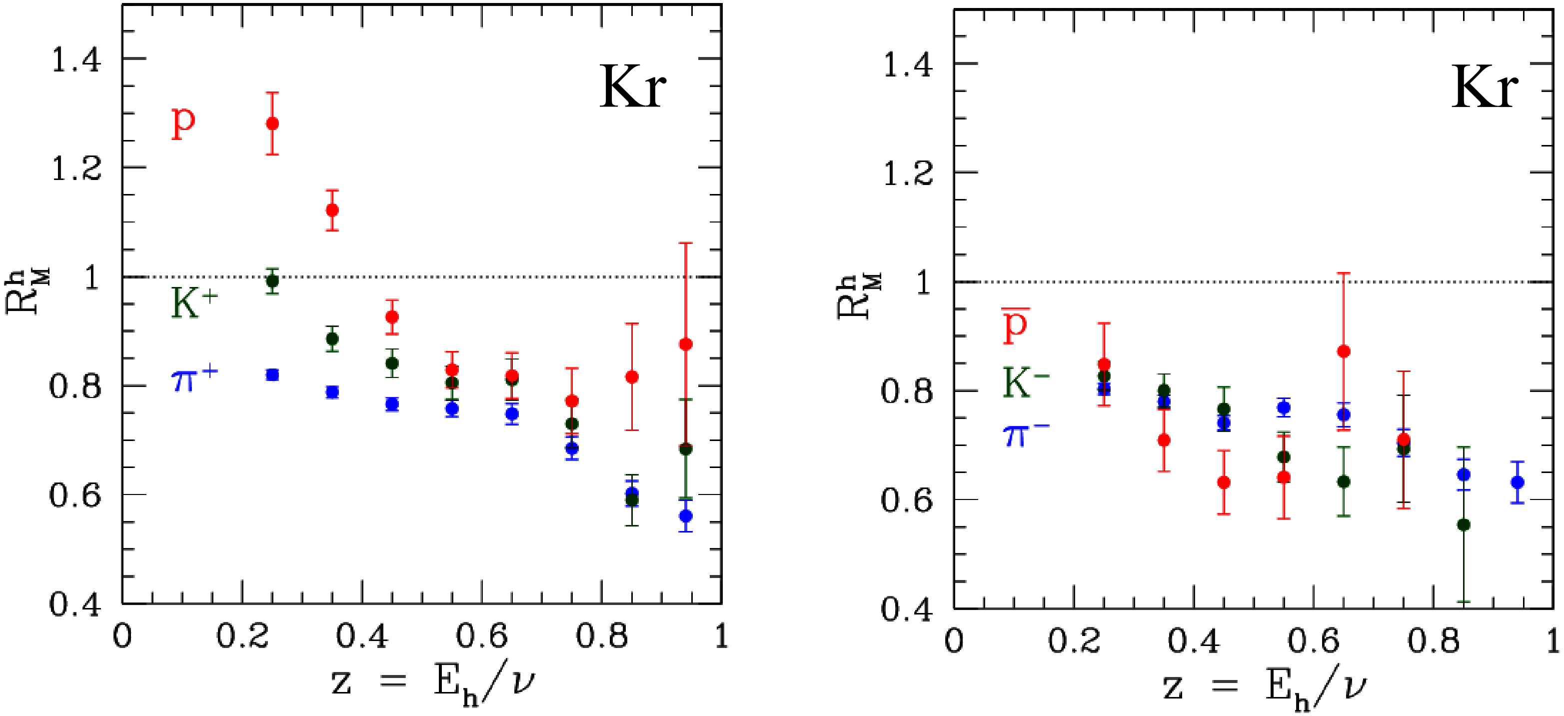
$$R_{h/\pi} = \frac{dN^h/d^2p_T}{dN^\pi/d^2p_T}$$

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

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? [Kopeliovich] - String flip? [Grygorian])

Baryon sector

- Baryon vs. antibaryons
- Is the baryon anomaly in nDIS only for protons? (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

