# Space-time evolution of hadronization probed in e+A collisions

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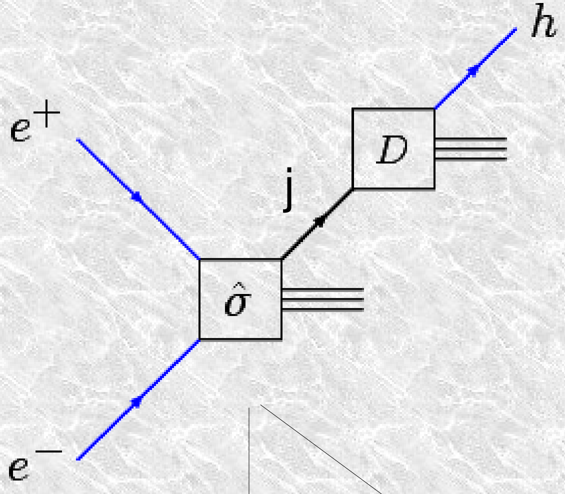
Based on: A.A., PLB in press [nucl-th/0604041]
A.A., EPJC in press [nucl-th/0609010]

# Outline

- **Hadronization in nuclear matter**
  - space-time evolution, non-perturbative – confinement
  - calibration of jet-quenching signal in A+A
- **Short review of experimental data**
- **Hadron quenching in nDIS**
  - formation times
  - prehadron vs. hadron
  - energy loss vs. absorption
- **Can we distinguish energy loss from hadron absorption?**
  - failure of the "$A^{2/3}$ power law"
  - formation time scaling
  - $p_T$-broadening
- **Perspectives and conclusions**

# Hadronization
# in nuclear matter

# Hadronization in elementary collisions



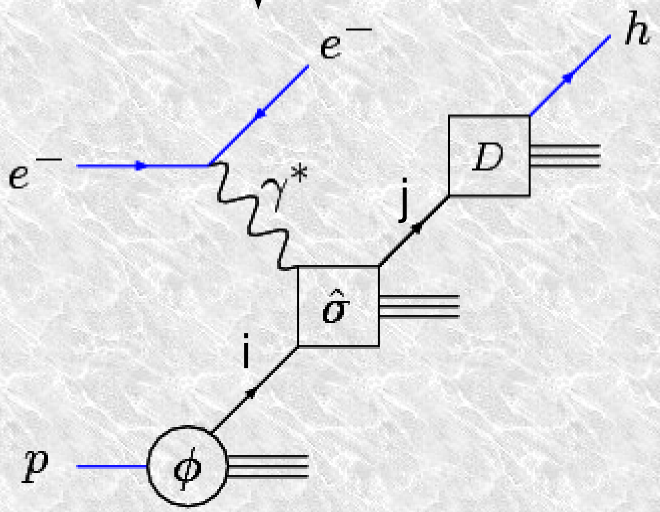
- **perturbative QCD factorization** of short and long distance physics

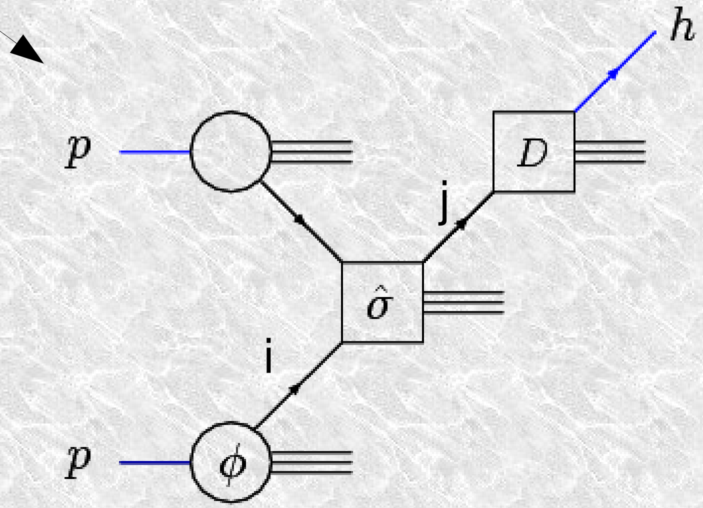
$$d\sigma_{\mathrm{hadronic}} = \Pi_i\, \phi_i \otimes \hat{\sigma}^{ij}_{\mathrm{partonic}} \otimes D_{j|h}$$

Parton Distribution Fns
(from inclusive DIS)

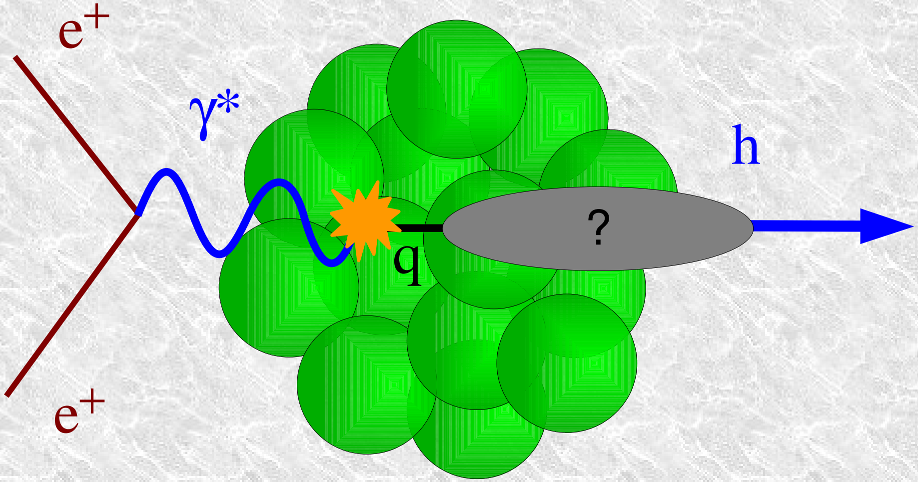
Fragmentation Fns
(from $e^+ + e^- \to h + X$)

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



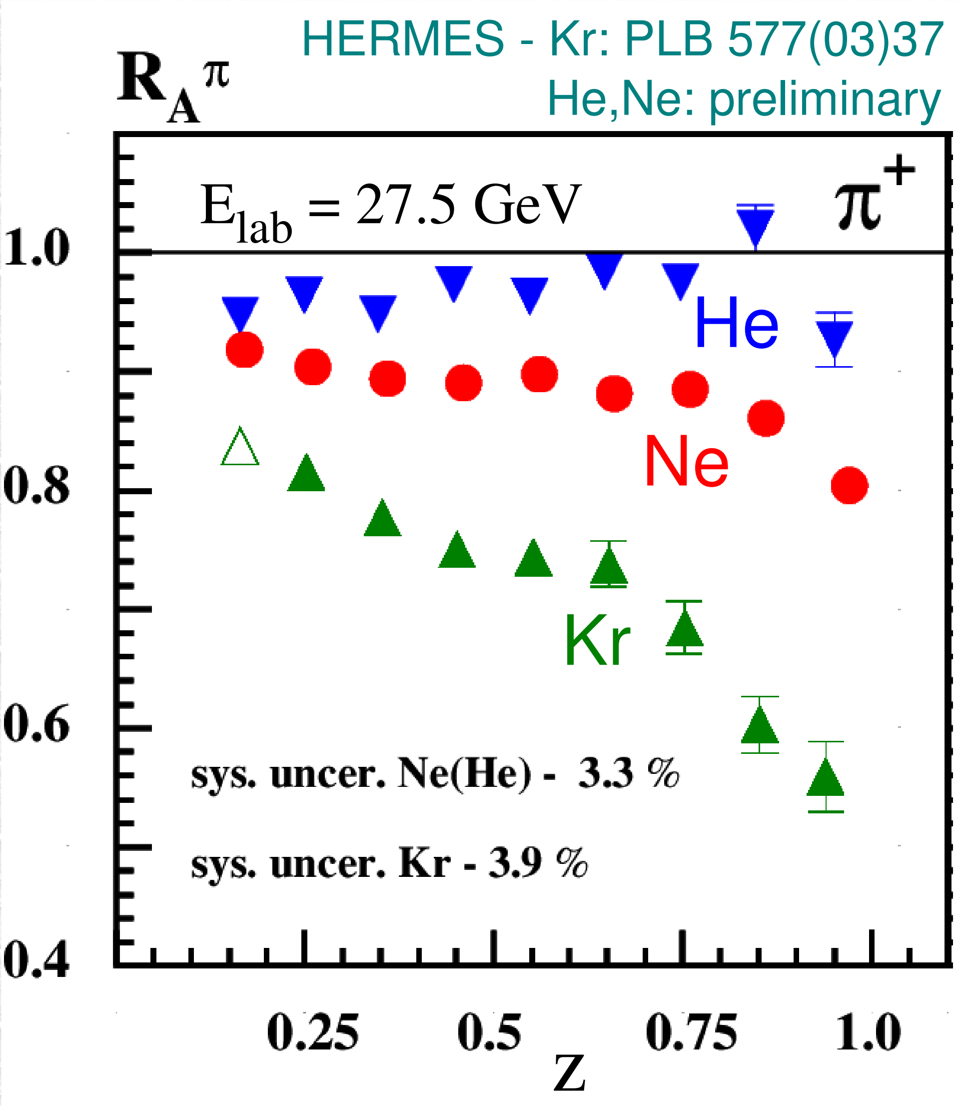


# Nuclear collisions 1 - nDIS



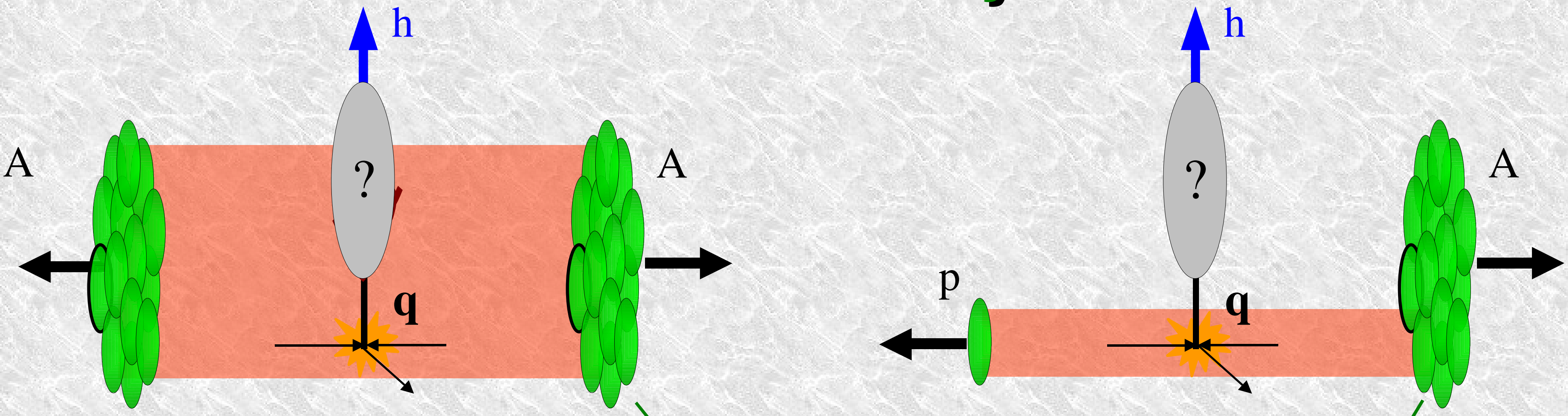
$$R^h_M(z) = \frac{\frac{1}{N_A^{DIS}}\frac{dN_A^h(z)}{dz}}{\frac{1}{N_D^{DIS}}\frac{dN_D^h(z)}{dz}}$$

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



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

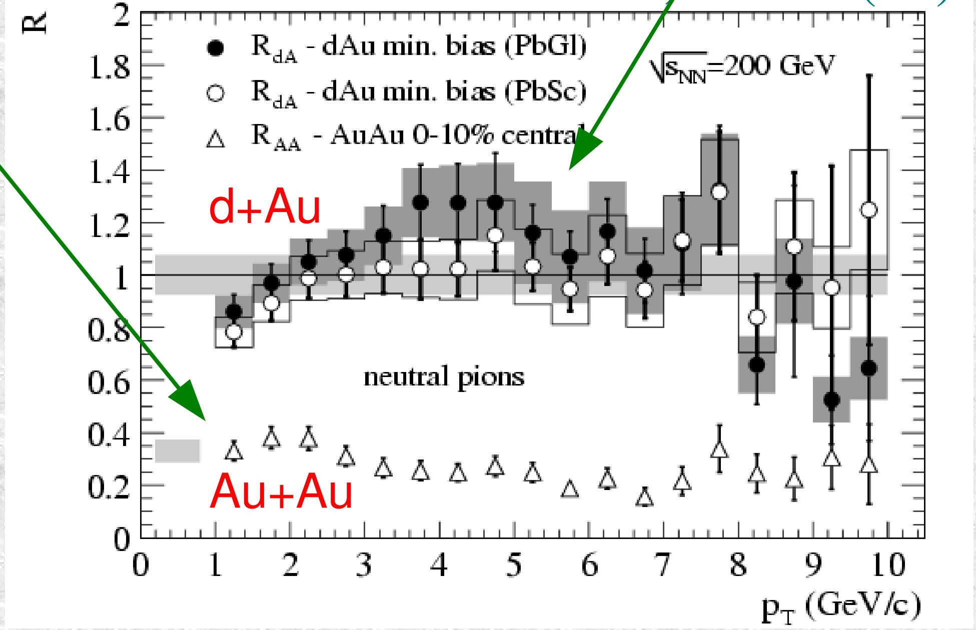
# Nuclear collisions 2 – Heavy ion collisions



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

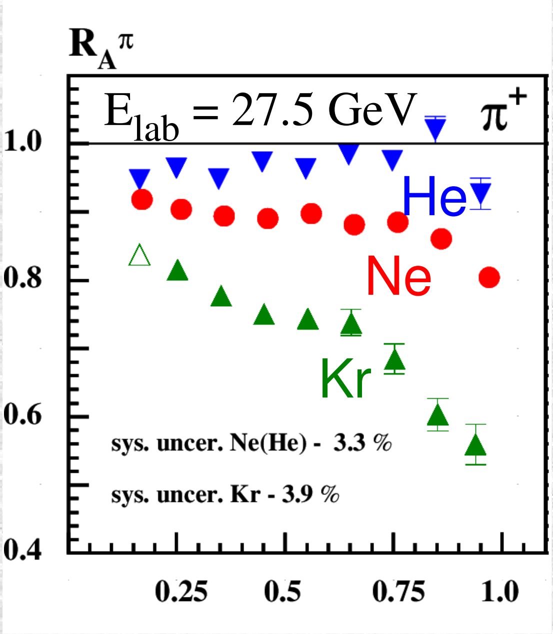
- Medium modifications of hadronization isolated by comparison of h+A and A+A

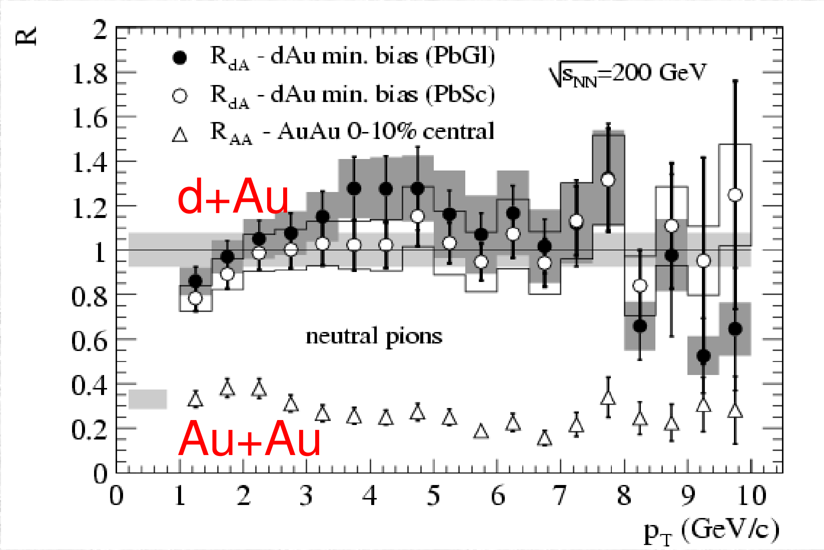
PHENIX, PRL91(02)



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

# Breakdown of universality in nuclei

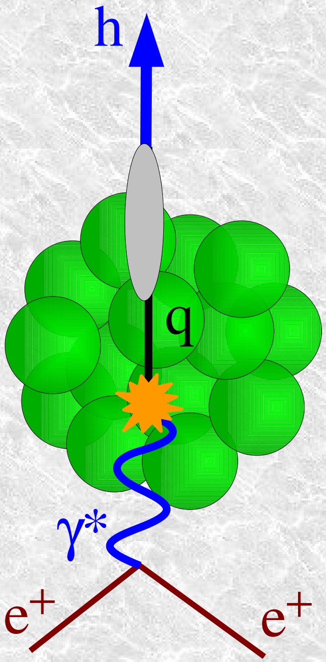


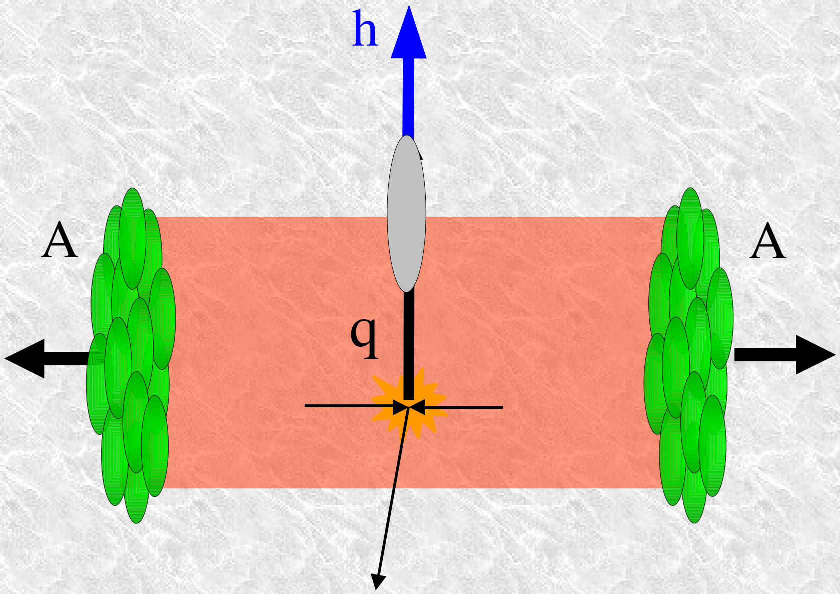


- Hadronization is no more process-independent
- Among possible causes:
  - struck quark interactions with the medium
  - (pre)hadron interactions with the medium
  - other medium nuclear, e.g., partial deconfinement [Dias de Deus '87]
  - in-medium modifications of parton showers [Borghini, Wiedemann '05]
  - breakdown of factorization [for nuclear PDF, see Qiu, Sterman '02]

This talk:
space-time evolution
of hadronization

# nDIS vs. A+A collisions





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

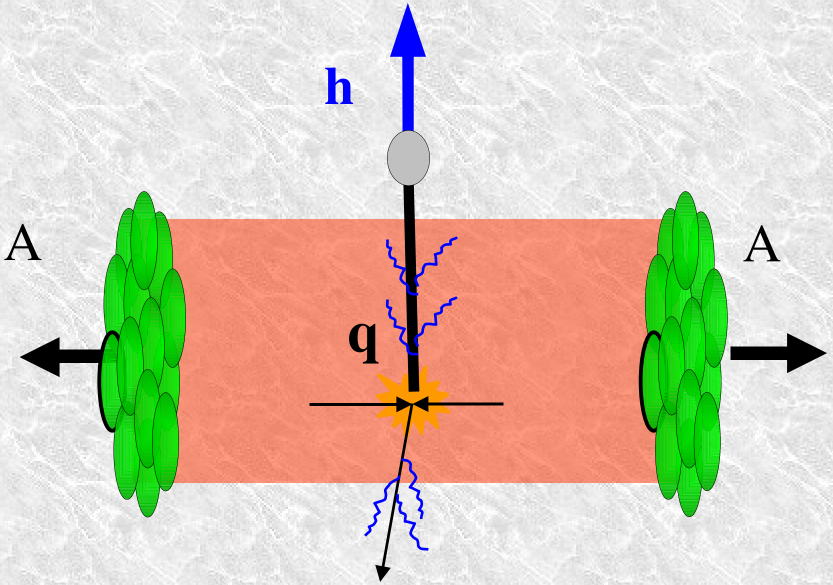
Jet-quenching in A+A

⇓

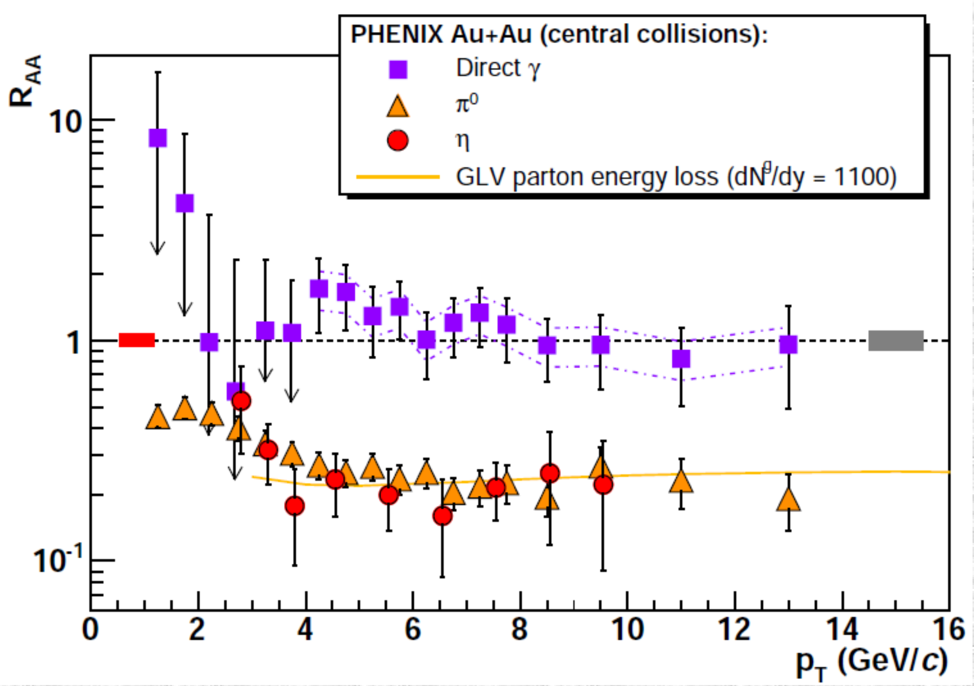
**properties of**
**hot nuclear matter**

# Energy loss paradigm: success!

- **Paradigm:** long lived partons hadron quenching due to energy lost by gluon brehmstralung



$$R_{AA} = \frac{(dN^h/d^2p_T)_{A+A}}{N_{coll}(b)\,(dN^h/d^2p_T)_{p+p}}$$



- pQCD energy-loss theory used to extract initial gluon density

  $dN^g/dy \approx 1000$

- Can be converted to initial state energy density:

  $\varepsilon \sim 14 - 20\ \mathrm{GeV/fm^3} > \varepsilon_c$

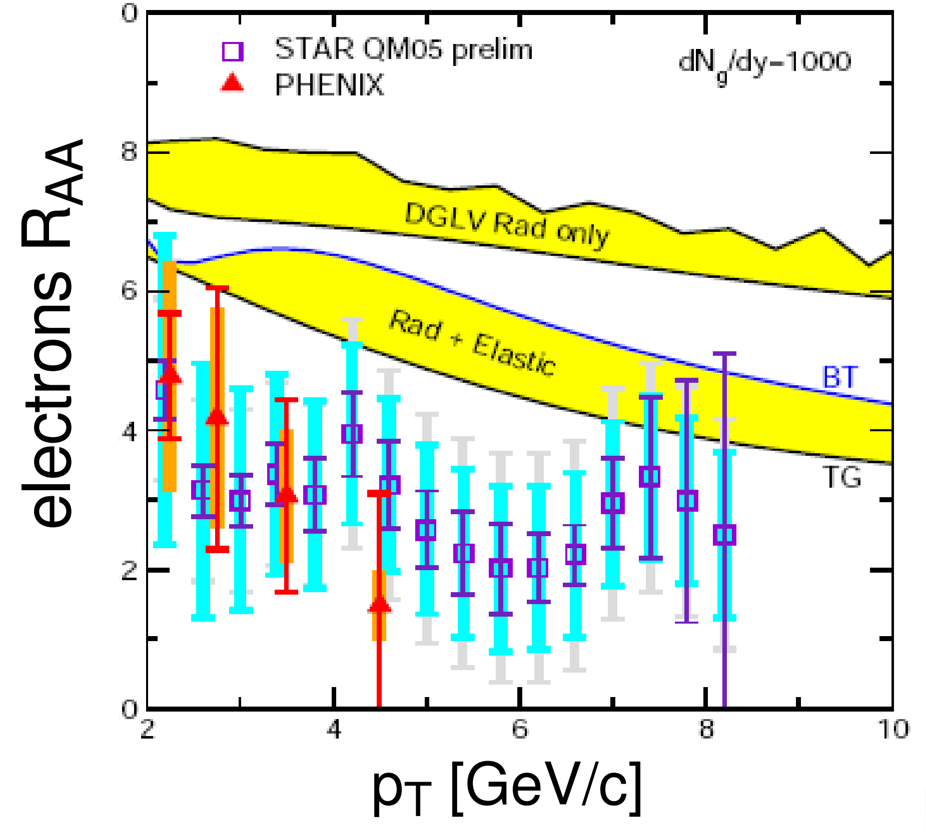
  allowing QGP phase transition

# Challenges: heavy quarks

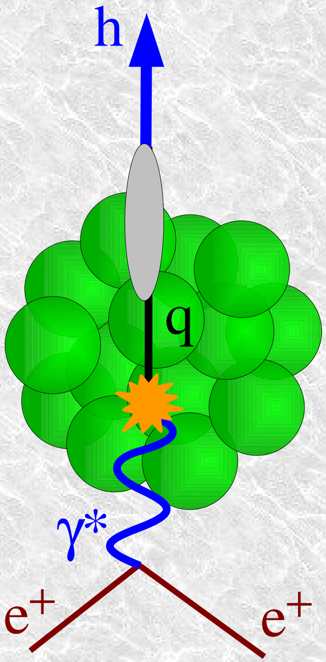
- Heavy flavour puzzle at RHIC
  [QM05: Djordjevic, Armesto, STAR, PHENIX]
  - single non-photonic $e^-$ as much suppressed as $\pi$
  - ***theory gives half of the observed suppression!***
- Additional mechanisms:
  - elastic energy loss?
    [Mustafa, Thoma]
    with running $\alpha_s$? [Peshier '06]
  - Uncertainties in NLO cross sect. (B/D ratio vs. $p_T$)?