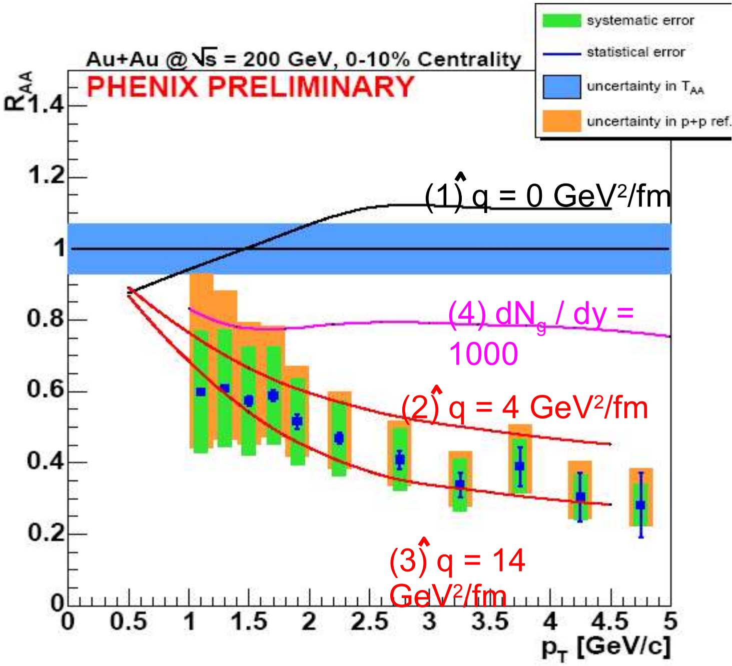
Heavy flavours ?

- 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!***

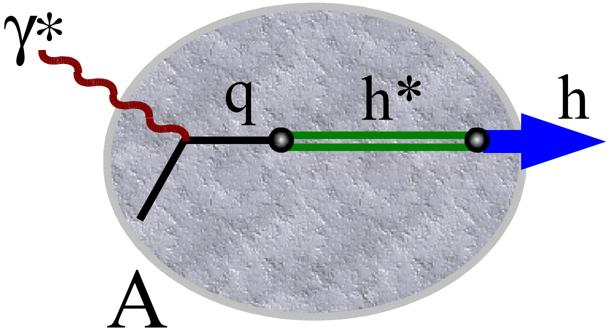
    (but compatible with c-quark suppression only...)

- **"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

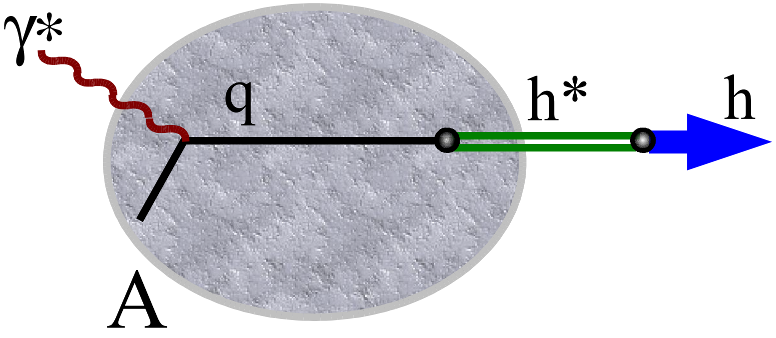


- Can JLAB measure identified D mesons?
  - study of c-quark attenuation in cold matter
  - help in solving heavy flavour puzzle

More exclusive observables



high-z

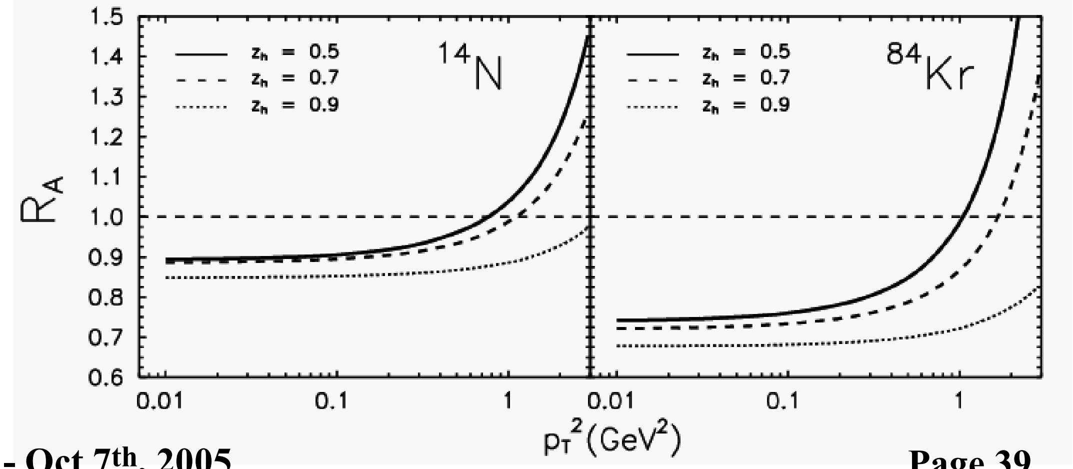


low *z*

- **<p_T^2> broadening** [see Nemchick, Hayashigaki, Kopeliovich talks]
  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

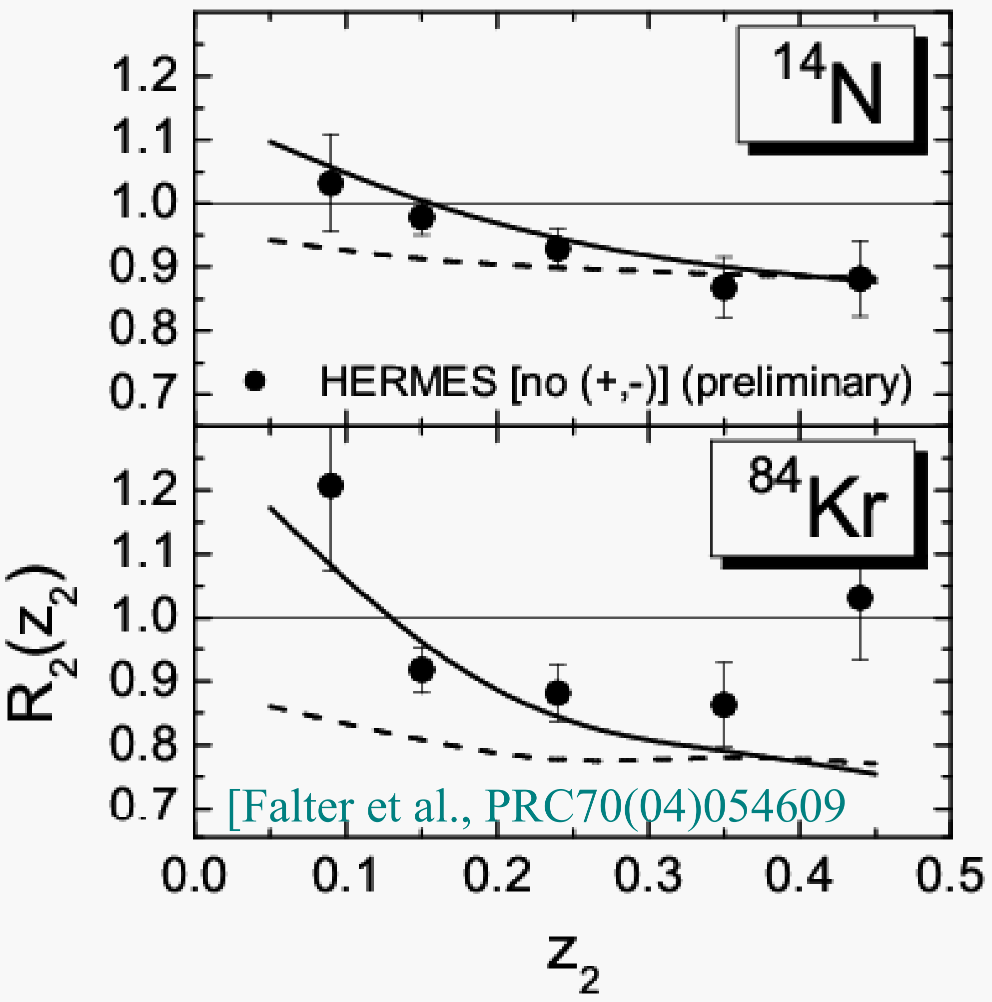
[Kopeliovich et al., NPA740(04)211]



More exclusive observables

- double hadron attenuation [see Falter, Muccifora]

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



[Falter et al., PRC70(04)054609

Can we invent new observables?