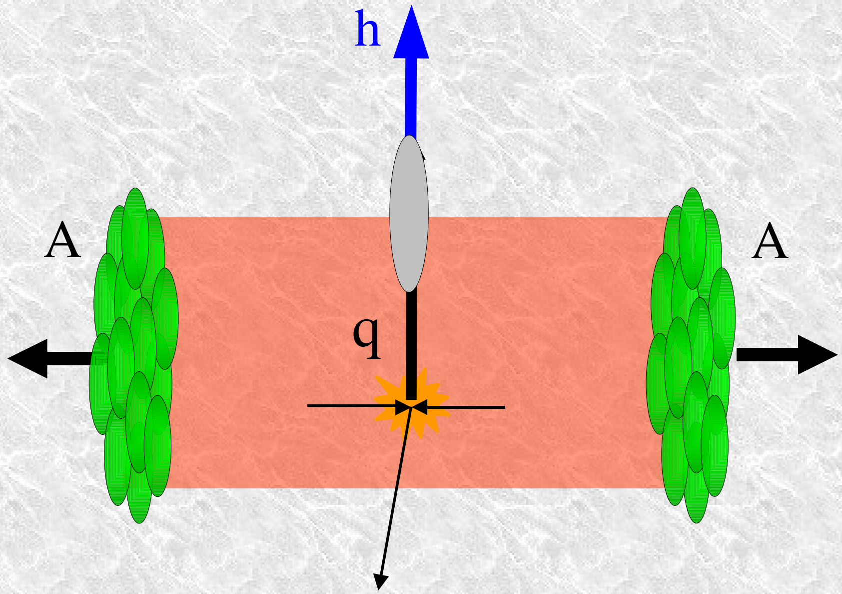
    This talk:
  - **do hadrons form inside QGP?**

Wicks et al., nucl-th/0512076



# Similarities and differences





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

at HERMES/Jlab

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

$E_q = p_T / z$

$E_h = p_T \approx$ **2 - 20 GeV**

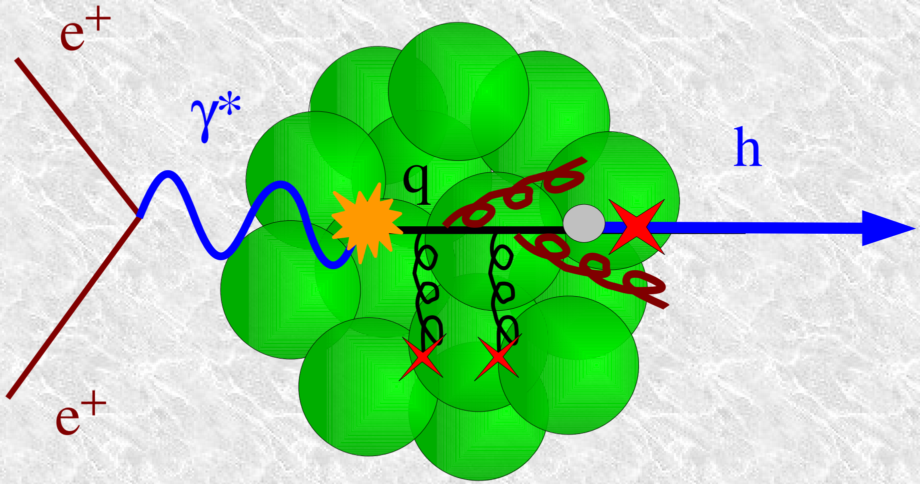
★ **HERMES/JLAB kinematics is relevant to RHIC mid-rapidity**

**…but beware the virtuality…**

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

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

# Summary of motivations



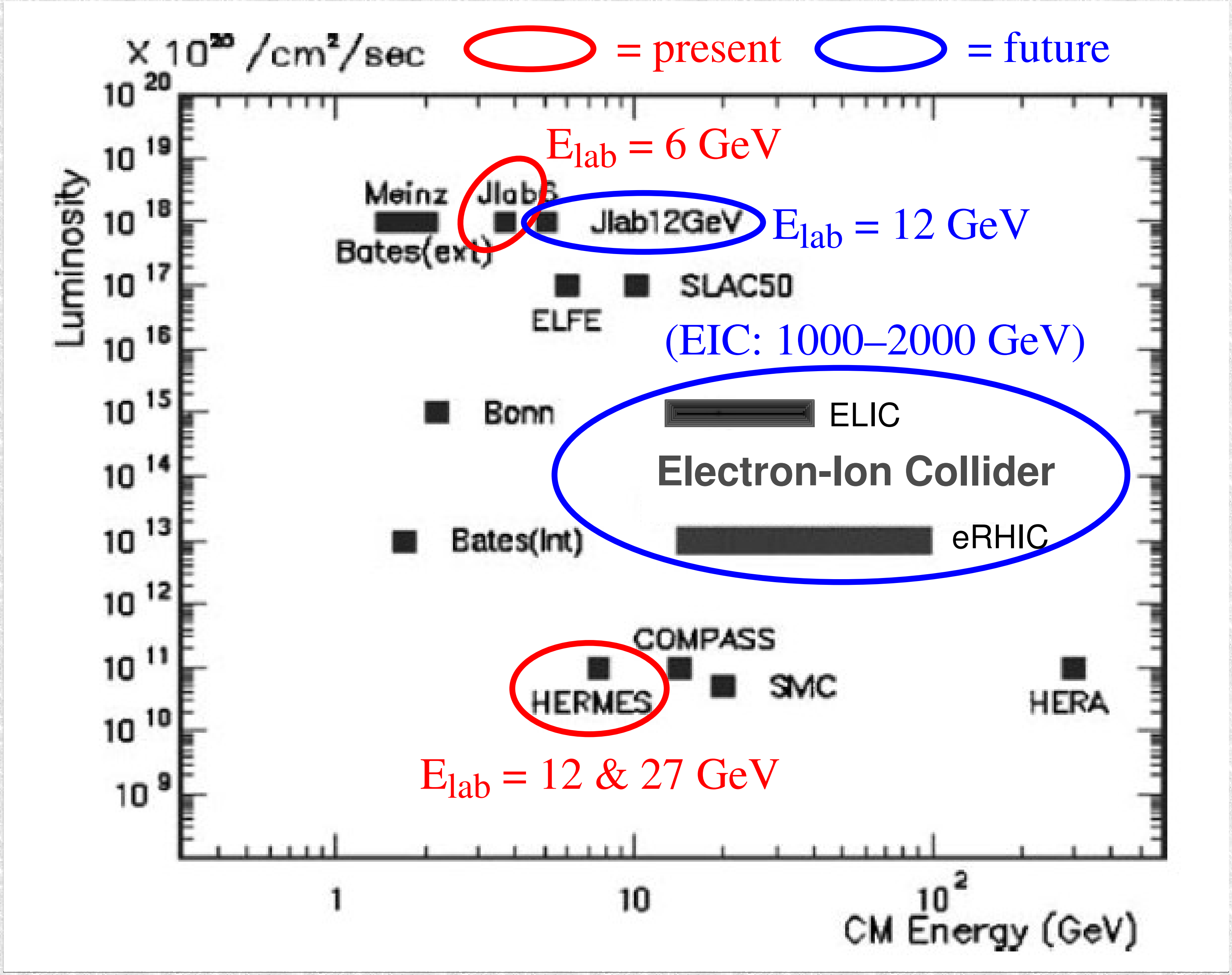
- **Nuclei as space-time analyzers**
  - nucleons as femto-detectors
  - medium rather well known
  - low final-state multiplicity

- **Non perturbative aspects of hadronization**
  - approaching microscopic understanding of Fragmentation Functions
  - how do partons dress up?
  - understanding of color confinement

- **Calibration of jet-quenching signal in A+A collisions**
  - properties of Quark-Gluon Plasma

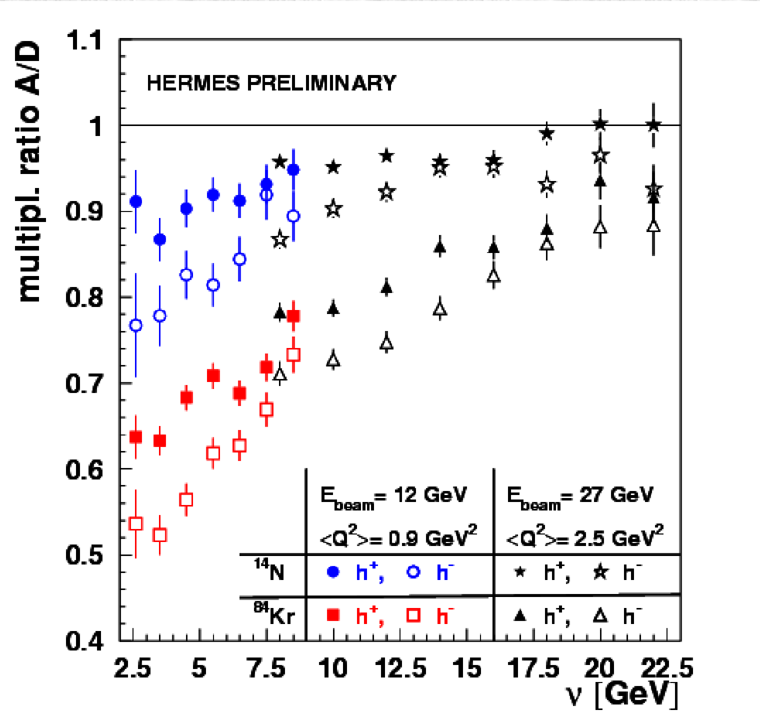
# Short review of e+A data

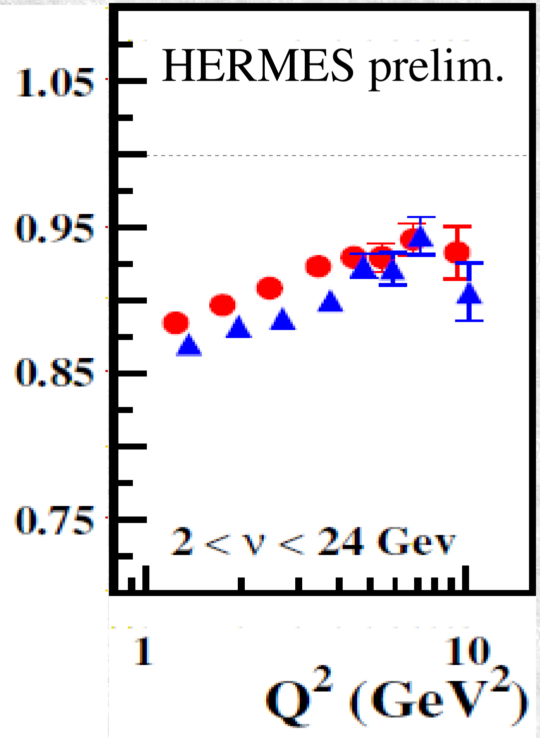
# Present and future facilities

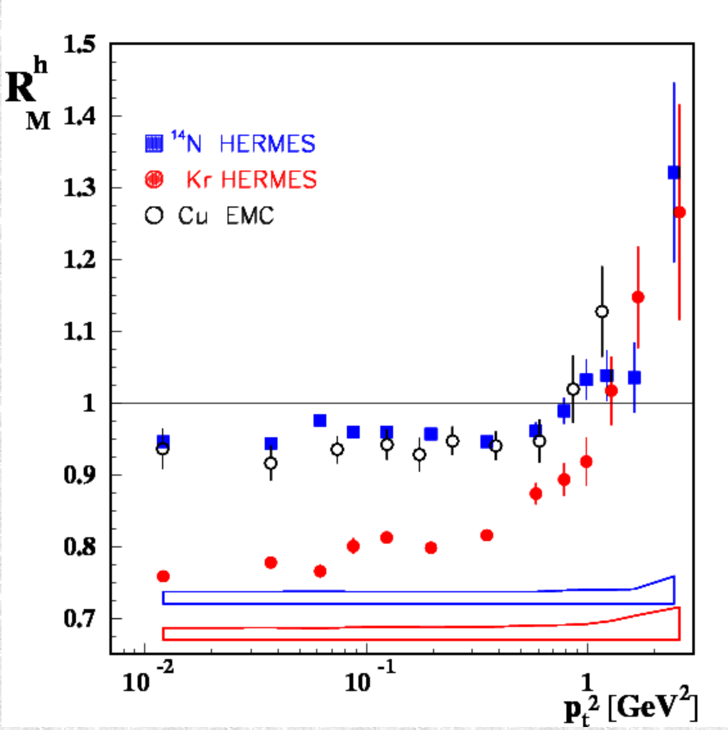


# Measurements at HERMES

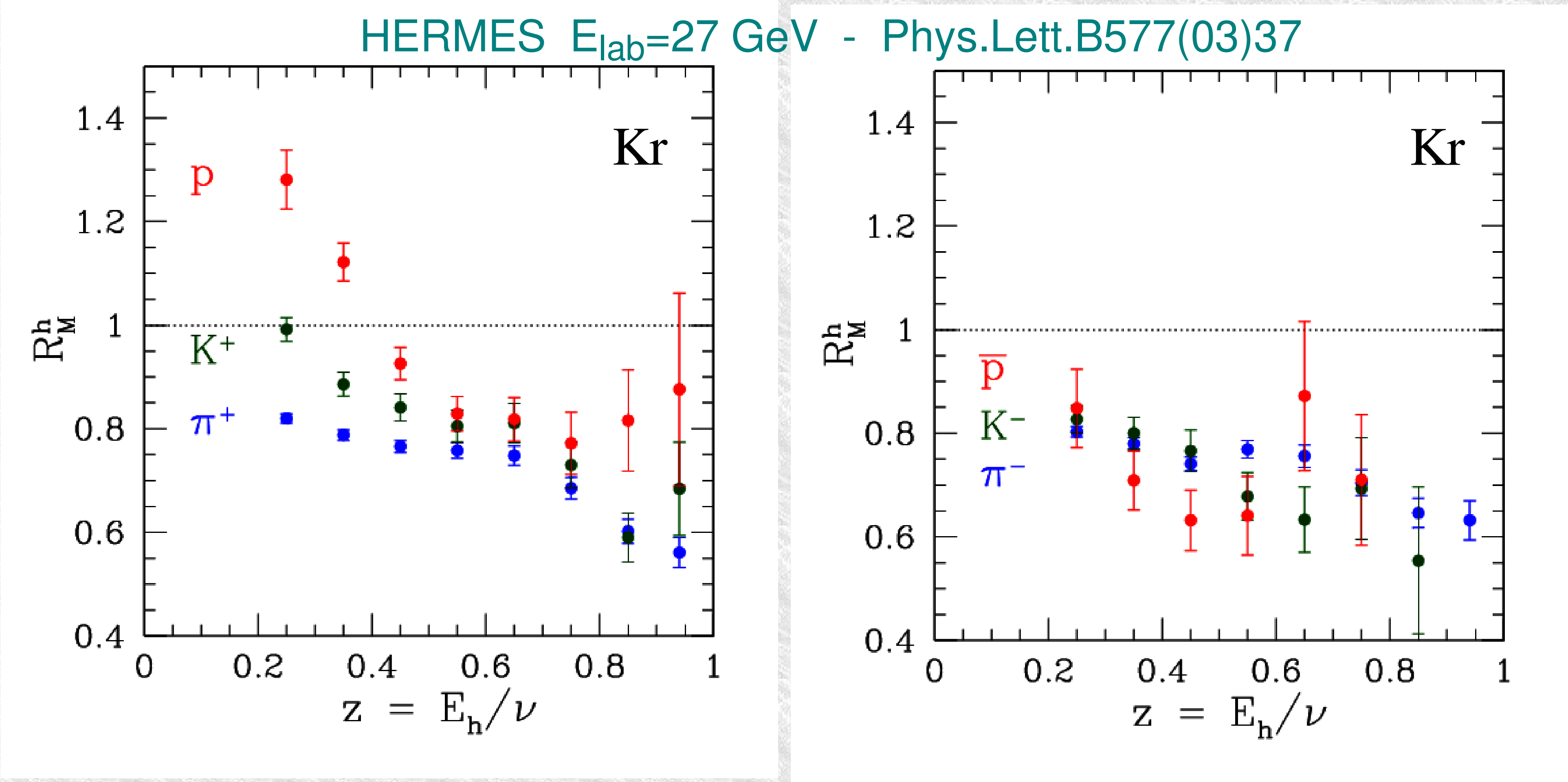
- HERMES: fixed target, $E_{lab}$ = 27.5 GeV and 12 GeV
- Hadron attenuation as a function of (fixed target kinematics)
  - $\nu$ = virtual $\gamma$ energy
  - $z = E_h/\nu$ = hadron's fractional energy
  - $Q^2$ = photon virtuality
  - $p_T$ = hadron transv. momentum
  - hadron flavour = $\pi^\pm$, $K^\pm$, p, $\bar{p}$
  - A = target mass number







# Measurements at HERMES


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

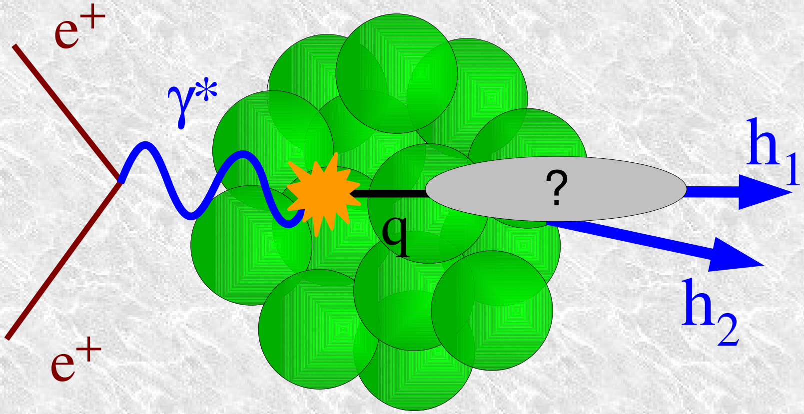
- **proton anomaly!**
- analogous to “baryon/meson anomaly” in p+p, p+A and A+A
  - what do they have in common?

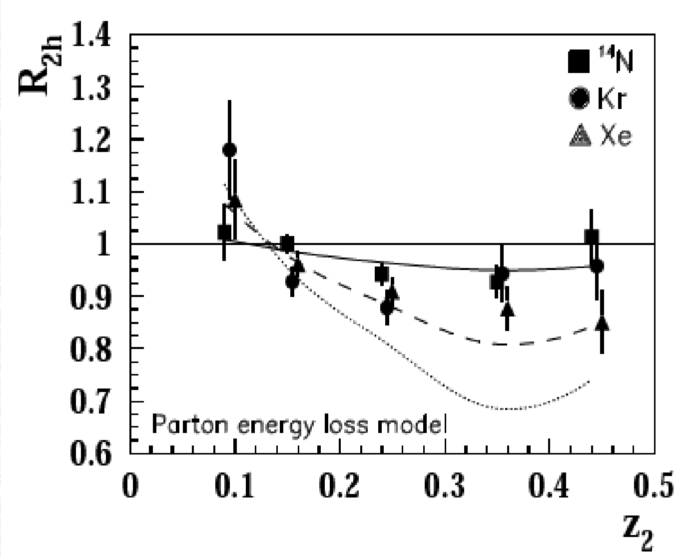
# Measurements at HERMES

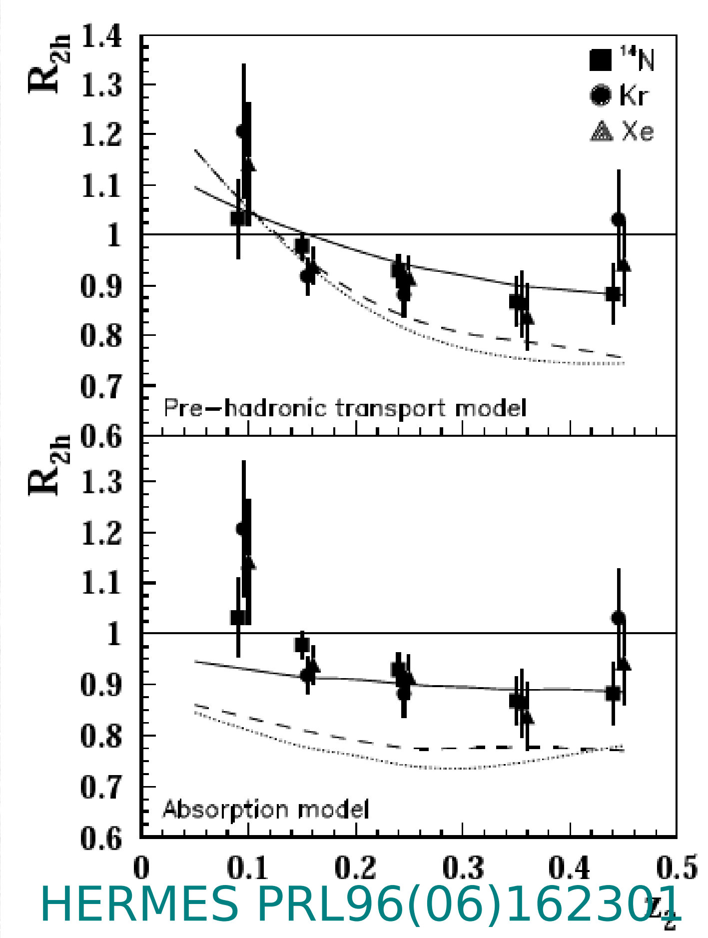
- **Double hadron attenuation** $R_2$
- in A+A: “same-side correlations”

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

$z_2 < z_1$ $z_1 > 0.5$

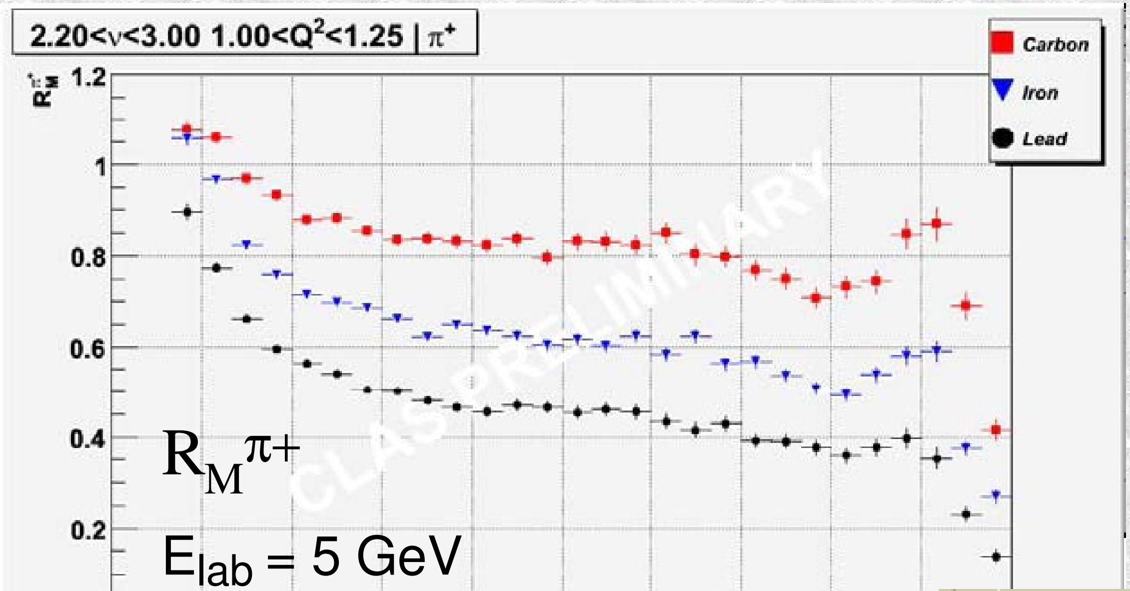






HERMES PRL96(06)162301

# Preliminary results at CLAS



$R_M^{\pi+}$

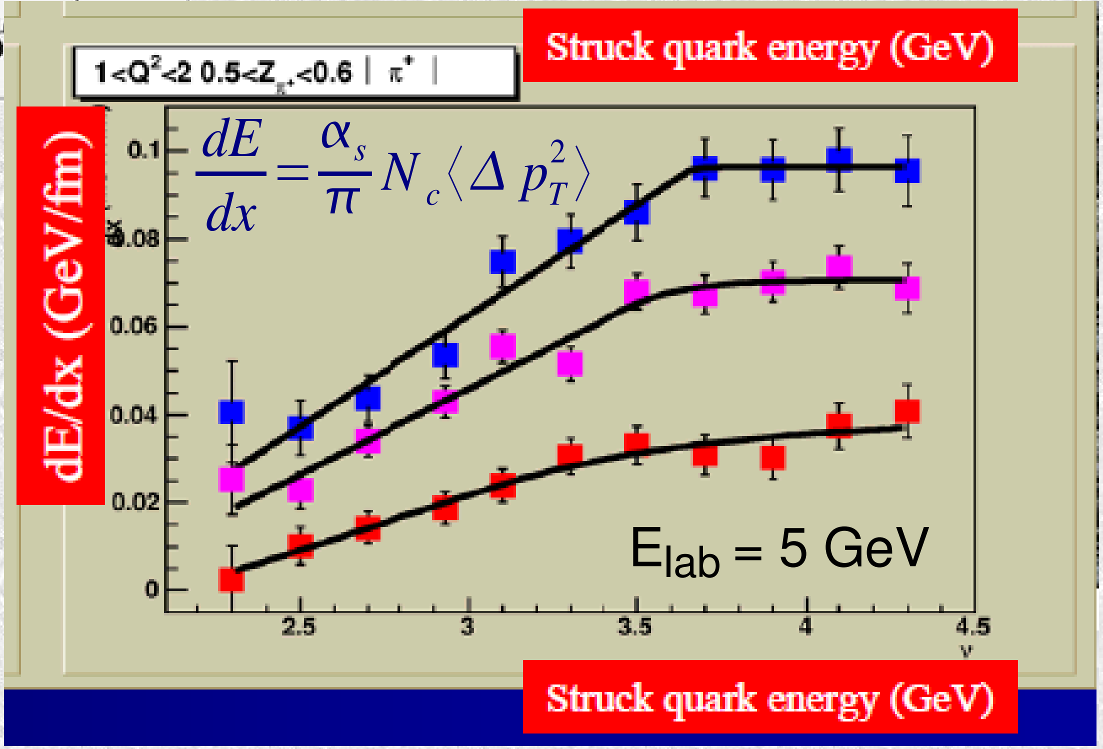
$E_{lab}$ = 5 GeV

K.Hafidi, nucl-ex/0609005

- CLAS: fixed target
  $E_{lab}$ = 5 GeV

Will Brooks, 13 June 2006
JLAB user's group workshop

Transverse momentum broadening

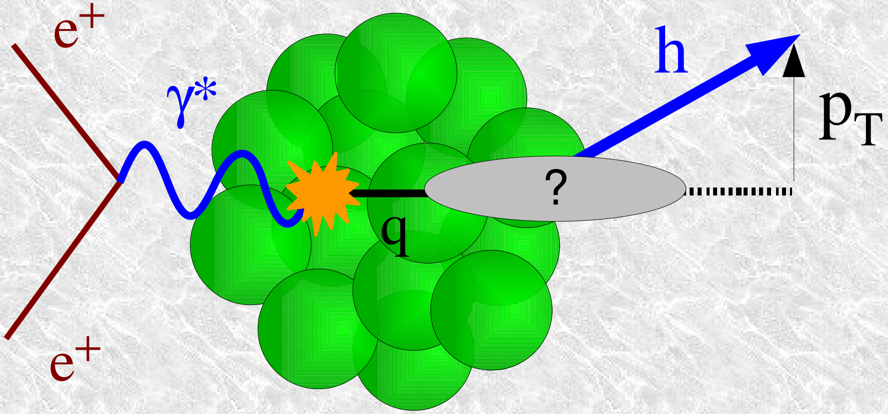


Struck quark energy (GeV)

$$\frac{dE}{dx} = \frac{\alpha_s}{\pi} N_c \langle \Delta p_T^2 \rangle$$

$E_{lab}$ = 5 GeV

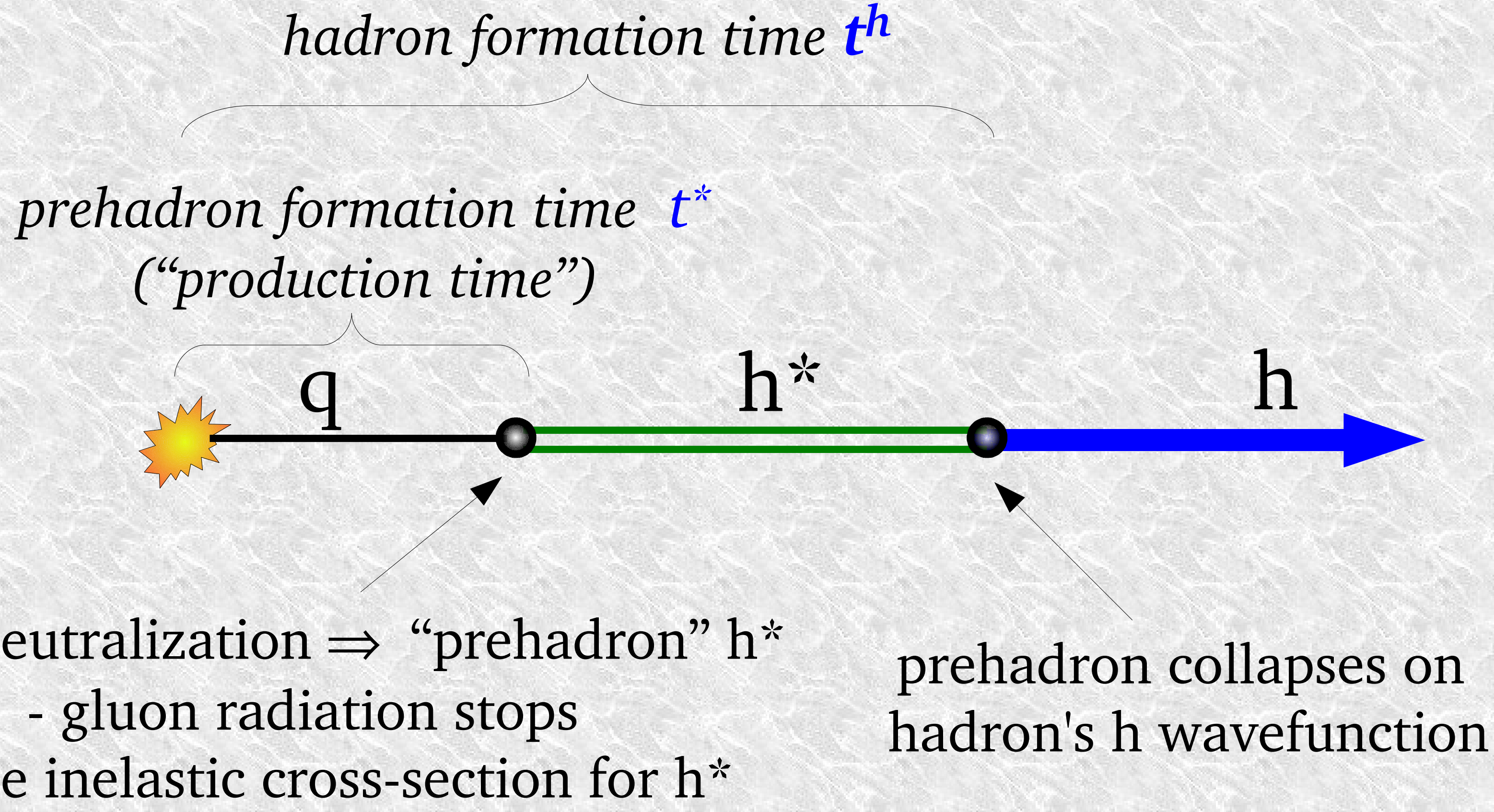
Struck quark energy (GeV)



# Hadron formation times

# Prehadron vs. hadron

- Hadronization is non perturbative ⇒ (many) models
- General features:



*hadron formation time* $t^h$

*prehadron formation time* $t^*$
*("production time")*

q

h*

h

Color neutralization ⇒ "prehadron" h*
- gluon radiation stops
- large inelastic cross-section for h*

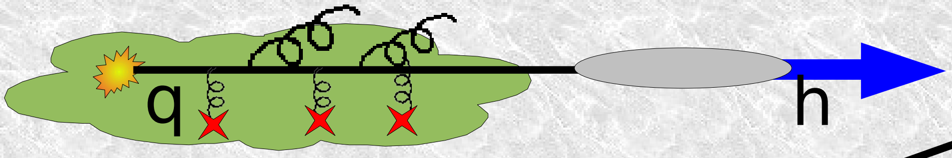
prehadron collapses on
hadron's h wavefunction

- *NOTE:*
  - It's tricky to rigorously define $t^*$ , $t^h$: consider them as working tools

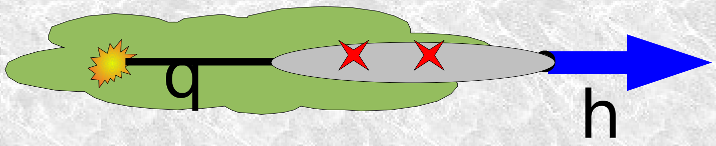
# Hadron attenuation in nDIS

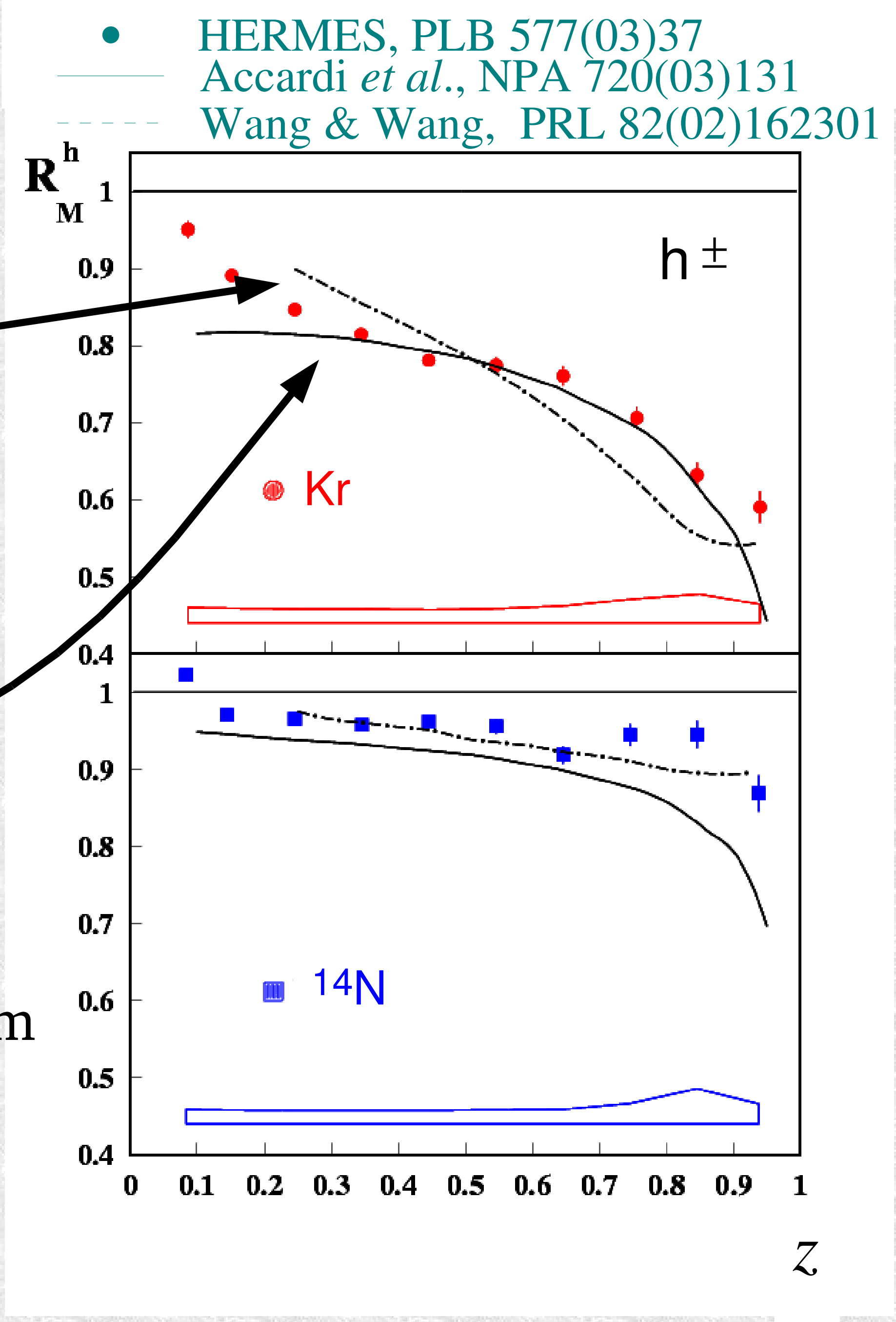
$$R^h_M(z) = \frac{\frac{1}{N_A^{DIS}}\frac{dN_A^h(z)}{dz}}{\frac{1}{N_D^{DIS}}\frac{dN_D^h(z)}{dz}}$$

- **Energy loss (gluon bremsstrahlung)**
  [Arleo; Wang *et al.*]
  - hadronization outside the medium
  - gluon radiation off struck quark



- **Prehadron absorption**
  [Accardi *et al.*;
  Falter *et al.*; Kopeliovich, *et al.*]
  - color neutralization inside the medium
  - prehadron-nucleon scatterings





# Formation time estimates 1

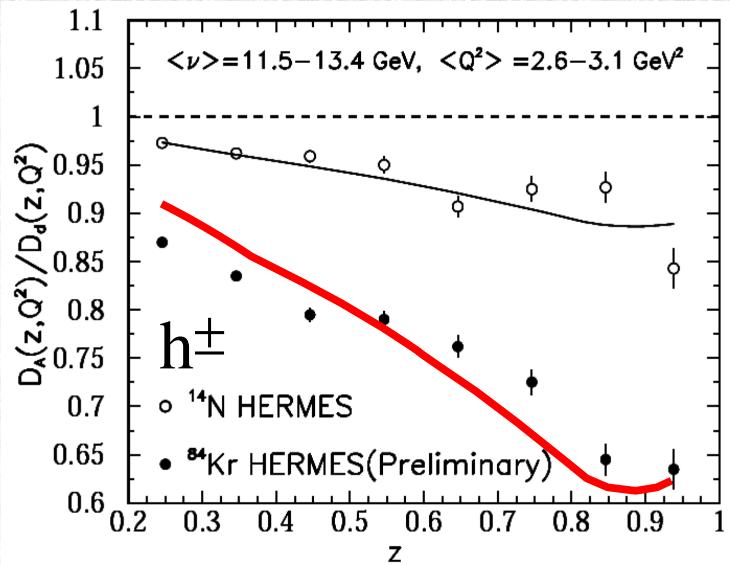
- Hadron formation time = time for partons to build up a color field and develop hadron wave function
  - hadron's rest frame: $\tau^h \sim R_h$
  - lab frame: $t^h \sim R_h \frac{E_h}{m_h}$ (in DIS $t^h \sim R_h \frac{z\nu}{m_h}$ )

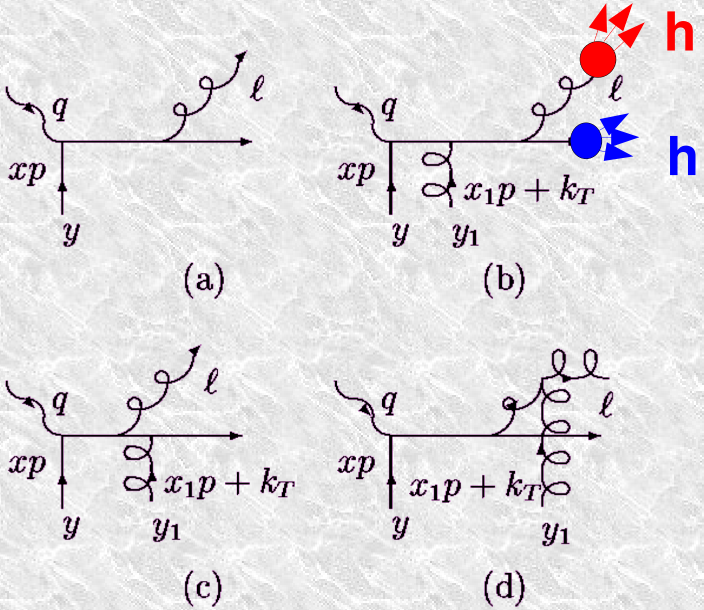
boost factor

- For a 7 GeV pion at HERMES $t^\pi \sim 35$ fm $>> R_A$
  - pions are formed outside A, quark energy loss only
  - Note, however: $t^K \sim t^p \sim 8$ fm !!
- This is used in energy loss models to justify the assumptions, but **neglects interactions of forming color field with the medium**

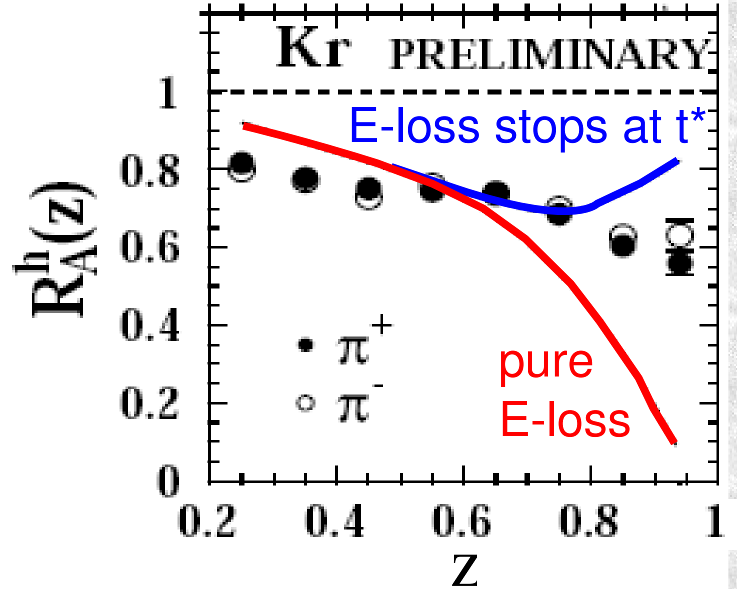
# Formation time estimates 1 – energy loss models

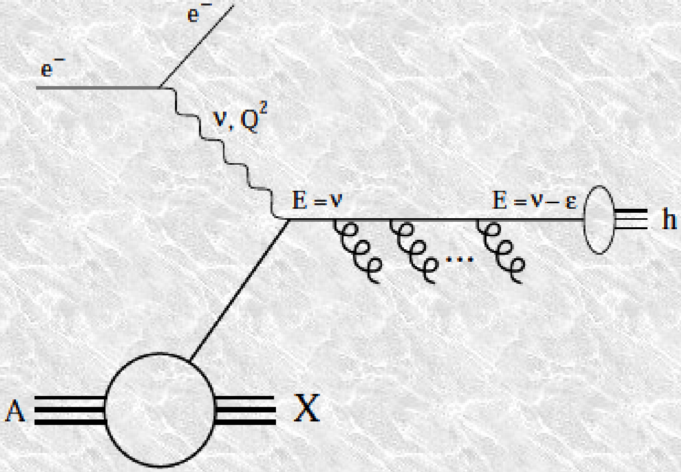
- Twist-4 modified Fragmentation Fns. [Wang&Guo '00, Wang & Wang '02]





- Quark energy loss *à la* BDMPS [Arleo '02]

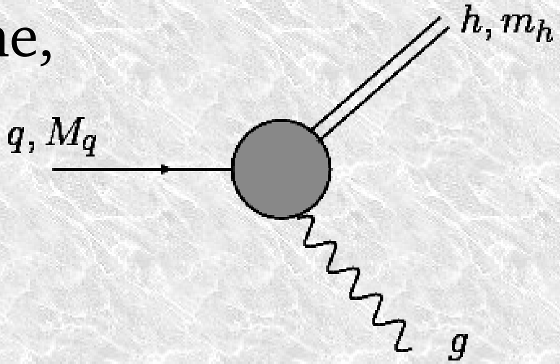




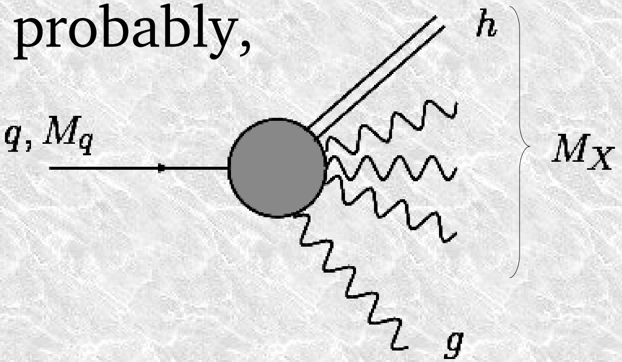
# Formation time estimates 2 – pQCD estimate

- pQCD estimate [see Vitev, QM'05]

assume,



more probably,



$$\left[p^+, \frac{M_q^2}{2p^+}, \mathbf{0}\right] \rightarrow \left[zp^+, \frac{\mathbf{k}^2 + m_h^2}{2zp^+}, \mathbf{k}\right] + \left[(1-z)p^+, \frac{\mathbf{k}^2}{2(1-z)p^+}, -\mathbf{k}\right]$$

$$\boxed{\Delta y^+ \simeq \frac{1}{\Delta p^-} = \frac{2z(1-z)p^+}{\mathbf{k}^2 + (1-z)m_h^2 - z(1-z)M_q^2}}$$

| | π | K | p | D | B |
|---|---|---|---|---|---|
| HERMES (ν~13 GeV, z~0.5) | 37 fm | 11 fm | 4 fm | 1.2 fm | 0.1 fm |
| RHIC ($p_T^h$ ~ 7 GeV z~0.7) | 26 fm | 6 fm | 4 fm | 1.2 fm | 0.1 fm |

~ Inside the medium !!