- E.g., pT-broadening is sensitive only to quark propagation:
  - **can we invent an observable which is sensitive to prehadron absorption only?**

- **Something else??**

Conclusions

- **Hadron absorption predicts $R_M \sim A^{2/3}$ as well,**
  - not as easy as naively thought to separate it from energy loss

- **Analysis in terms of cA^{α} fits proposed**
  - meaningful test of theory models
  - will help in cross-checking theory ideas of interplay of absorption and energy loss effects
  - $\alpha=\alpha(A)$ at large A - breaking of a simple A^{α} law

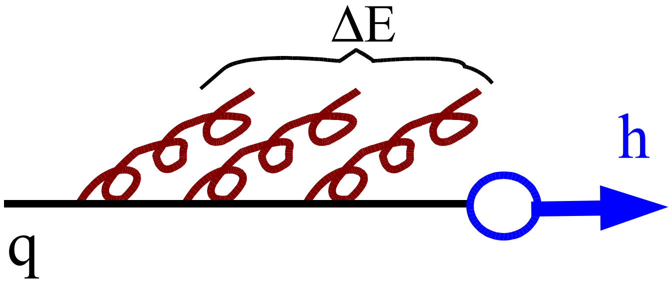
- **For future experiments**
  - Use a few more targets to complete the light-to-heavy scan and allow precise cA^{α} fits
  - Concentrate resources on collecting high statistics to access
    1) heavy unflavoured mesons (ϕ,η,ω)
    2) charmed mesons (D) → help for charm/bottom puzzle at RHIC
    3) other baryons (Λ) → light on baryon anomaly
    4) more exclusive observables (pT-broadening, Cronin vs. z , 2 particle correlations,...)

The end

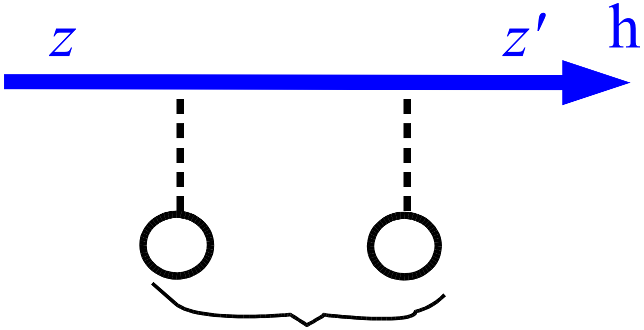
A note on "energy loss"