# Formation time estimates 3 – 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 are analytically computable
  - At large $z \to 1$

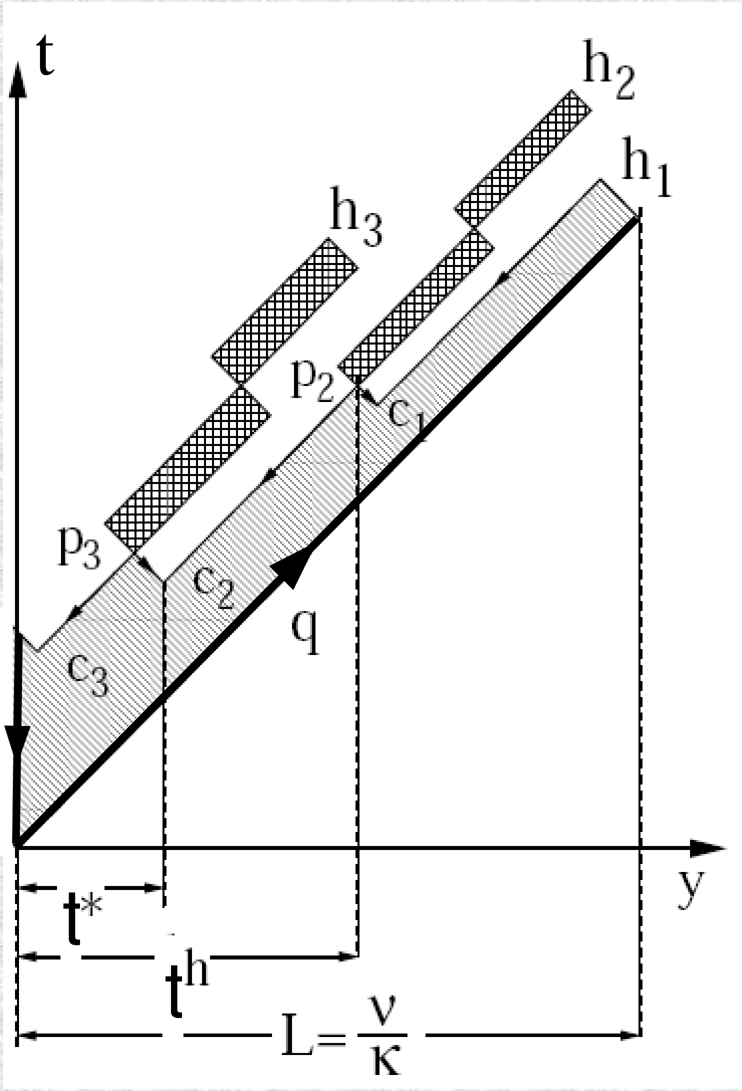
    $E_h \to \nu \;\Rightarrow$ string breaks early to leave

    all energy to the hadron: $\langle t^* \rangle \to 0$
  - At small $z \to 0$

    hadron created at high rank after

    many string breakings: $\langle t^* \rangle \to 0$

nucleus
remnant
X



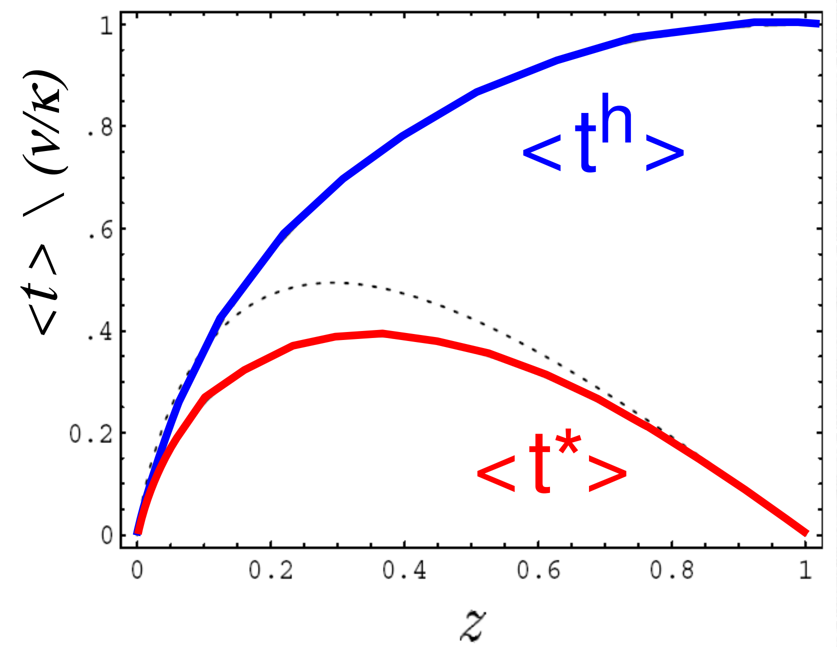
$$\begin{cases} \langle t^* \rangle = \; f(z)\,(1-z)\,\dfrac{z\nu}{\kappa} \\[2ex] \langle t^h \rangle = \; t^* + \dfrac{z\nu}{\kappa} \end{cases}$$

string-tension
(non perturbative scale)

energy conservation

# Formation time estimates 3 – Lund model

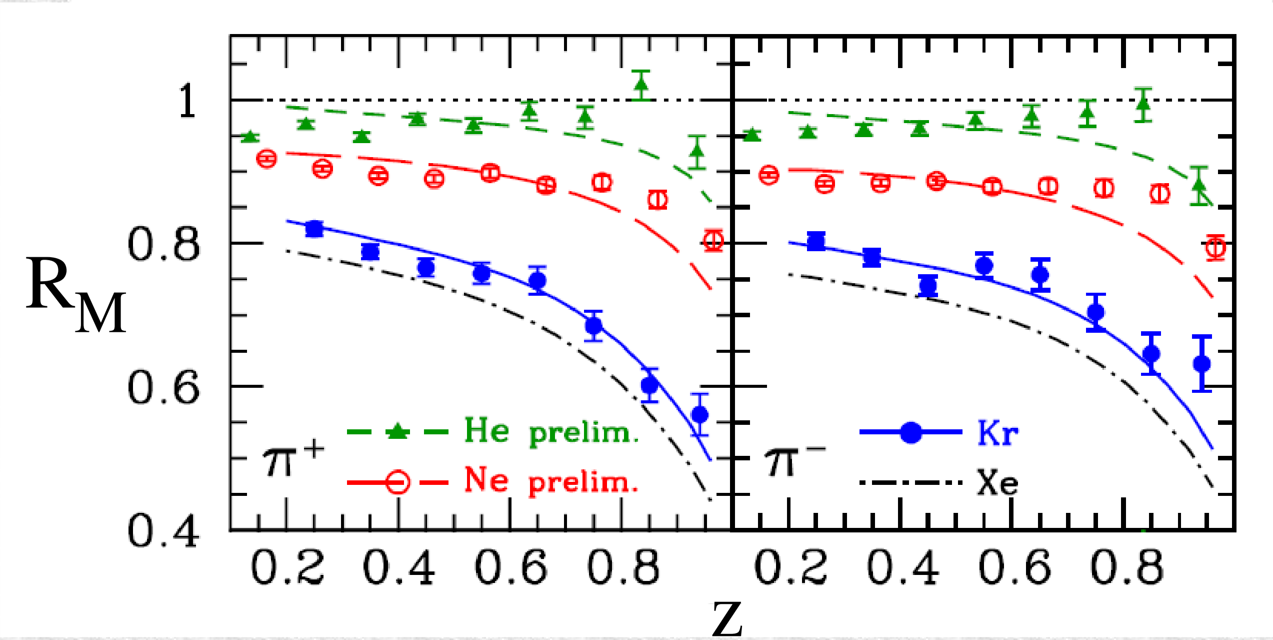
$$\begin{cases} \langle t^* \rangle = f(z)\,(1-z)\,\dfrac{z\nu}{\kappa} \\ \langle t^h \rangle = t^* + \dfrac{z\nu}{\kappa} \end{cases}$$



- For a 7 GeV pion at Hermes

  $\langle t^* \rangle < 5$ fm ~ $O(R_A)$ $\quad \langle t^h \rangle \sim 10$ fm $> R_A$

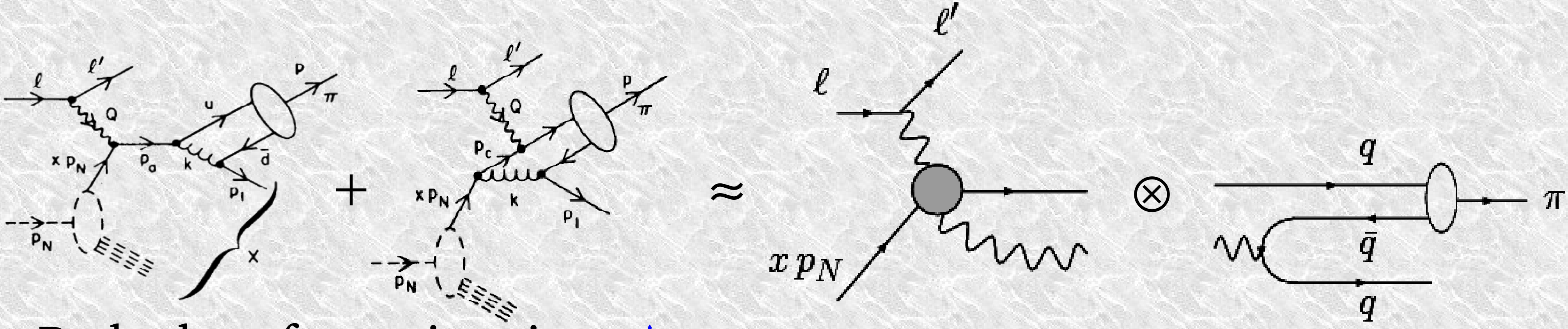
- Prehadron absorption with this estimate [A.A. et al., NPA 761(05)67]



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

# Formation time estimates 4 – Dipole model

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



- Prehadron formation time $t^*$
  = time at which gluon becomes decoherent with parent quark
  - At large $z \to 1$
    $E_h \to \nu \;\Rightarrow$ quark must be short-lived
    (otherwise radiates too much energy)

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

boost

energy conservation

virtuality (perturbative scale)

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

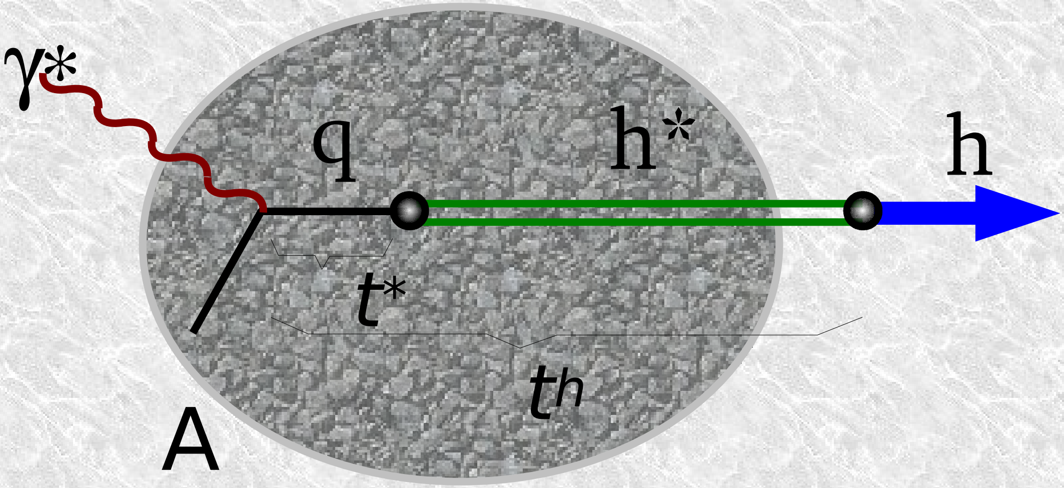
# Can we distinguish energy loss from prehadron absorption?

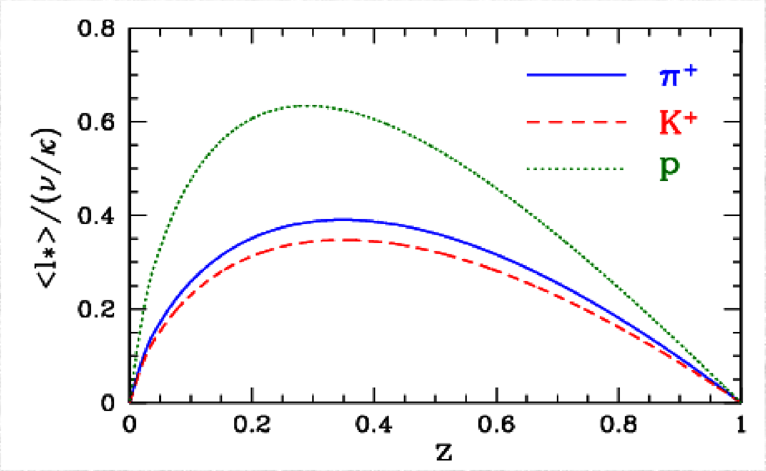
# I - Hadron absorption model

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

# Hadron absorption model – 1

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 $<t^*>(z,\nu)$, $<t^h>(z,\nu)$ taken from theLund model
  - for a 10 GeV π: $<t^*> \sim 4$ fm $<t^h> \sim 10$ fm

# Hadron absorption model – 2

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

- (Pre)hadron suppression factor $S^A$ by transport diff. eqns.
- (Pre)hadron-nucleon cross sections:

  $\sigma^* = 0.35\,\sigma^h$ - fitted to $e^+ + \mathrm{Kr} \to \pi^+ + X$

  $\sigma^h$ - from Particle Data Group
- Full integration over $\gamma^* q$ interaction point $(b,y)$

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

prob. that $h^*$ is formed at $x$

absorption of $h^*$ up to $x'$

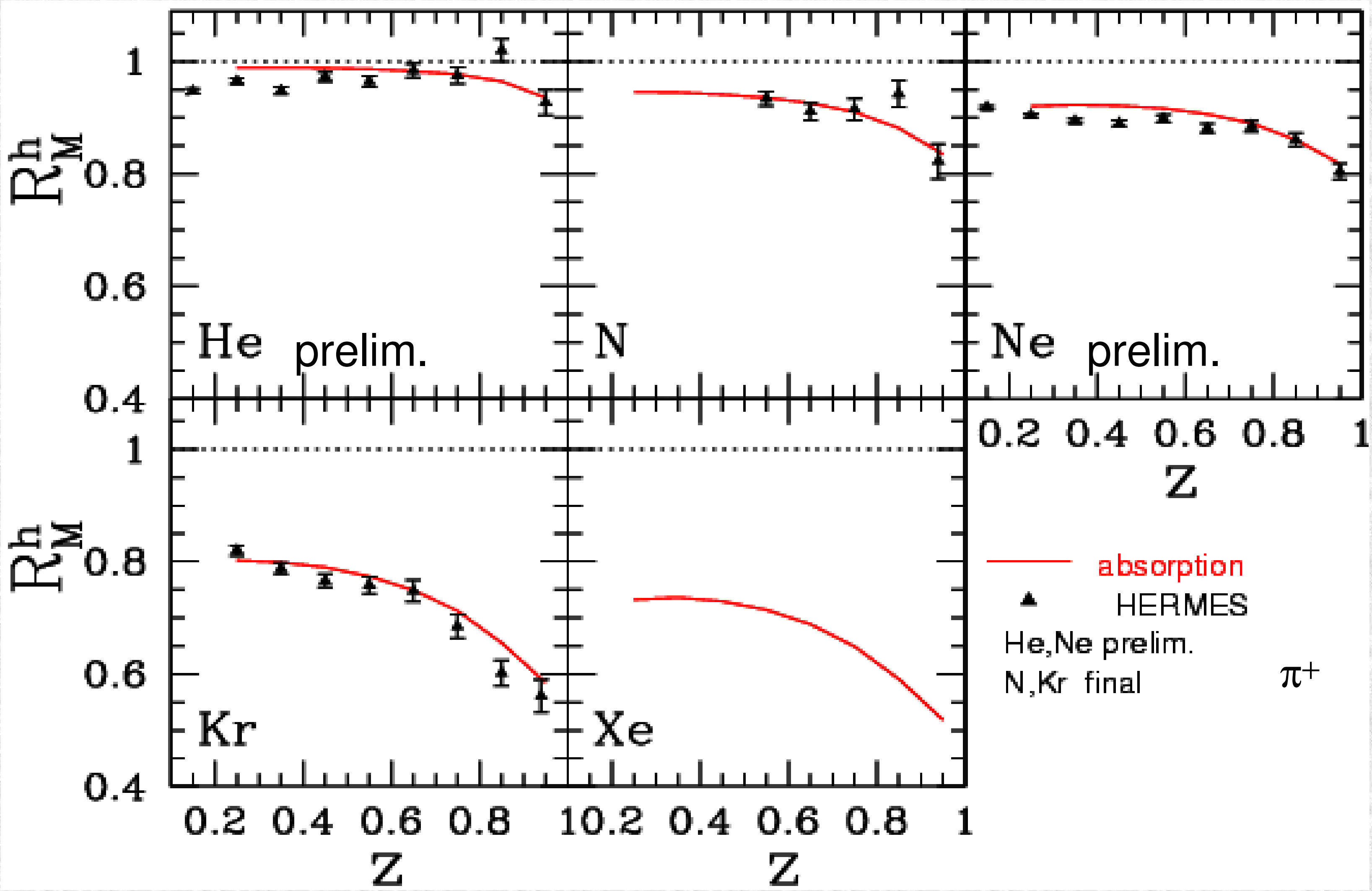
prob. that $h$ is formed at $x'$

absorption of $h$ from $x'$ to $\infty$

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

# Hadron absorption model - results

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



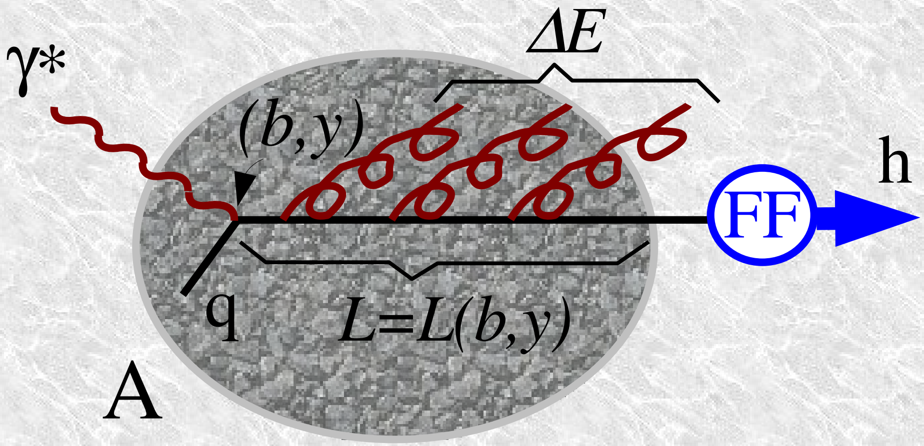
Note: in ref. above, curves differ by inclusion of $Q^2$-rescaling due to additional hypothesis of partial deconfinement in nuclei

# II - Energy loss model

A.A. (QM'05) nucl-th/0510090

# Energy loss model

A.A. (QM'05) nucl-th/0510090



- Quark hadronizes outside the nucleus
- Gluon bremsstrahlung ⇒ $\Delta E = \nu\,\Delta z$
  ⇒ modified Fragmention Function

[see Arleo EPJ C30(02)213]

$$D_q^h(z,Q^2) \longrightarrow \frac{1}{1-\Delta z}\, D_q^h\!\left(\frac{z}{1-\Delta z},Q^2\right)$$

- *New*: realistic geometry + quenching weights $\mathcal{P}(\Delta z, L)$ corrected for finite in-medium path $L=L(b,y)$

[Salgado-Wiedemann '03]

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

Quenching weight:
prob. of radiating *Δz*

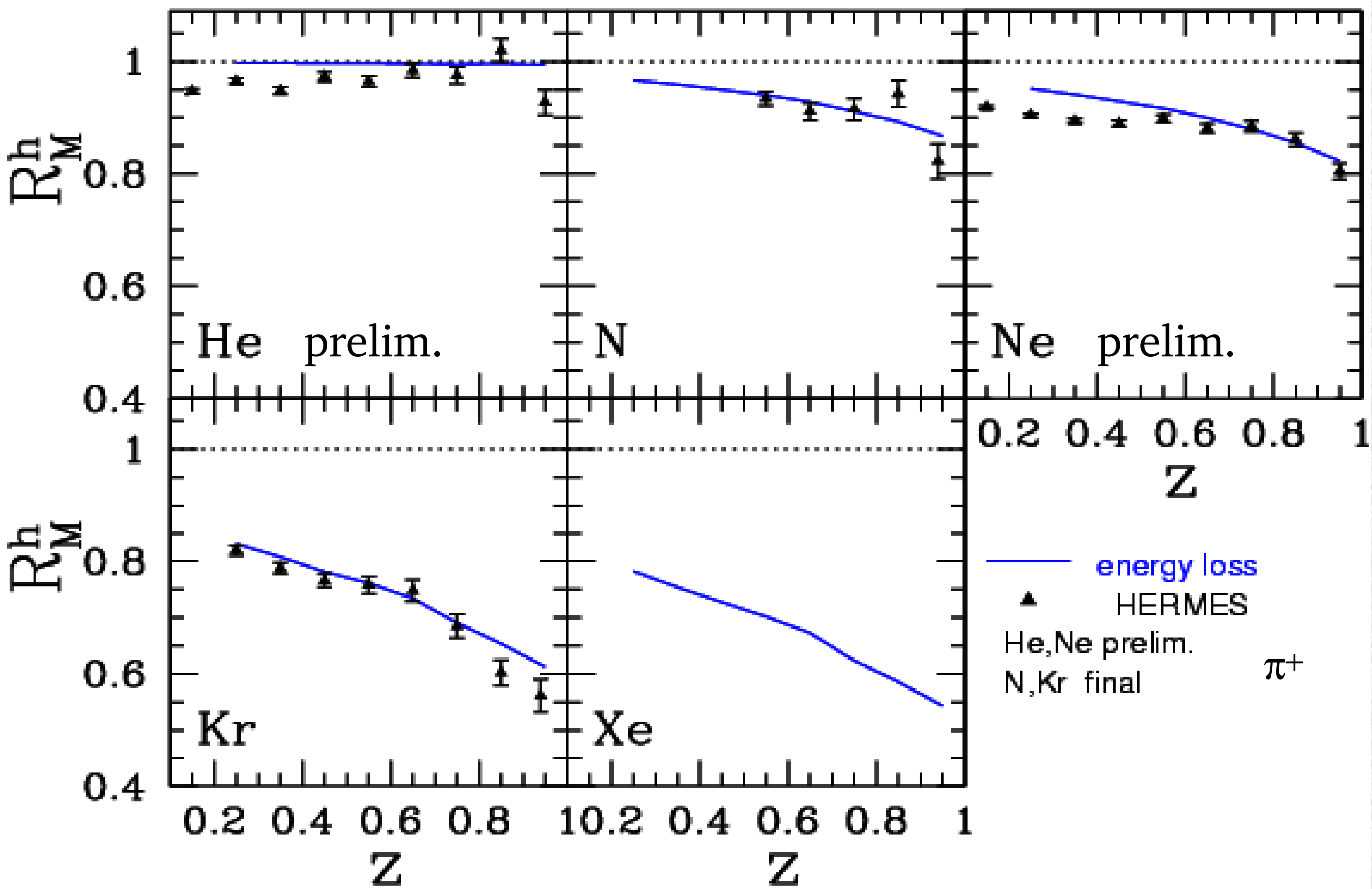
prob. of radiating no gluons

- Transport coefficient $\langle\hat{q}\rangle(b,y) = \hat{q}_0 \dfrac{\langle\rho\rangle(b,y)}{\rho(0,0)}$ where $\hat{q}_0 = \langle\hat{q}\rangle(0,0)$

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

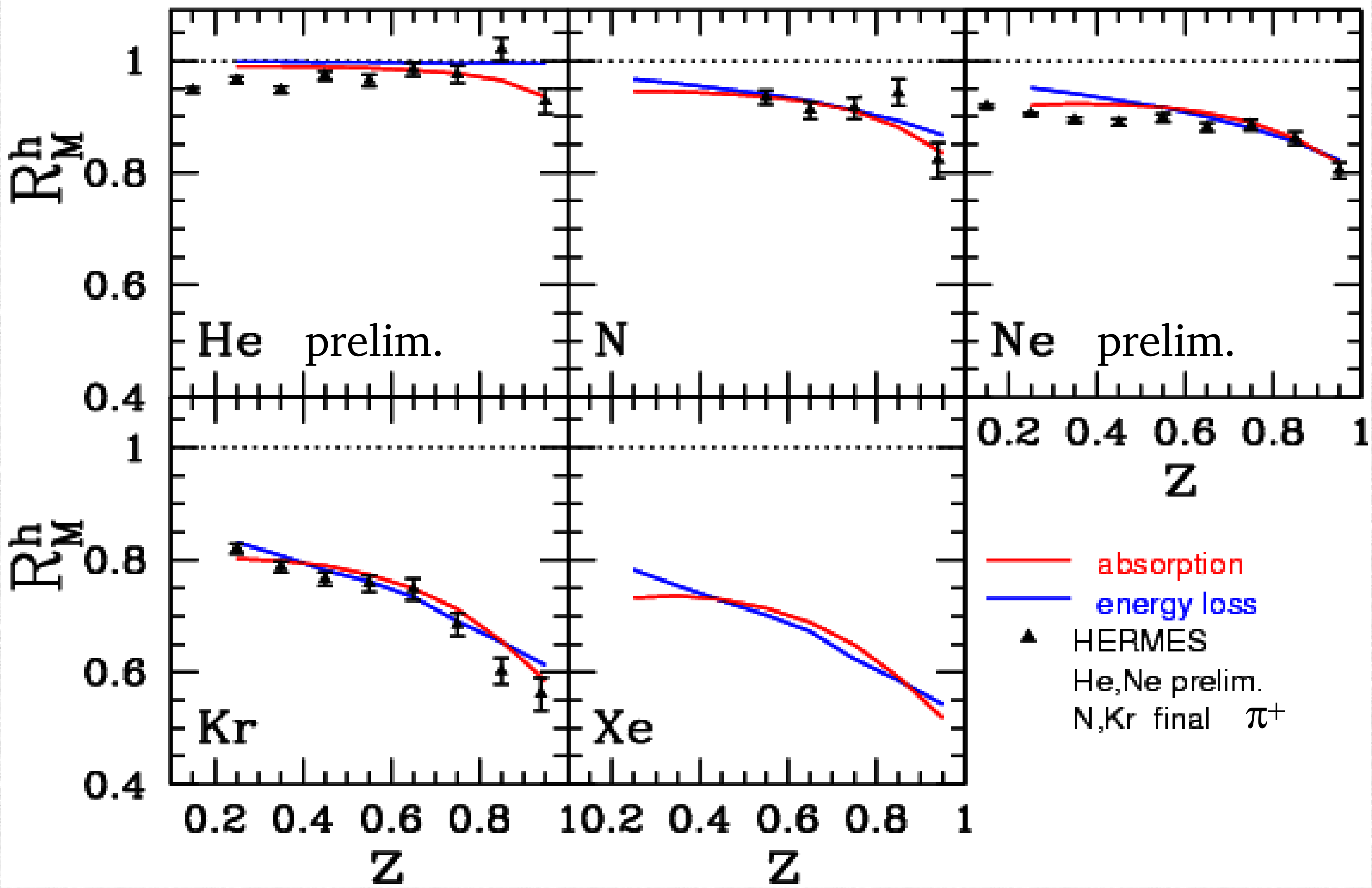
# Energy loss model - results

A.A. (QM'05) nucl-th/0510090



# Energy loss vs. absorption

A.A. (QM'05) nucl-th/0510090



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

# III – How to tell energy loss from absorption?

# 1) The "$A^{2/3}$ power law"

A.A., Gruenewald, Muccifora, Pirner, NPA 761(2005)67

- Conventional thinking: the $A^{2/3}$ law
  - Energy loss (LPM effect in QCD): $1 - R_M \sim <\Delta z> \sim L^2 \sim A^{2/3}$
  - Hadron absorption: $1\text{-}R_M \sim$ ~~$< \textit{no. of nucleons seen} > \sim L \sim A^{1/3}$~~

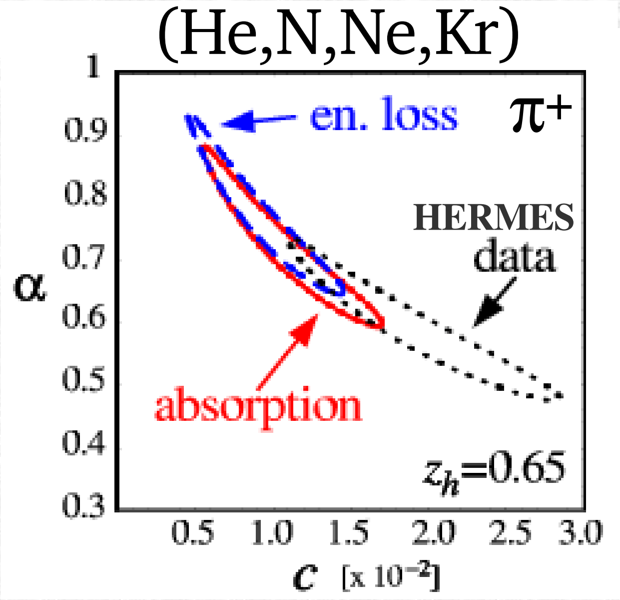
**WRONG!**

- $A^{2/3}$ also for absorption models!
  - extra dimensionful scale: prehadron formation length $<l^*>$
  - neutralize it ⇒ extra power of A $(R_A/<l^*>)^n \sim A^{n/3}$
  - typically $n=1$

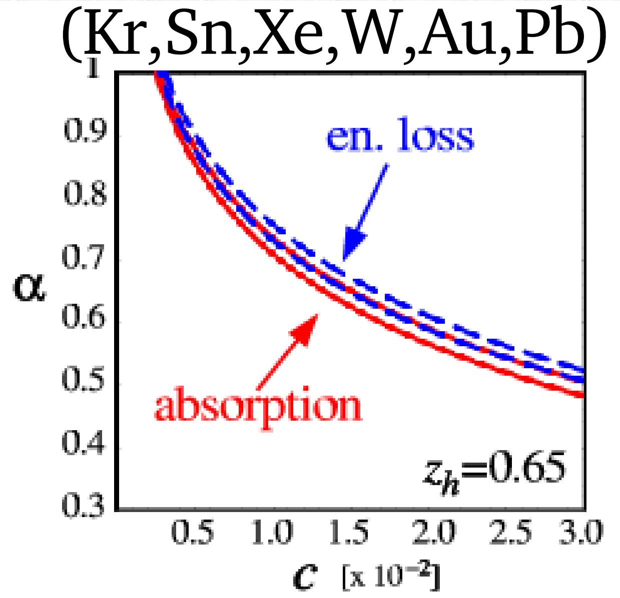
# 1) The "$A^{2/3}$ power law"

A.A., Gruenewald, Muccifora, Pirner, NPA 761(2005)67

- Don't believe it?
  - try fitting $1-R_M = c\,A^{\alpha}$
    [Accardi et al., NPA 761 (05);
    Accardi, Acta Phys. Hung. in press]
  - $A^{2/3}$ broken on large nuclei



- **Absorption & en. loss mimick each other**
  - not possible to distinguish (separate) the 2 mechanisms
  - not even using heavy nuclei up to Pb



**A-dependence of $R_M$ does not test dominance of partonic or prehadronic physics**

# 2) Scaling of $R_M$ – basic idea

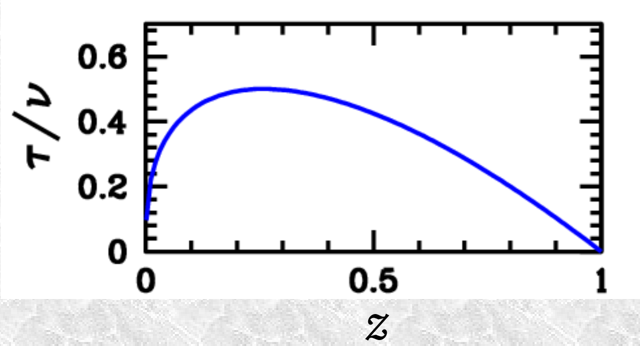
A.A., nucl-th/0604041, PLB in press

- $R_M$ should scale with $\tau = \tau(z,\nu)$ not with $z$ and $\nu$ separately

$$\boxed{R_M = R_M[\tau(z,\nu)] \quad \text{with} \quad \tau = C\, z^{\lambda}\,(1-z)\,\nu}$$

- "Scaling exponent" $\lambda$ can distinguish absorption and energy-loss
  - **absorption models**: $\lambda > 0$

    [finite formation time]

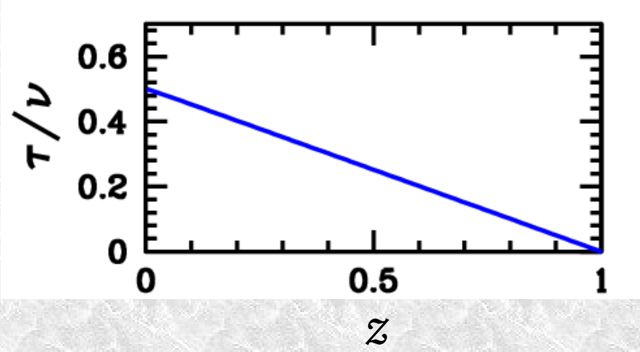


  - **energy loss models**: $\lambda \leq 0$

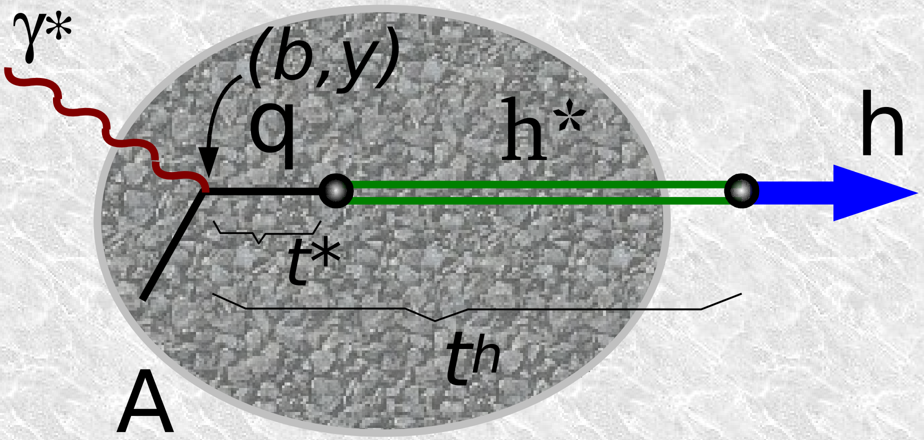
    [from energy conservation:

    $\varepsilon < (1-z_h)\,\nu$ ]

    radiated energy



# 2) Scaling of $R_M$ – Absorption models



- Extreme situation: if quark has no interactions,
  ⇒ $R_M$ depends only on the prehadron's in-medium path, i.e. $\langle t^* \rangle$

- General form of $\langle t^* \rangle$ :

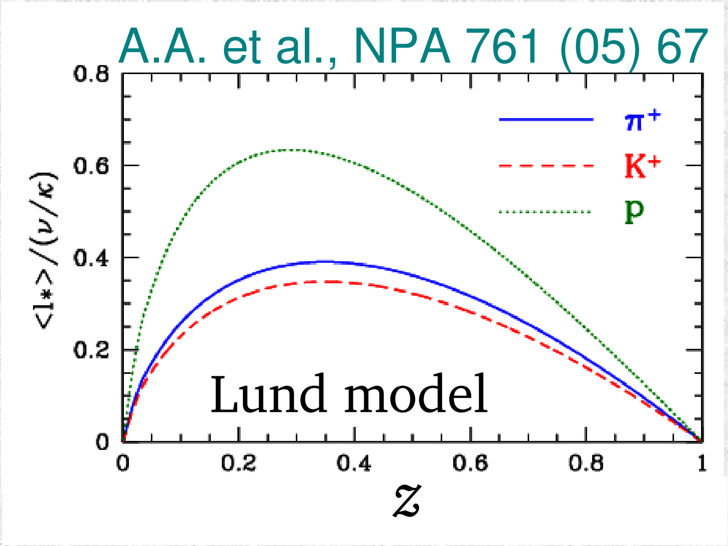
Lorentz boost

$$\langle t^* \rangle = f(z)\,(1-z)\,\frac{z\,\nu}{\kappa} \;\sim\; \tau(z,\nu)$$

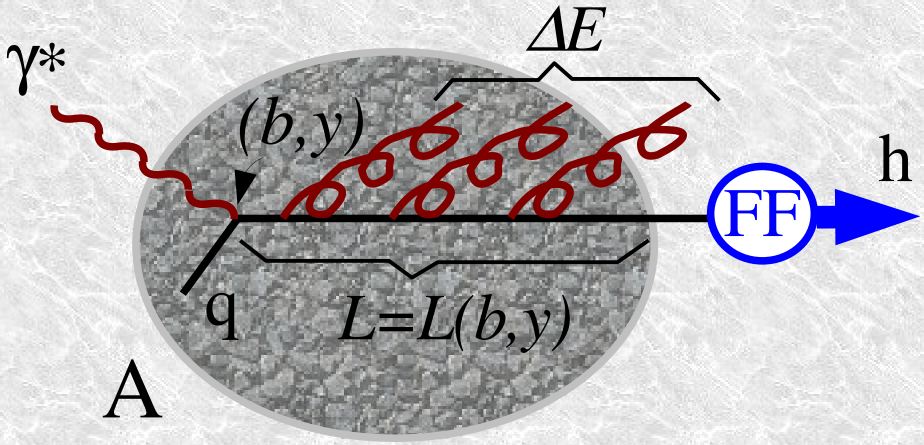
energy conservation

model dep. scale (e.g. string tension)

**obtain τ-scaling with $\lambda > 0$**


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

# 2) Scaling of $R_M$ – Energy loss models



- define average energy loss:

energy conservation: $\varepsilon < \nu - E_h$

$$\langle \epsilon \rangle = \int_0^{(1-z_h)\nu} d\epsilon\, \epsilon\, \mathcal{P}(\epsilon) = f[(1-z_h)\nu]$$

- Approximate: $R_M \approx \frac{1}{1-\langle\epsilon\rangle/\nu} D\left(\frac{z_h}{1-\langle\epsilon\rangle/\nu}\right) \Big/ D(z_h)$

- Use KKP at $Q^2 = 2$ GeV$^2$ $D(z_h) = C z_h^\alpha (1-z_h)^\beta$

- Obtain **approximate τ scaling with λ≈0**:

$$R_M \approx \frac{1}{\left(1 - \frac{1}{\nu} f[(1-z_h)\nu]\right)^{\alpha+\beta+1}} \left(1 - \frac{f[(1-z_h)\nu]}{(1-z_h)\nu}\right)^\beta$$

~ τ(λ=0)

in practice, **λ ≲ 0**

# 2) Scaling analysis

A.A., nucl-th/0604041, PLB in press

- HERMES data presented as:
  - *z*-distributions: $R_M(z)$ with $<\nu> = <\nu>(z)$
  - $\nu$-distributions: $R_M(\nu)$ with $<z> = <z>(\nu)$
- Scaling analysis of $R_M$ – remember $\tau = C z^{\lambda} (1-z) \nu$
  1) Fix $\lambda$
  2) For each $z$ compute $\tau=\tau(z,<\nu>)$ and $R_M(\tau) = R_M(z)$

     For each $\nu$ compute $\tau=\tau(<z>,\nu)$ and $R_M(\tau) = R_M(\nu)$
  3) Fit $\phi(\tau)$ to $\{\tau,R_M\}$ obtained above – $\chi^2 = \chi^2(\lambda)$

$$\phi(\tau)=a+b\tau+c\tau^2+d\tau^3+e\tau^4$$

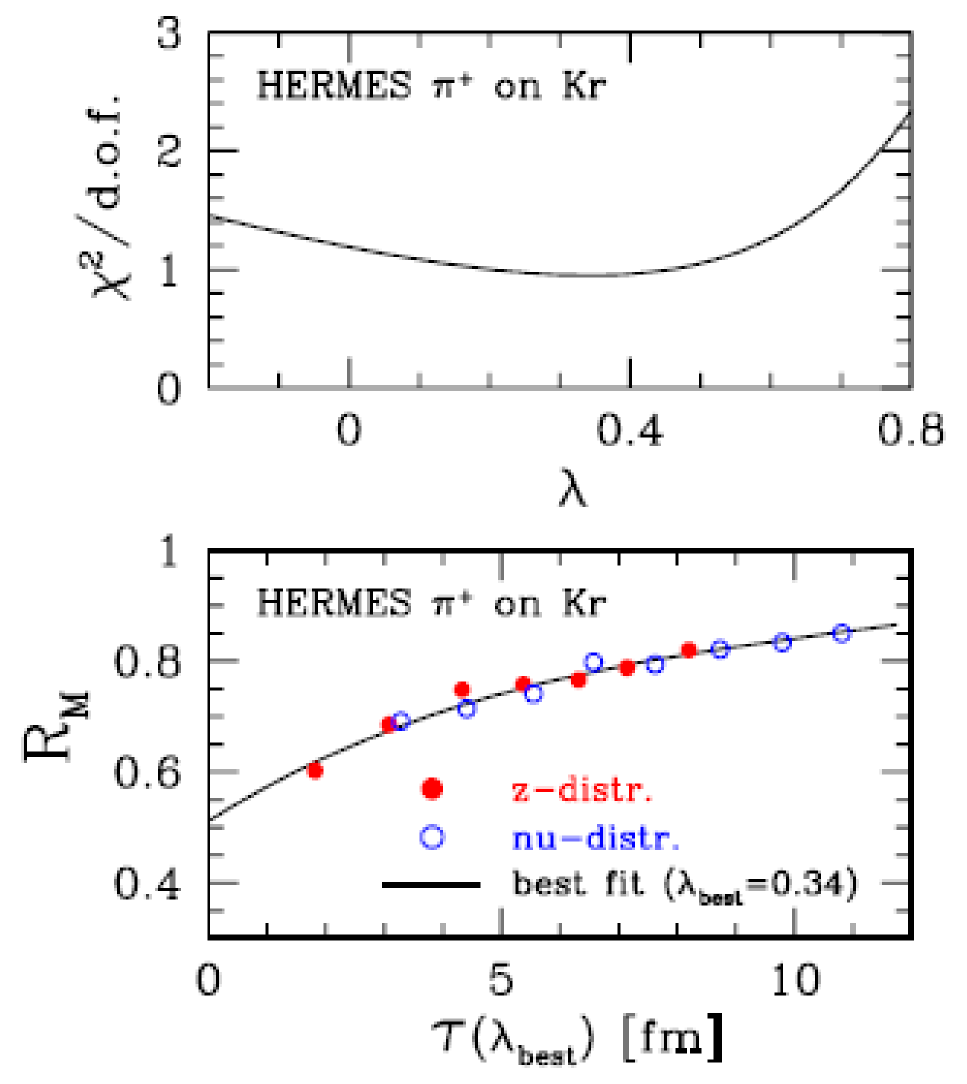
( cross-checked by $\phi(\tau)=\dfrac{a+b\tau+c\tau^2}{a+d\tau+e\tau^2}$ )

  4) Best-fit $\lambda_{best}$ by $\chi^2$ minimization
  5) If $\chi^2(\lambda_{best})/\text{d.o.f.} \lesssim 1 \Rightarrow R_M$ scales with $\tau$, and is charachterized by $\lambda_{best}$
- NOTE: the overall scale of $\tau$ cannot be extracted

  ($R_M$ scales, or doesn't scale, independently of the value of the overall constant *C*)

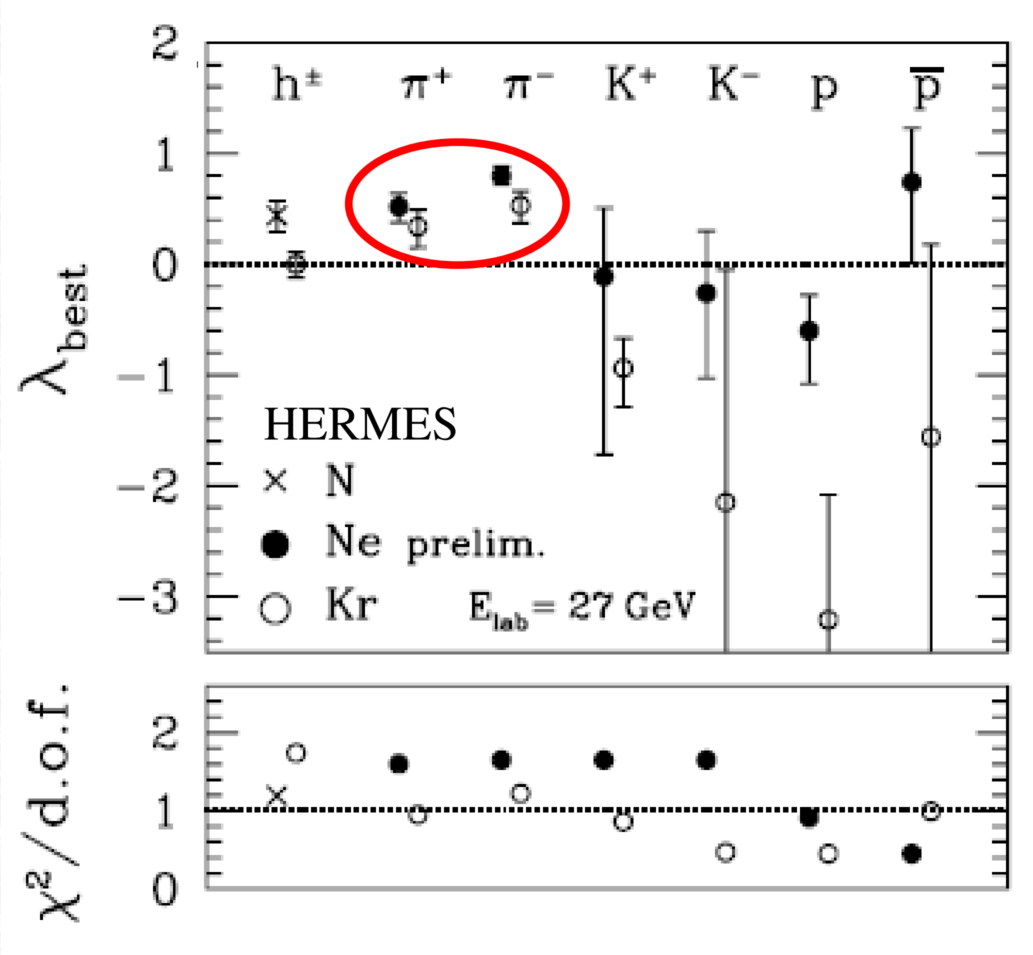
# 2) Scaling analysis - example

A.A., nucl-th/0604041, PLB in press



# 2) Results – $E_{lab}$ = 27 GeV

A.A., nucl-th/0604041, PLB in press

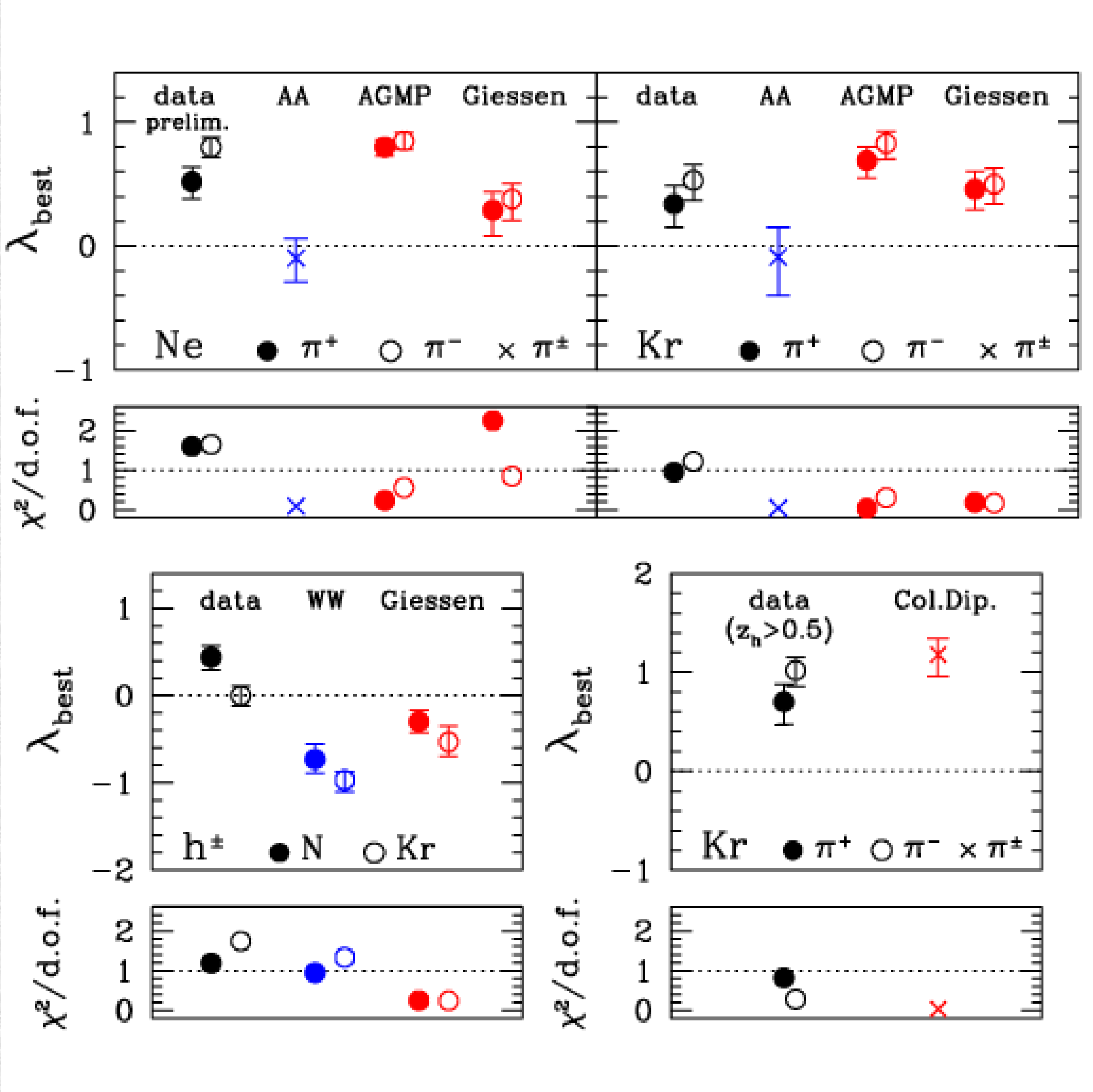


- λ(π)>0 : Formation-time scaling for pions!