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

- Gluon bremsstrahlung



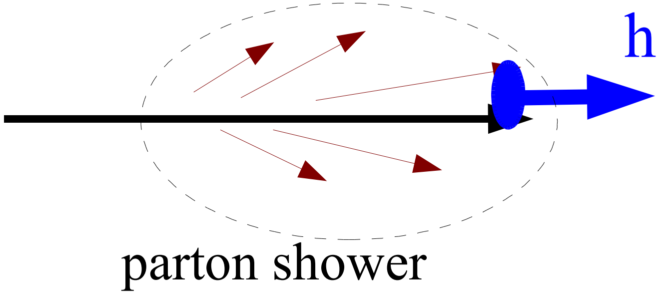
- Hadron-nucleon rescatterings



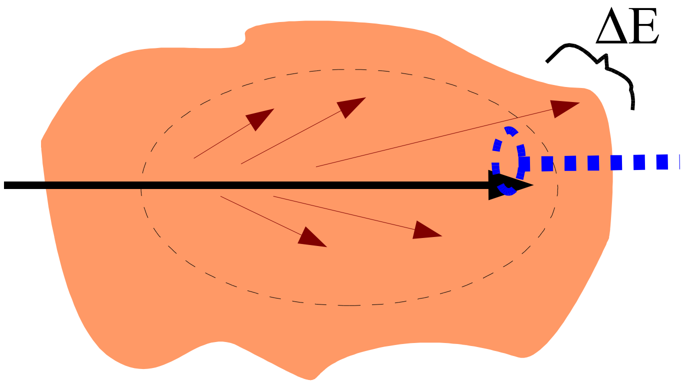
$\Delta E = (z-z')\nu$

- "Missed" hadronization in a colour screening medium

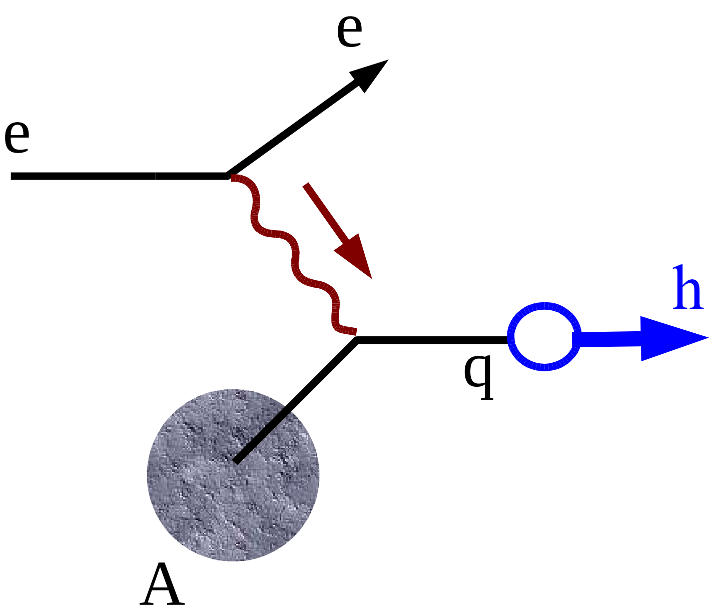
a) vacuum



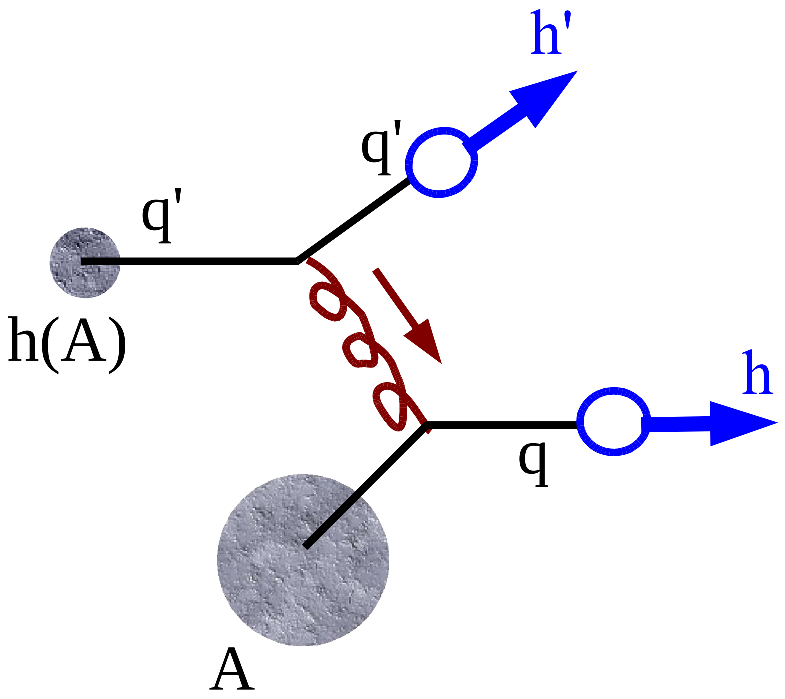
b) screening medium



Let's push the analogy



lepton *e* initial and final momenta are measurable



quark *q′* initial and final momenta are not

- Closest analogy of h(A)+A with DIS:
  - measure 2 hadrons from *q* and *q′* fragmentation
  - some control over Q^2 (needs also u- and s-channels)
  - needs convolutions over *z′* in pQCD formuale