**Hadronization starts inside the nucleus!**

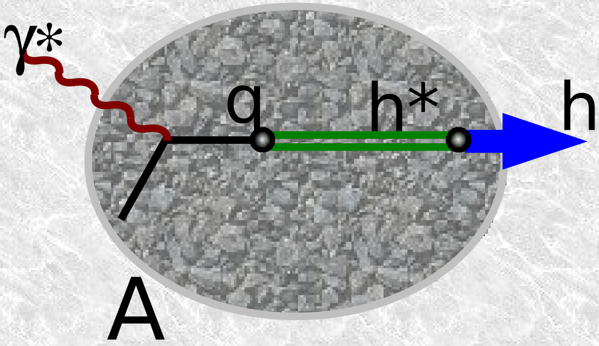
# 2) Data vs. theory

A.A., nucl-th/0604041, PLB in press

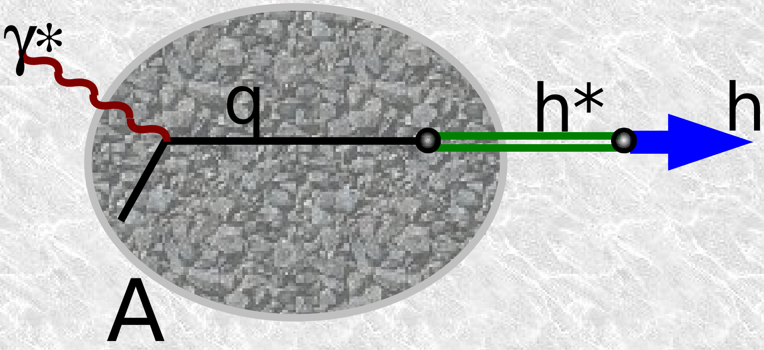


- **Experimental data:**
  - HERMES
- **Energy loss models:**
  - AA = Arleo + realistic geometry (A.A.)
  - WW = Wang & Wang
- **Absorption models:**
  - AGMP = Accardi, Gruenewald, Muccifora, Pirner
  - Giessen = Falter et al.
  - Col.Dip. = Kopeliovich et al.

# 3) $p_T$ – broadening



high-z



low *z*

- **$\langle p_T^2 \rangle$ broadening** [Kopeliovich et al., NPA 740(04)211]
  1) Directly proportional to quark's in-medium path
  2) Can measure prehadron formation time *t**
  3) Detect hadronization inside or outside the nucleus

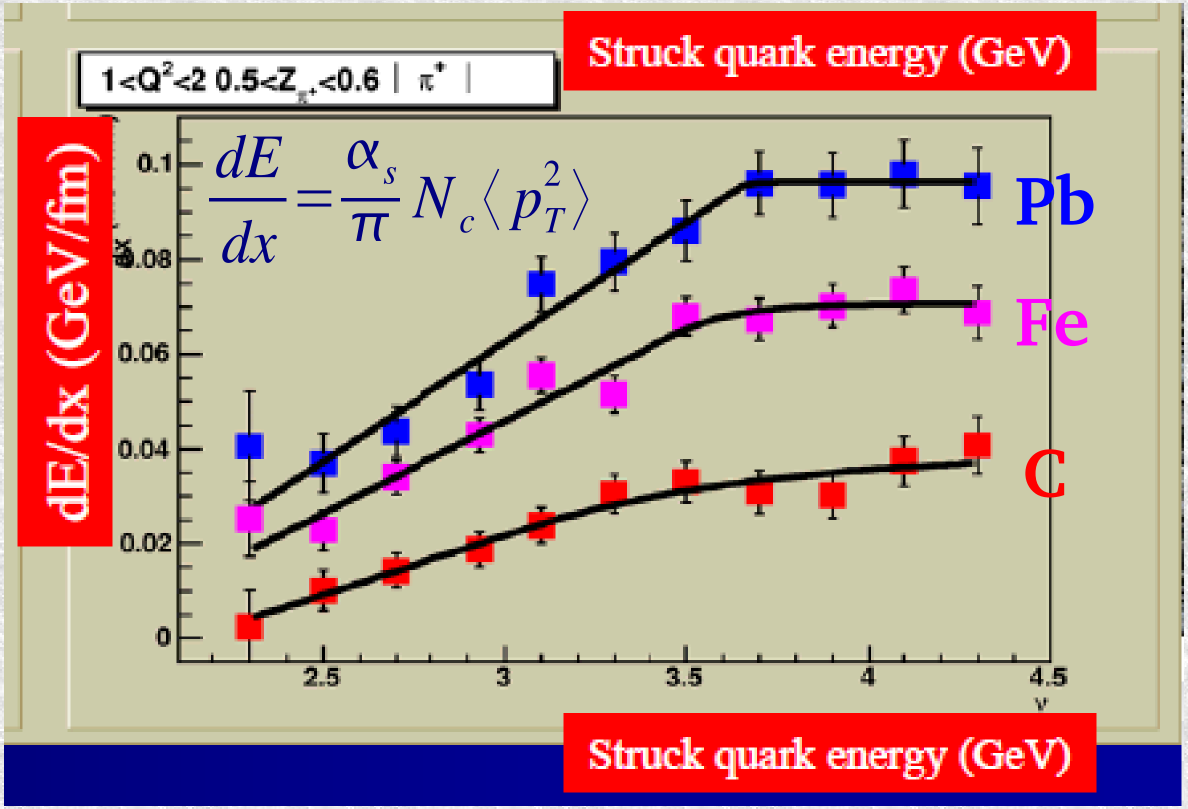
dipole x-sect.

$$\Delta\langle p_T^2(L)\rangle = 2C(s)\int_0^L dz\,\rho_A(z), \quad \text{where:} \quad C(s) = \left.\frac{d\sigma_{\bar{q}q}(r_T,s)}{dr_T^2}\right|_{r_T=0}$$

- Can be cross-checked by the scaling analysis of $R_M$

# 3) $p_T$ – broadening

- If prehadron inside nucleus ⇒ quark path length varies with $z_h$, $\nu$
- $\Delta p_T$ should:
  1) rise with ν until $<t^*> \sim R_A$, then level off
  2) decrease as $z_h \to 1$
  3) possibly, decrease as $Q^2$ increases



JLAB $E_{lab}$=5 GeV – preliminary results

Will Brooks, JLAB user's group workshop, 13 June 2006

# 3) $p_T$ – broadening

- **“Model independent” measurement of $<l^*>=l_p$**
  [Kopeliovich,Nemchik,Schmidt, hep-ph/0608044]

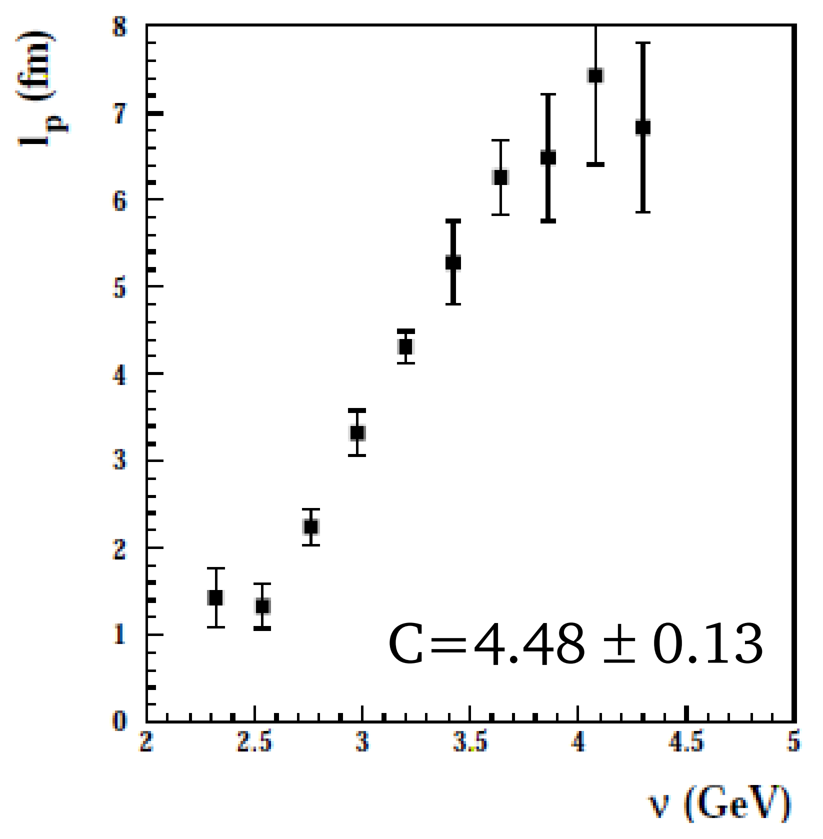
$$\Delta p_T^2 = \frac{2C z_h^2}{A} \int d^2b \int_{-\infty}^{\infty} dz\, \rho_A(b,z) \int_z^{z+l_p} dz'\, \rho_A(b,z')$$

where

dipole cross-section

$$C(s) = \left. \frac{d\sigma_{\bar{q}q}(r_T,s)}{dr_T^2} \right|_{r_T=0}$$

1) fit $l_p$ to data for each nucleus
2) determine $C$ by minimizing
   differences of $l_p$ among nuclei

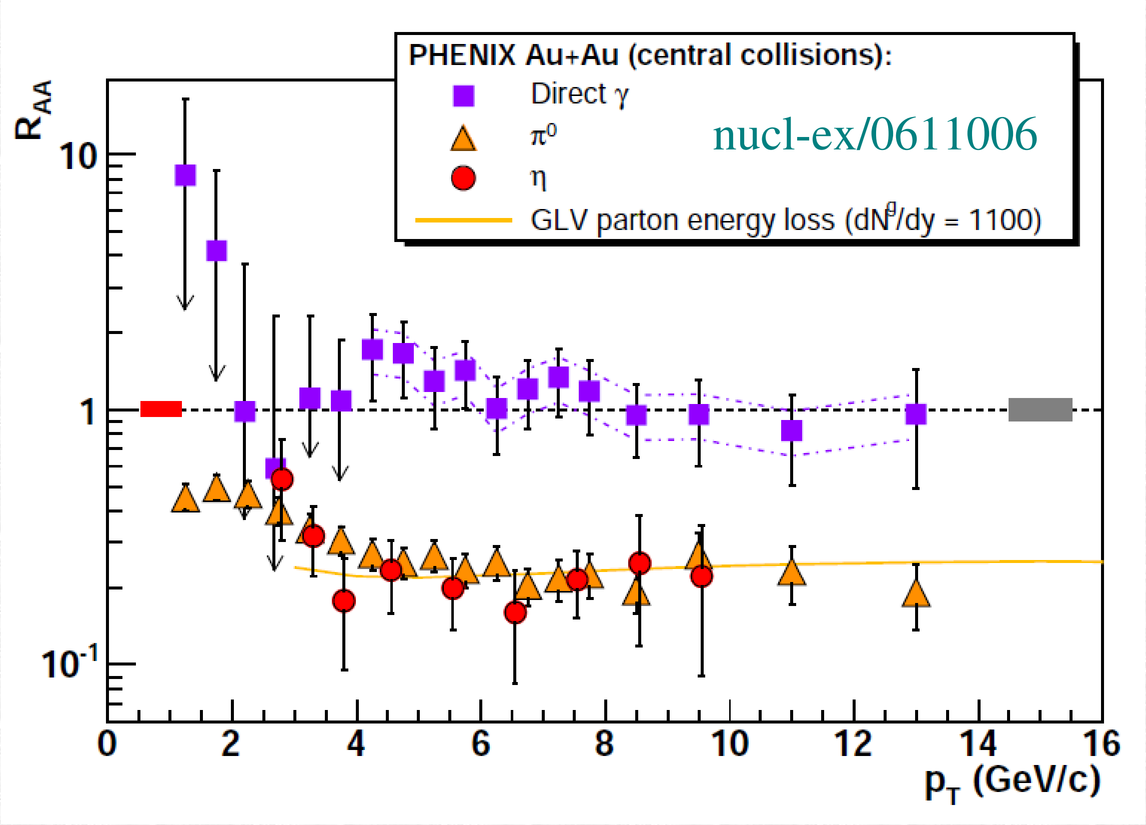


C=4.48 ± 0.13

# Perspectives

# Perspectives 1 – mesons

- Why is η as much suppressed as π in Au+Au collision?
  - points towards long lived quark
  - but scaling analysis suggests pions formed on short time scales



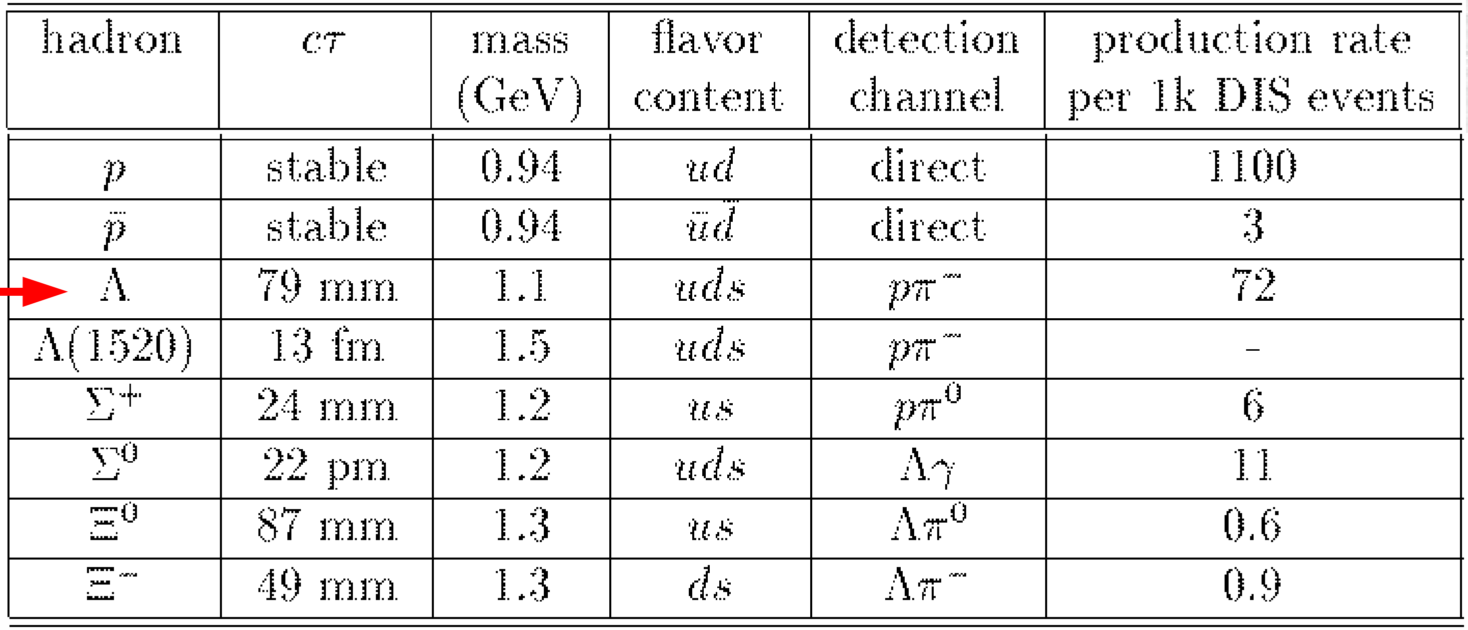
nucl-ex/0611006

- Is it so also in nDIS? [η is heavier ⇒ hadronizes earlier]
  - measurement possible at HERMES, CLAS @ JLAB

# Perspectives 2 – baryons

- Is the baryon anomaly in nDIS only for protons? ⇒ measure $\Lambda$!
  (at RHIC $R_{dAu}$ and $R_{AuAu}$ similar for p and $\Lambda$)
- possible at HERMES and CLAS @ JLAB

production rate @ CLAS++ 12 GeV (not folded with PID) [W.Brooks, FizikaB13(04)321]



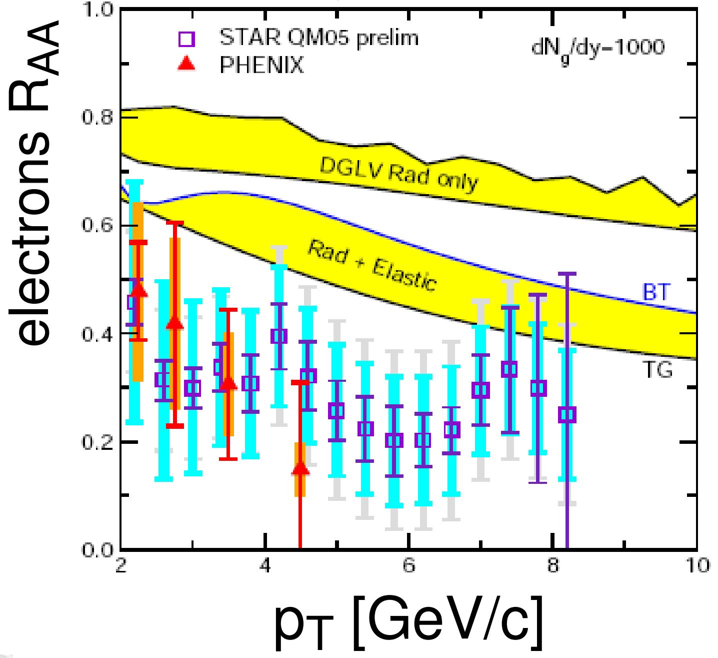
| hadron | $c\tau$ | mass (GeV) | flavor content | detection channel | production rate per 1k DIS events |
|---|---|---|---|---|---|
| $p$ | stable | 0.94 | $ud$ | direct | 1100 |
| $\bar{p}$ | stable | 0.94 | $\bar{u}\bar{d}$ | direct | 3 |
| $\Lambda$ | 79 mm | 1.1 | $uds$ | $p\pi^-$ | 72 |
| $\Lambda(1520)$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

- More in general: clarify baryon production:
  - proton anomaly / antiproton normality
  - diquark content of nucleons
  - baryon transport

# Perspectives 3 – heavy quarks

- Heavy-quark energy loss and hadronization of D, B mesons in the spotlight at RHIC
  - measure D, B in e+A !
- At HERMES
  - luminosity is to low for D meson
- At Jlab 12 GeV
  - high luminosity may compensate for low-ν and large-*x* (and PID)
  - chances for D meson measurement close to but not zero
- Needs an Electron-Ion Collider!

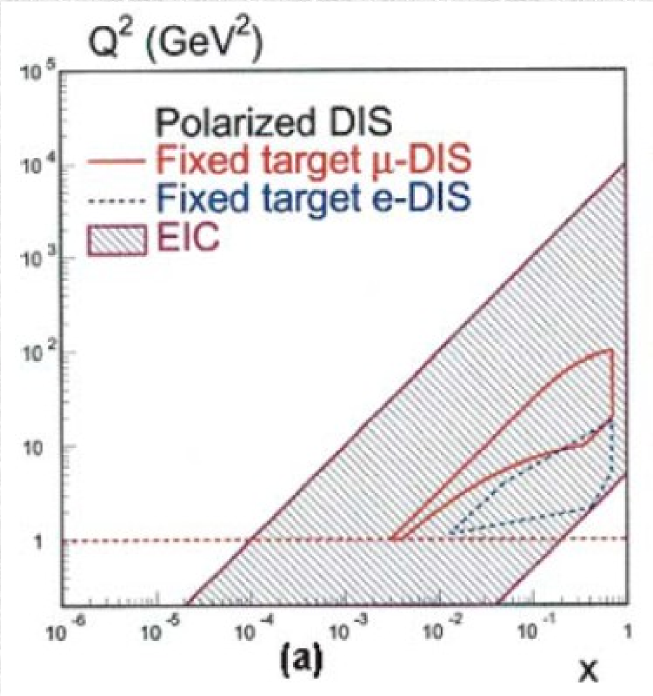
Wicks et al., nucl-th/0512076



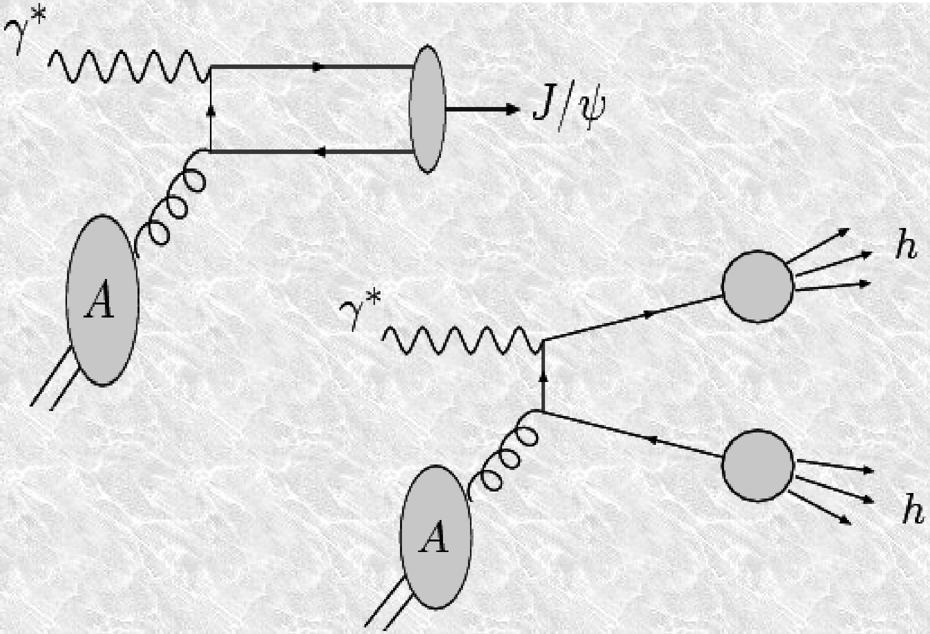
# Perspectives 4 – eRHIC / ELIC

- Can repeat HERMES / JLAB

- Large ν-span: 10 GeV < ν < 1600 GeV
  - hadronization inside/outside target
  - test parton energy loss in cold nuke matter
  - test of factorization for FF
  - larger phase space for heavy hadrons
  - jet physics



- Small *x*:
  - heavy quarks ⇒ D, B mesons
  - J/ψ "normal suppression"
  - "away-side" correlations: hadron-hadron, γ-hadron



# Conclusions

- Space-time evolution of hadronization important:
  - on its own: understanding of color confinement
  - for correct interpretation of hadron suppression in A+A

- **$\tau$-scaling analysis suggests small formation times for $\pi$**
  - measures $t^*(\pi) \propto z^{0.6}(1-z)\,\nu$
- **pT-broadening confirms small t***
  - measures $t^*(\pi) \propto 7$ fm at $\nu \sim 4$ GeV and $Q^2 \sim 1.5$ GeV$^2$
- A new challenge to the energy loss paradigm in A+A?

- Rich hadronization physics to be studied at
  - HERMES @ DESY
  - CLAS, Hall-A @ JLAB, JLAB12
  - eRHIC/ELIC

- Enough phenomenology in nDIS: can we address the space-time evolution of hadronization at a more fundamental level?

# The end

# Backup slides

# 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 geometry: Woods-Saxon parametrization for A>2
  Reid's soft-core for 2D

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

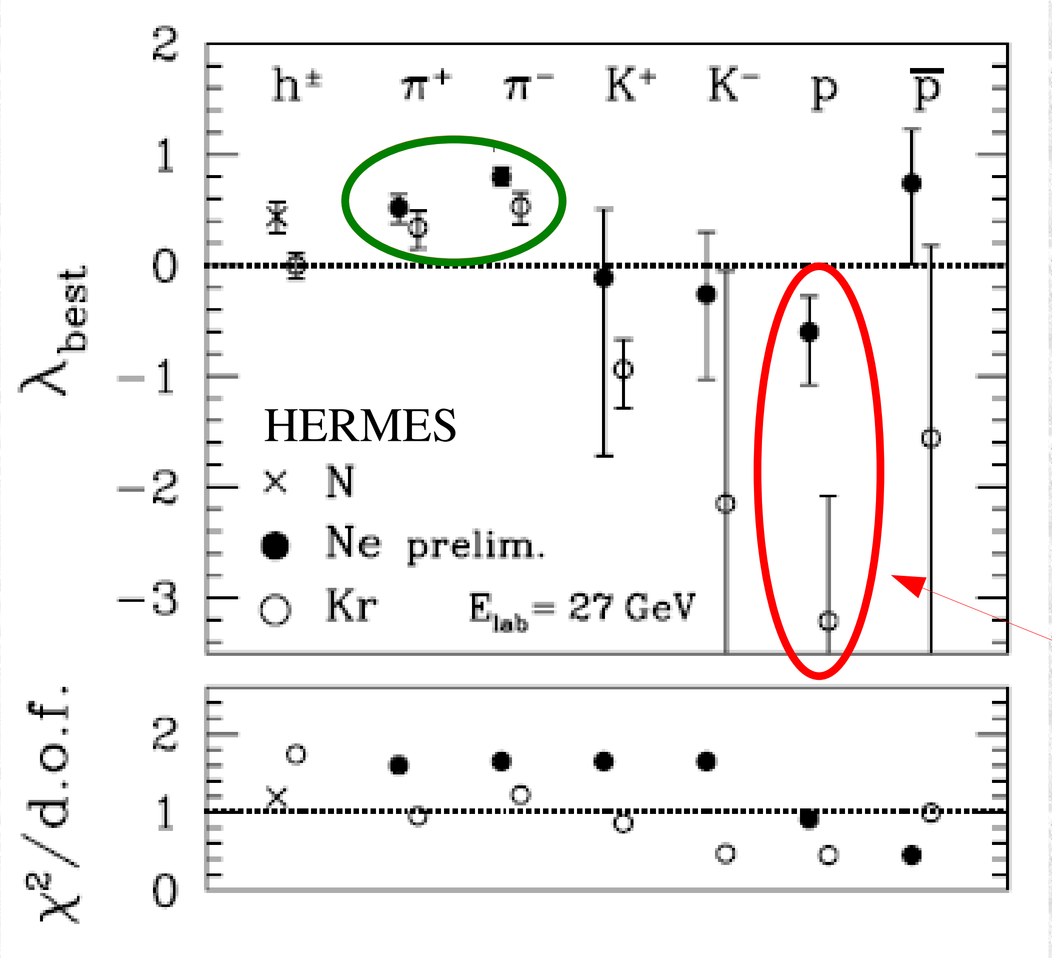
$$\langle\rho\rangle(b,y) = \int_y^\infty dz\,\rho(b,z) \Big/ L(b,y) \Big(= \rho_{HS} \ \text{ for Hard-Sphere}\Big)$$

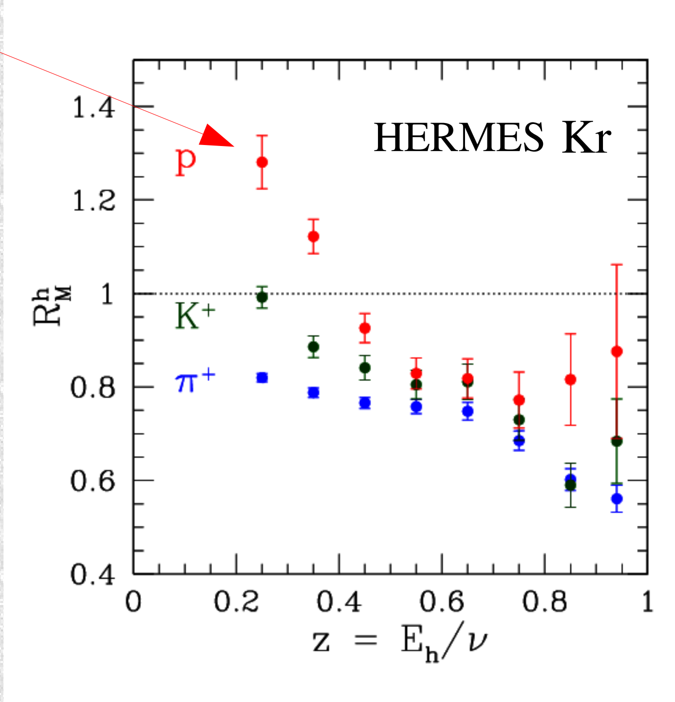
- Transport coefficient

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

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

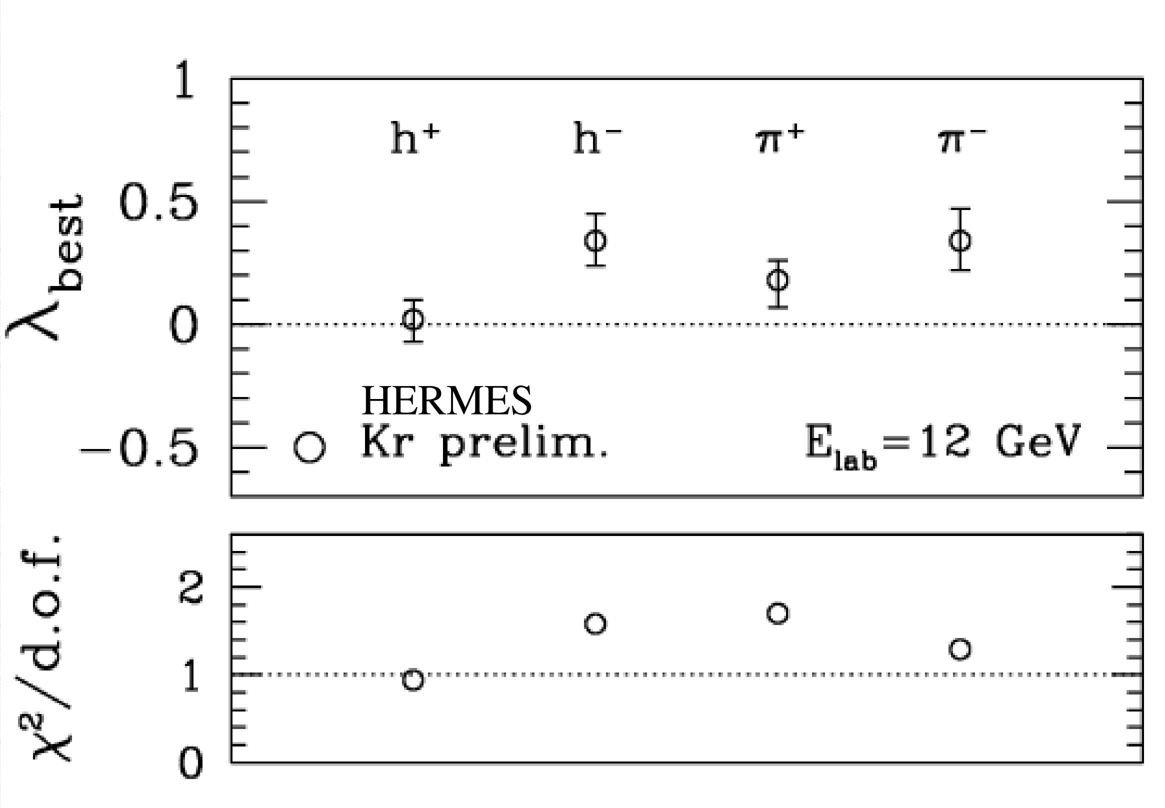
# Results – $E_{lab}$ = 27 GeV





- $\lambda(\pi)>0$ : **Formation-time scaling for pions!**
- Why $\lambda_{best}(h^{\pm}) \sim 0$ on Kr?
  - proton anomaly!

# Results – $E_{lab}$ = 12 GeV

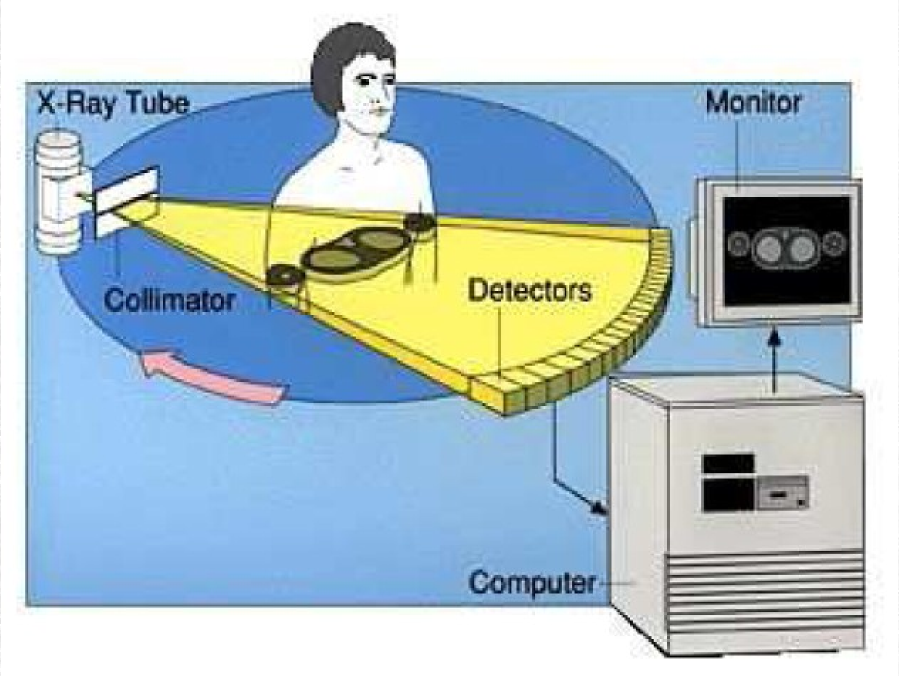


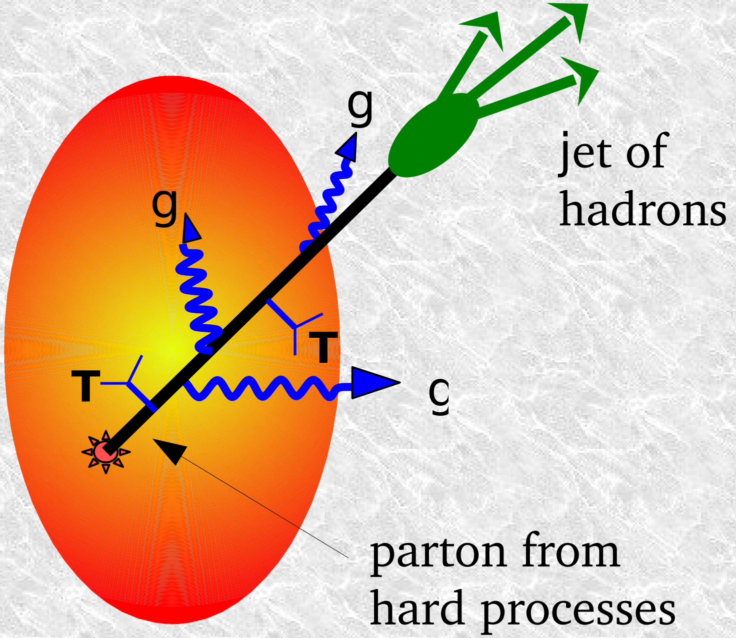
- pions are still positive! confirms results at 27 GeV
- $\lambda_{best}(h^+) \sim 0$ but $\lambda_{best}(h^-) > 0$
  - proton anomaly hypothesis confirmed!

# The energy loss paradigm

Review: Gyulassy, Vitev, Wang, Zhang, nucl-th/0302077
Baier, Dokshitzer, Levai, Mueller, Peigne, Schiff, Wiedemann, Zakharov, ...

- Jet tomography: QCD analog of Computed Axial Tomography (CAT)





**Computed Axial Tomography**

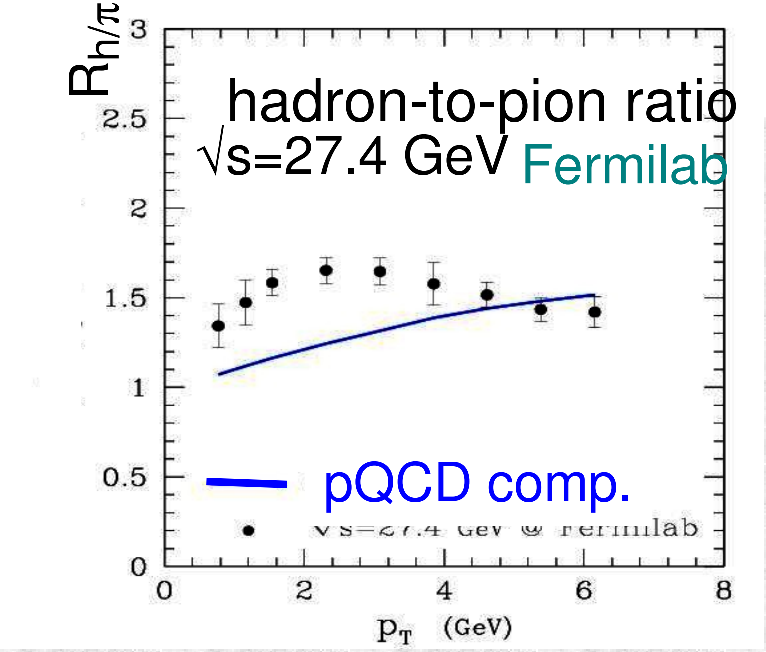
- Calibrated x-ray source
- x-ray absorption
- properties of the medium

**Single hadron tomography**

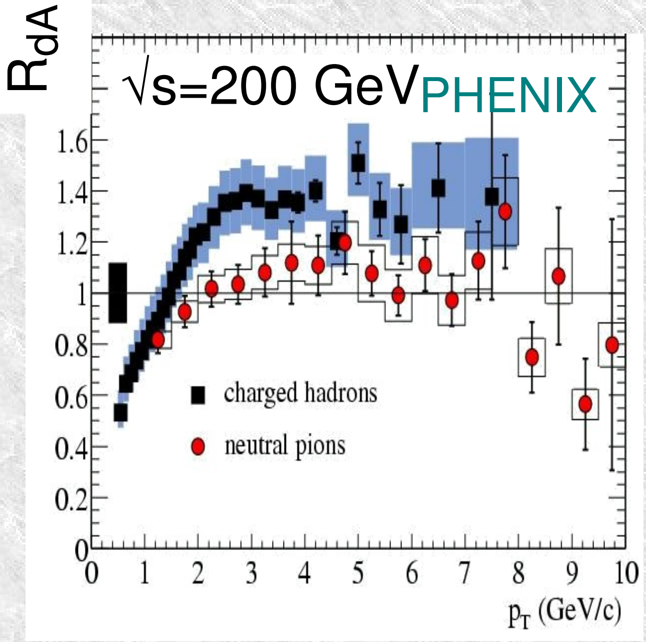
- Calibrated hard partons source
- energy loss (gluon bremsstrahlung) computed in pQCD
- properties of the medium

# Challenges: baryon anomaly

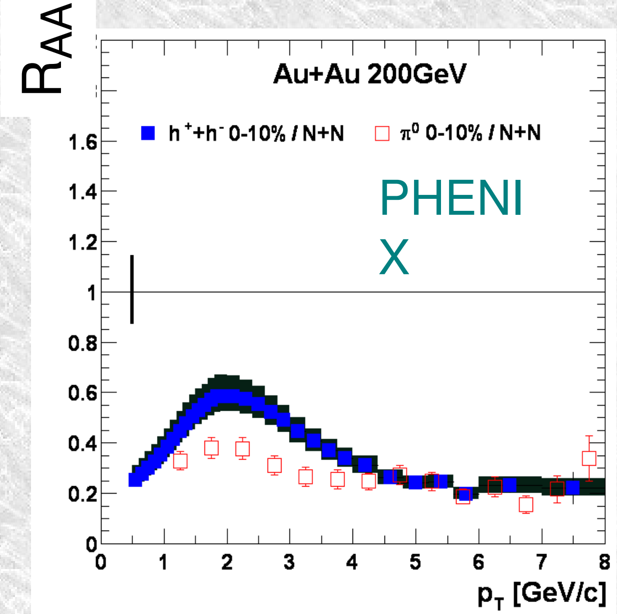
## in p+p



## in h+A



## in A+A



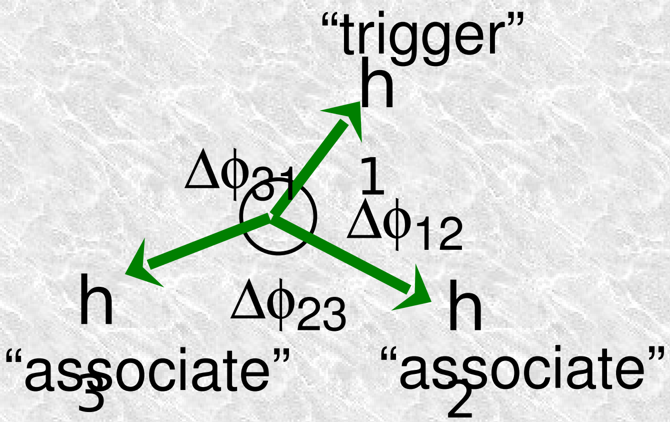
$$R_{h/\pi} = \frac{dN^h/d^2p_T}{dN^\pi/d^2p_T}$$

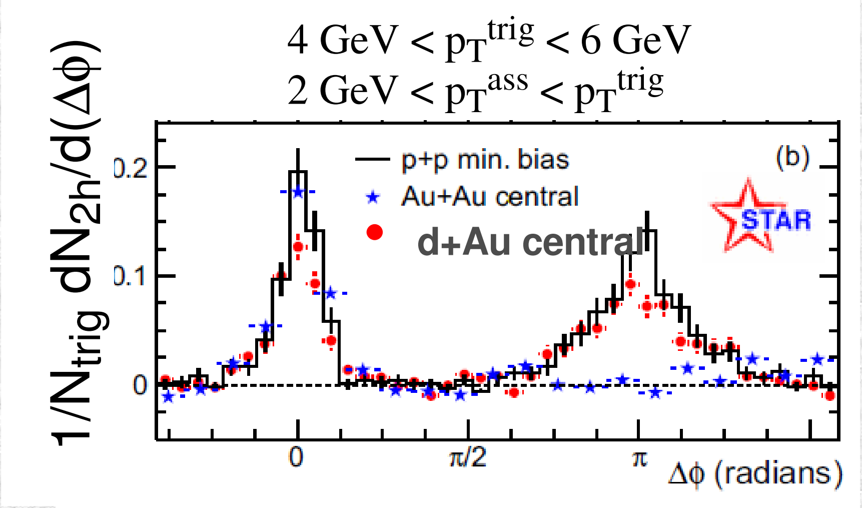
$$R_{BA} = \frac{1}{T_{BA}(b)} \frac{(dN^h/d^2p_T)_{d+A}}{(d\sigma^h/d^2p_T)_{p+p}}$$

- **p+p, p+A:** difference in meson and baryon production at medium $p_T$ not understood in pQCD + quark fragment.
- **A+A :** baryon anomaly persists – h/π ratio increases

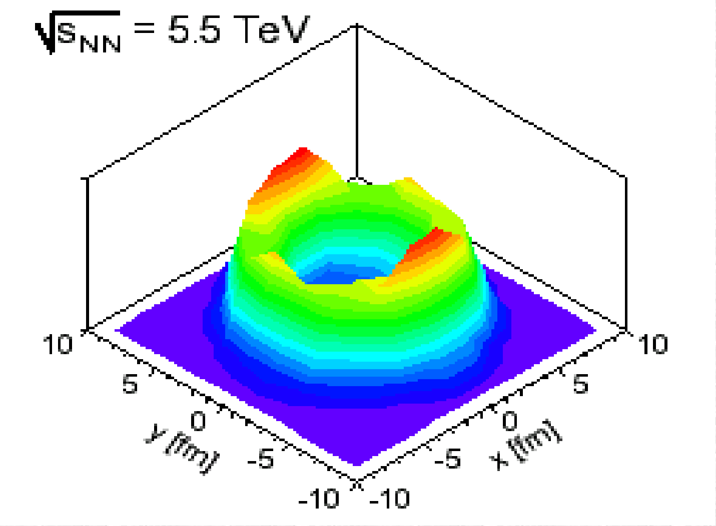
# Challenges 3: surface emission

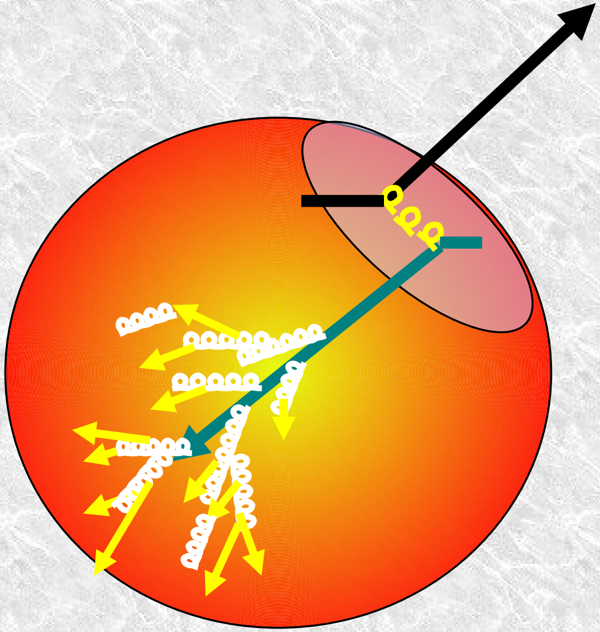
- Disappearance of the back-to-back jet



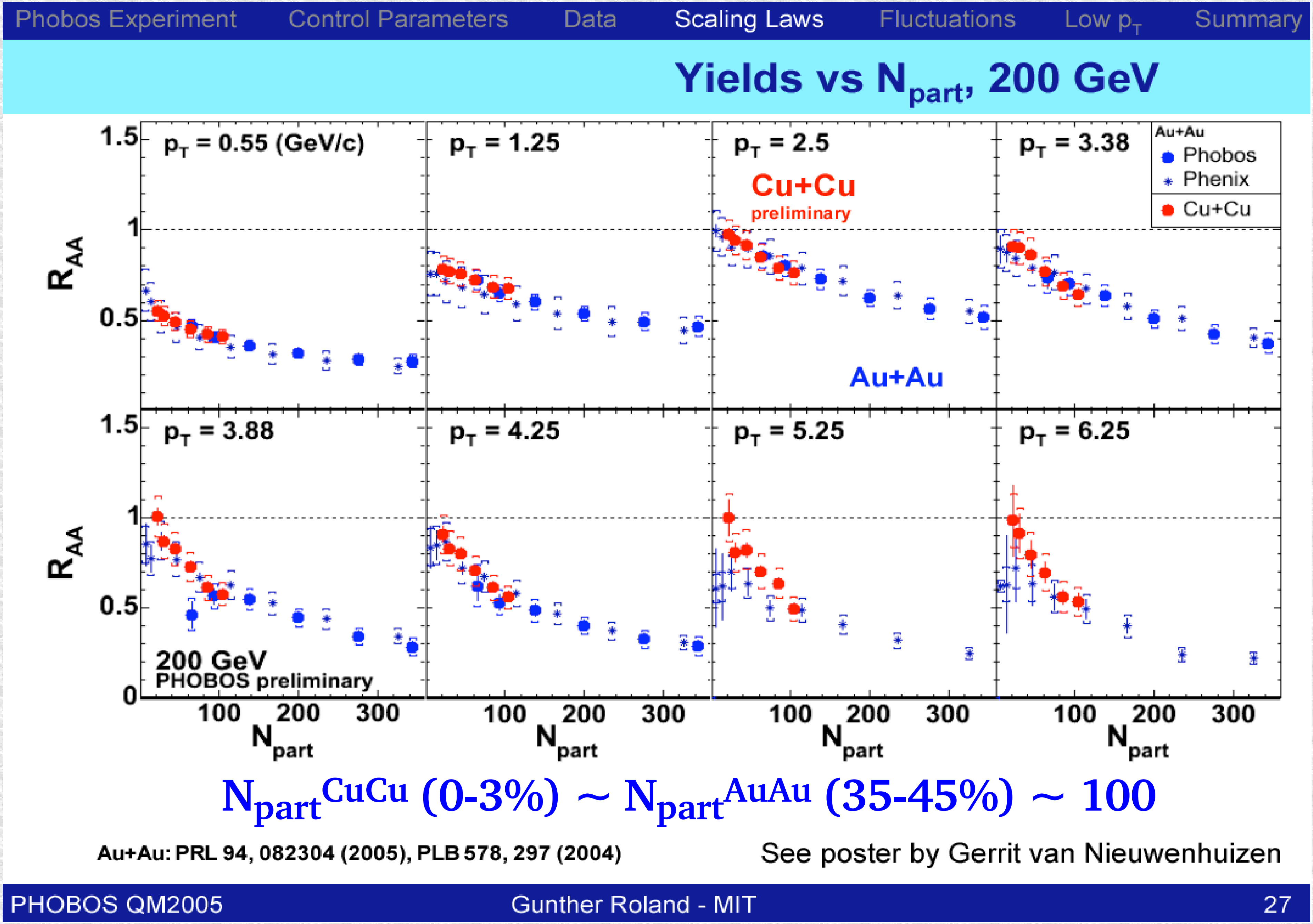


- Montecarlo simulations [Dainese et al.]





# Challenges 3: surface emission



## Yields vs $N_{part}$, 200 GeV

$N_{part}^{CuCu}$ (0-3%) ~ $N_{part}^{AuAu}$ (35-45%) ~ 100

Au+Au: PRL 94, 082304 (2005), PLB 578, 297 (2004)

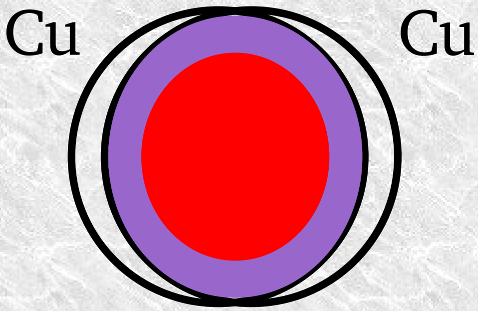
See poster by Gerrit van Nieuwenhuizen

PHOBOS QM2005 Gunther Roland - MIT 27

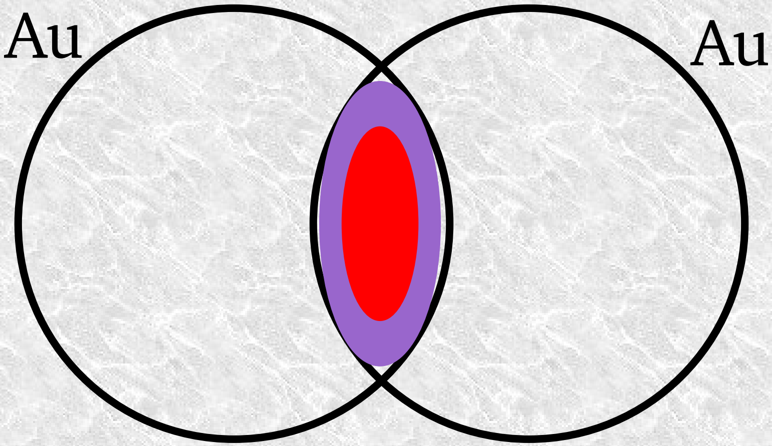
# Challenges 3: surface emission

- But… **Cu+Cu should quench more than Au+Au!**

$$(S/V)_{CuCu} < (S/V)_{AuAu}$$



$N_{part}^{CuCu}$ (0-3%) ~ 100

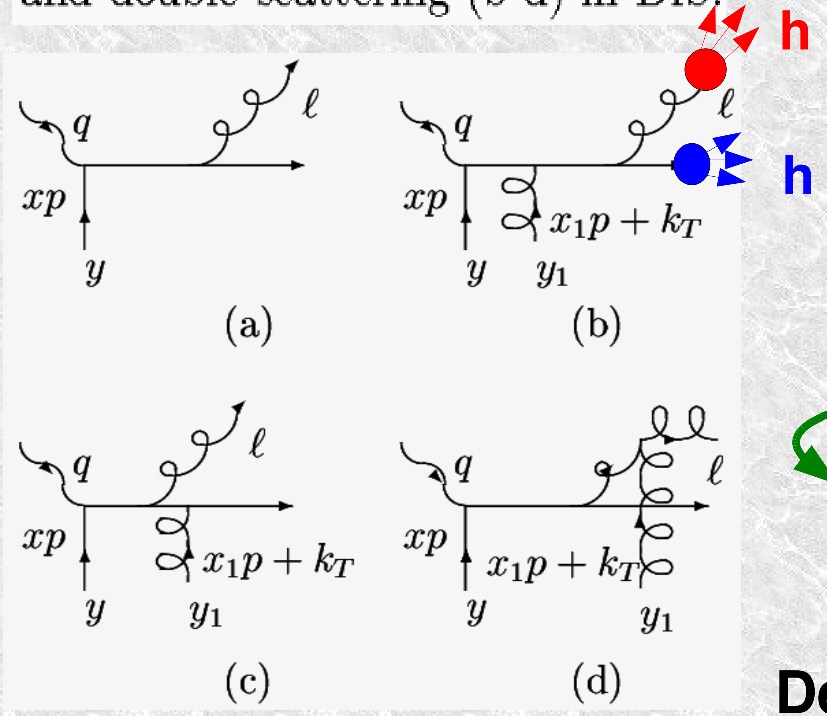


$N_{part}^{AuAu}$ (35-45%) ~ 100

# Twist-4 effects: quark rescattering and gluon bremsstrahlung

**Guo-Wang '00, Wang-Wang '02**

Gluon radiation from a single scattering (a) and double scattering (b-d) in DIS.



- Soft gluon emission
- quark rescattering + induced radiation

$$\tilde{D}_{q\to h}(z_h,Q^2) \equiv D_{q\to h}(z_h,Q^2) + \Delta D_{q\to h}(z_h,Q^2)$$

**LO**

**NLO + twist-4**

$$= \int_0^{Q^2} \frac{d\ell_T^2}{\ell_T^2}\frac{\alpha_s}{2\pi}\int_{z_h}^1 \frac{dz}{z}\Big[\Delta\gamma_{q\to qg}(z,x,x_L,\ell_T^2)D_{q\to h}(z_h/z) + \Delta\gamma_{q\to gq}(z,x,x_L,\ell_T^2)D_{g\to h}(z_h/z)\Big]$$

**Def:** quark fractional energy loss

**<zg>** = average energy carried by radiated gluon

- Result effectively approximated by:

$$\tilde{D}_{a\to h}(z) \approx \frac{1}{1-\Delta z}D_{a\to h}\left(\frac{z}{1-\Delta z}\right)$$

= 0.006 @ $Q^2$ =3 GeV$^2$ **fitted to HERM**

0.013 @ $Q^2$ =40 GeV$^2$ fitted to DY

Where:

$$\Delta z_{|\,\text{Wang}} = 0.6\,\langle z_g\rangle \propto A^{2/3}\,\overbrace{\alpha_s^2(Q^2)\,\tilde{C}(Q^2)}\,\frac{1}{\nu}\ln\left(\frac{m_N\nu}{Q^2}\right)$$

# An absorption+transport model for Au+Au

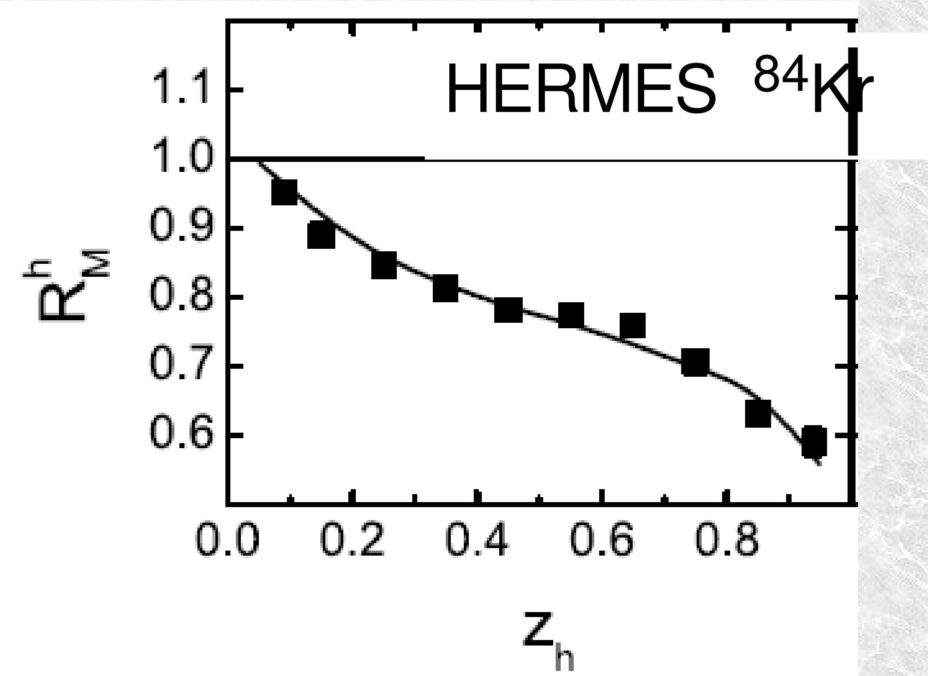
Falter et al., PRC 70(04)054609

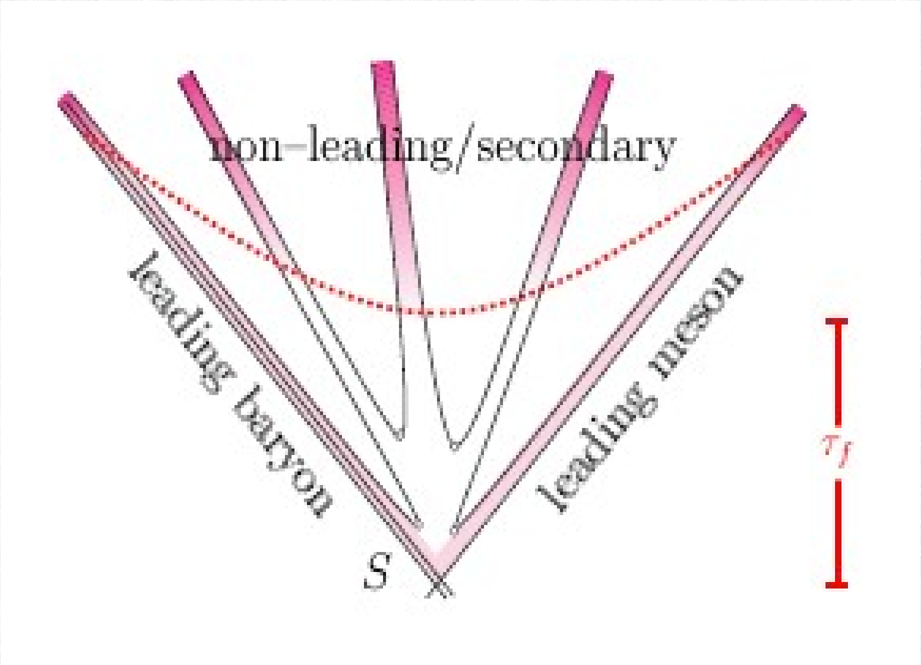
- Formation times: $t_* = 0$ fm and $t_h = (E_h/m_h)\,\tau_F$ with $\tau_F = 0.5$ fm

  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

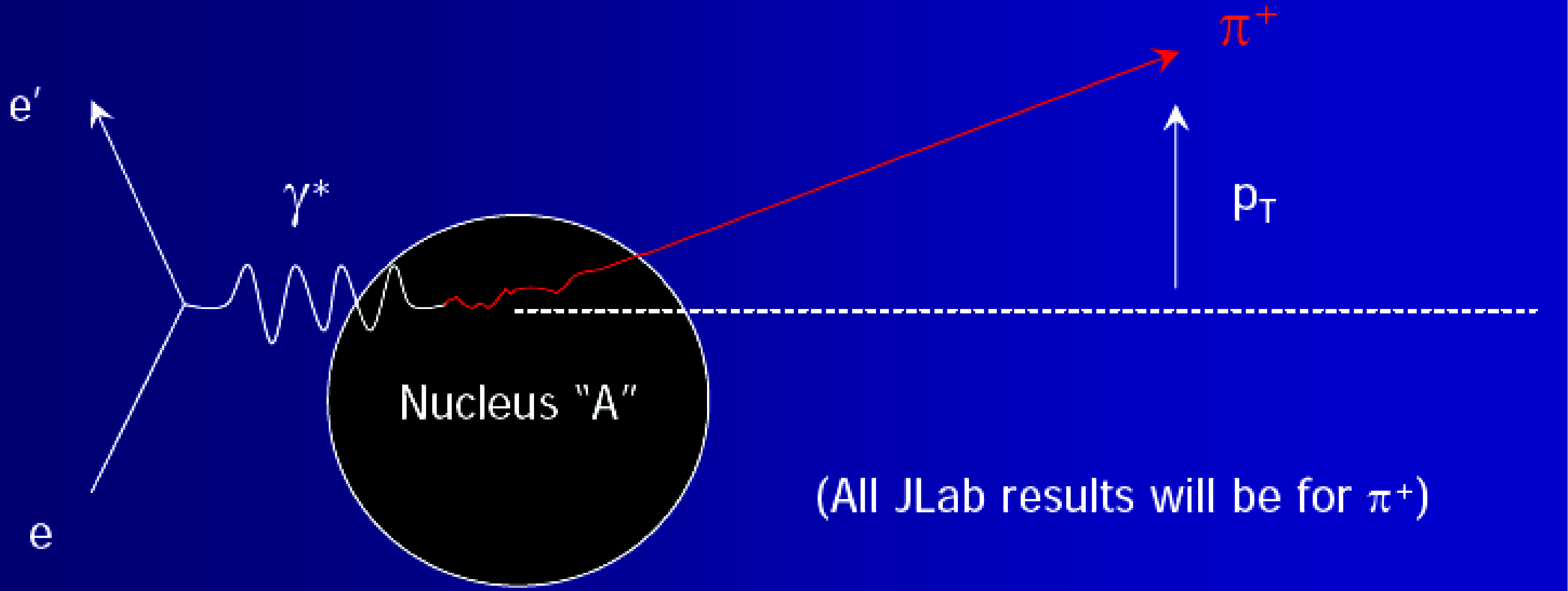




# Observable Number 1 – “$p_T$ Broadening”

Definition of “Transverse Momentum Broading”

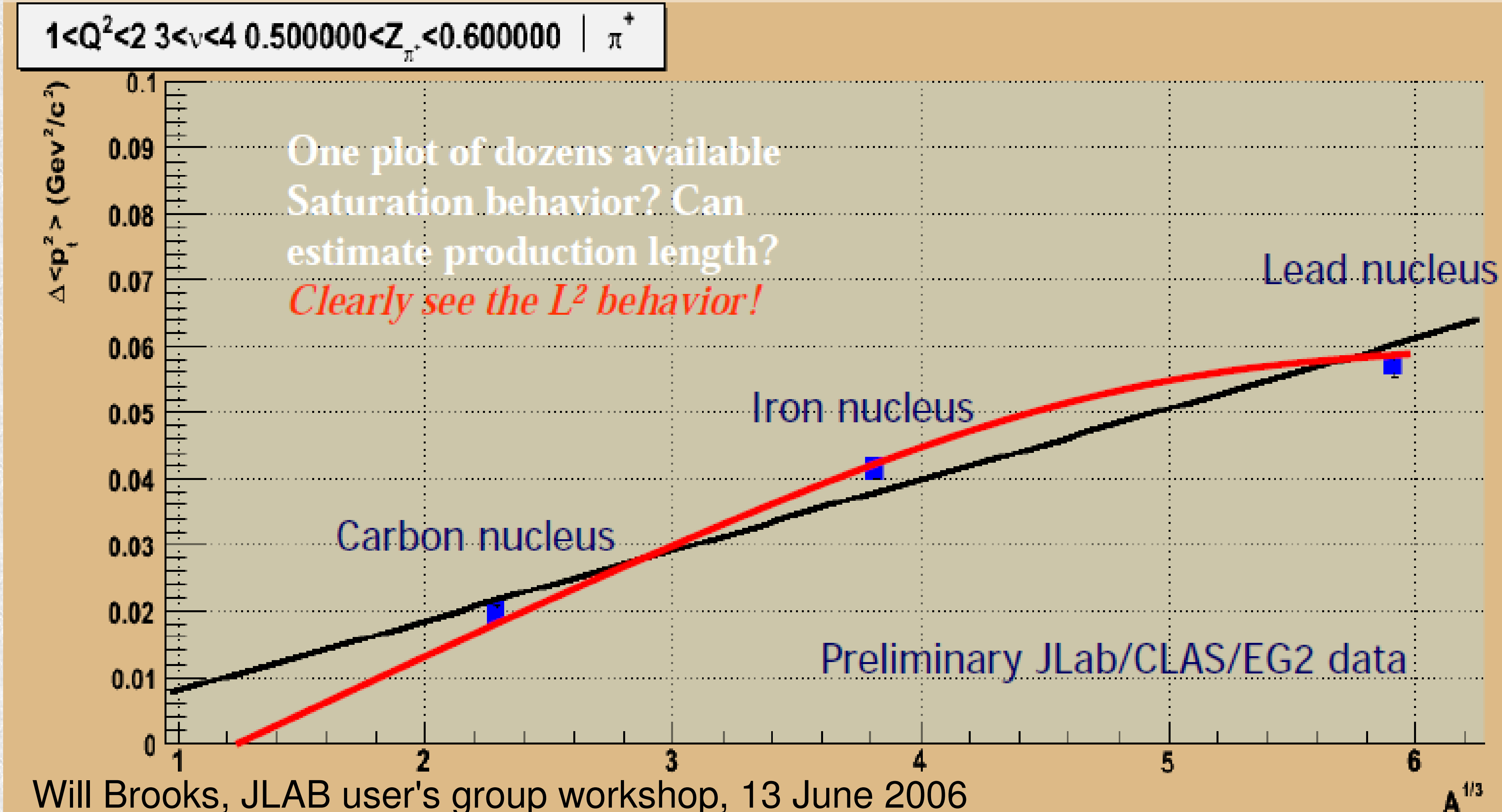
$$\Delta(p_T^2) = p_T^2(A) - p_T^2(^2H)$$



(All JLab results will be for $\pi^+$)

# $p_T$ broadening: "A" dependence, large ν, mid-z, $\pi^+$

- Transverse momentum broadening vs. nuclear radius is ~linear



One plot of dozens available

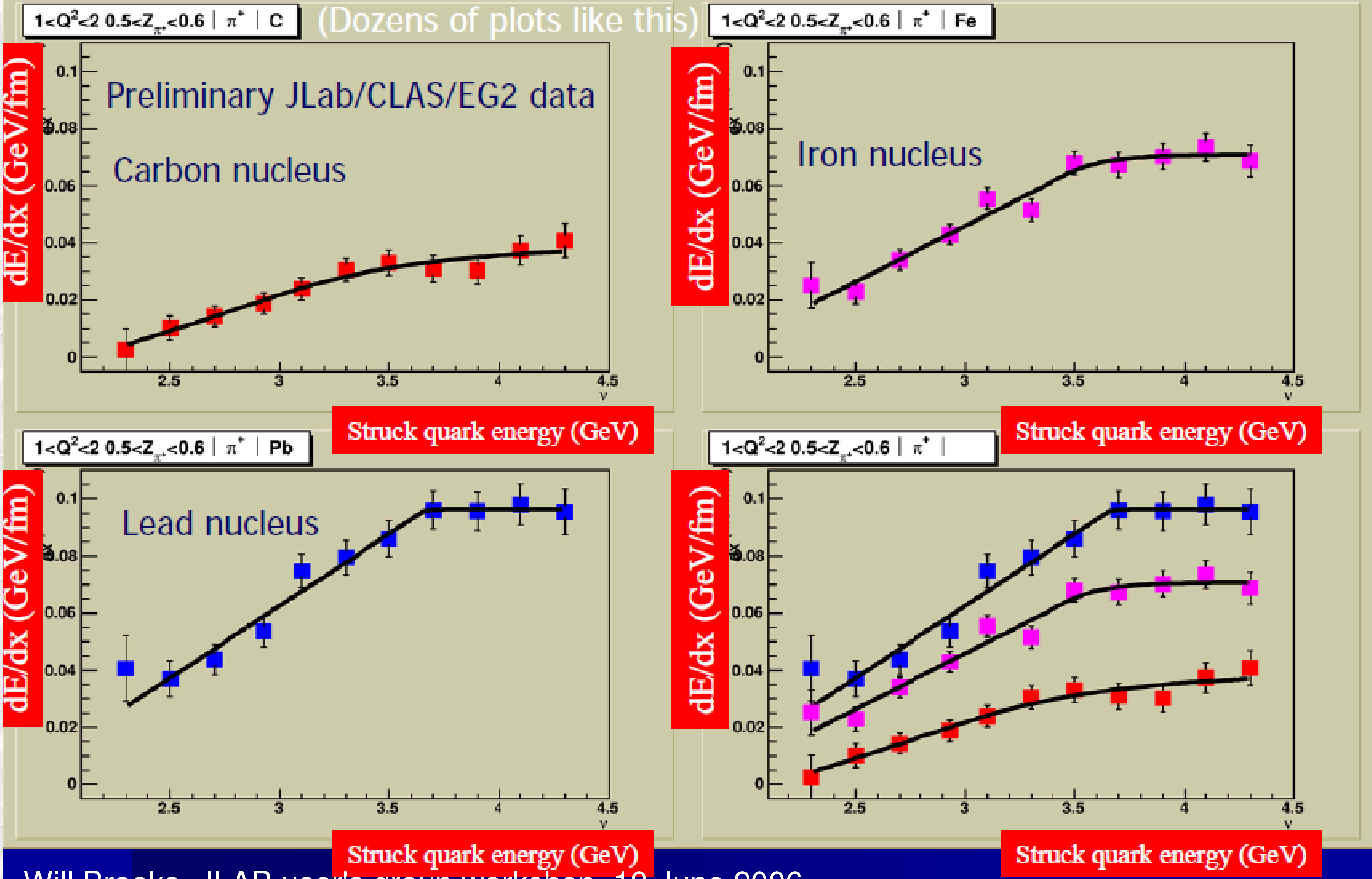
Saturation behavior? Can estimate production length?

*Clearly see the $L^2$ behavior!*

# Medium-Induced Quark Energy Loss

## *assuming perturbative formula* $dE/dx \approx \frac{\alpha_s}{\pi} N_c \langle p_T^2 \rangle_L$

(Dozens of plots like this)



Will Brooks, JLAB user's group workshop, 13 June 2006