Parton propagation and hadronization at the EIC

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Hampton U. & Jlab

ENC/EIC workshop
GSI, 28-30 May 2009

Jefferson Lab

Outline

- **Physics motivations**

- **Parton propagation and fragmentation**

- **How long is parton lifetime?**

  - selected HERMES data

- **Perspectives**
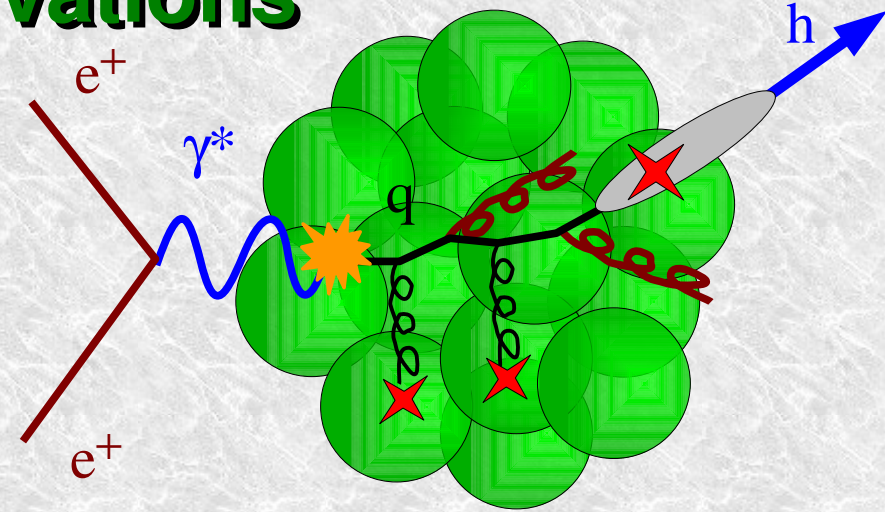
  - EIC, COMPASS, ENC

- **Conclusions**

Review soon to appear:

Accardi, Arleo, Brooks, d'Enterria, Muccifora
"Parton propagation and hadronization in QCD matter"

Physics motivations

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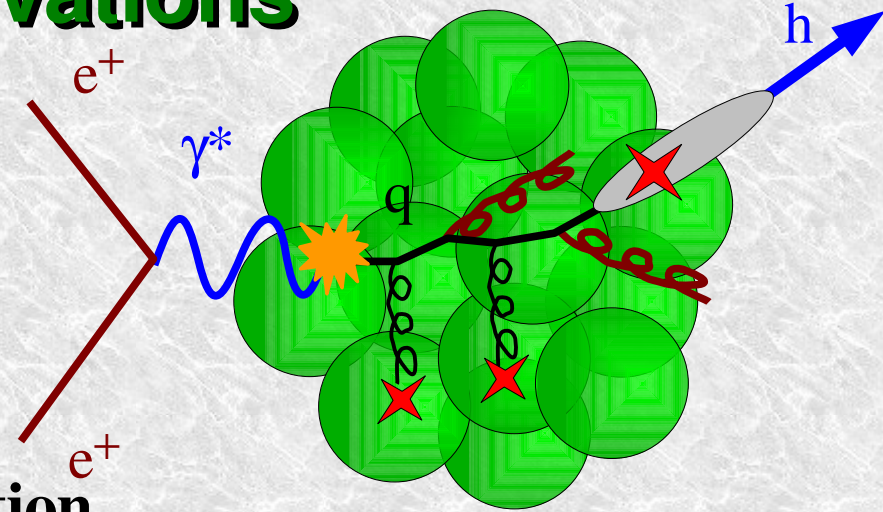- low final-state multiplicity

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Non perturbative aspects of hadronization
- approaching microscopic understanding of Fragmentation Functions
- how do partons dress up? Space-time evolution of hadronization
- color confinement dynamics

e^+

γ^*

q

h

Physics motivations

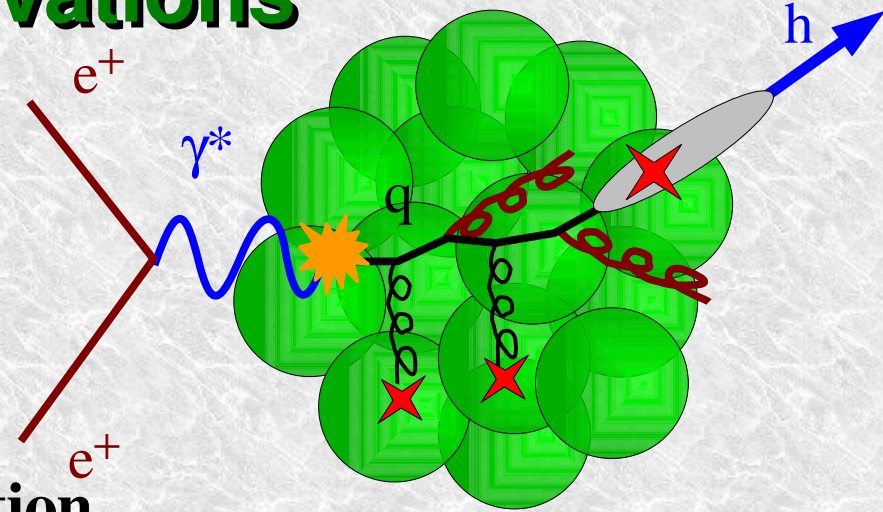- **Nuclei as space-time analyzers**
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- **Parton propagation in perturbative QCD**
  - QCD energy loss: basic pQCD, only indirectly tested so far
  - DGLAP parton showers

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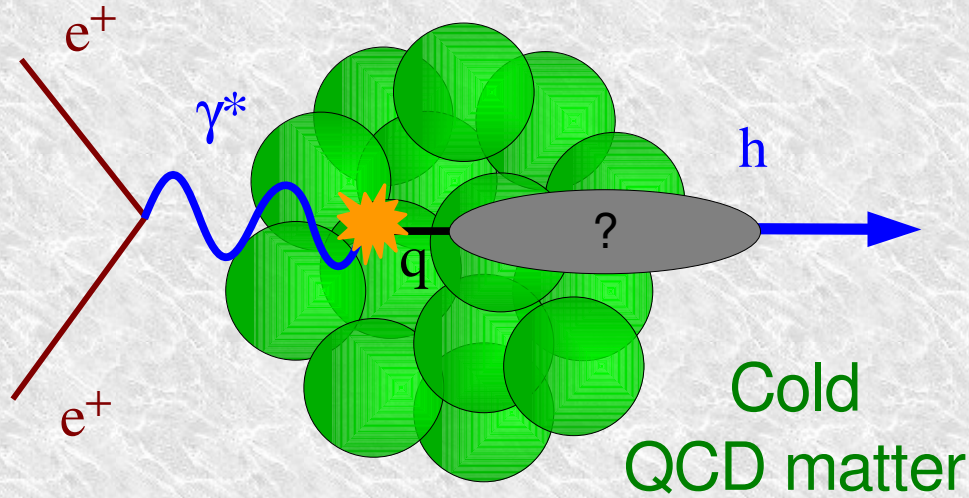- **Parton propagation in perturbative QCD**
  - QCD energy loss: basic pQCD, only indirectly tested so far
  - DGLAP parton showers

- **Connection to other fields**
  - Calibration of jet-quenching in A+A $\Rightarrow$ properties of QGP
  - Tuning of parton showers in Monte-Carlo generators
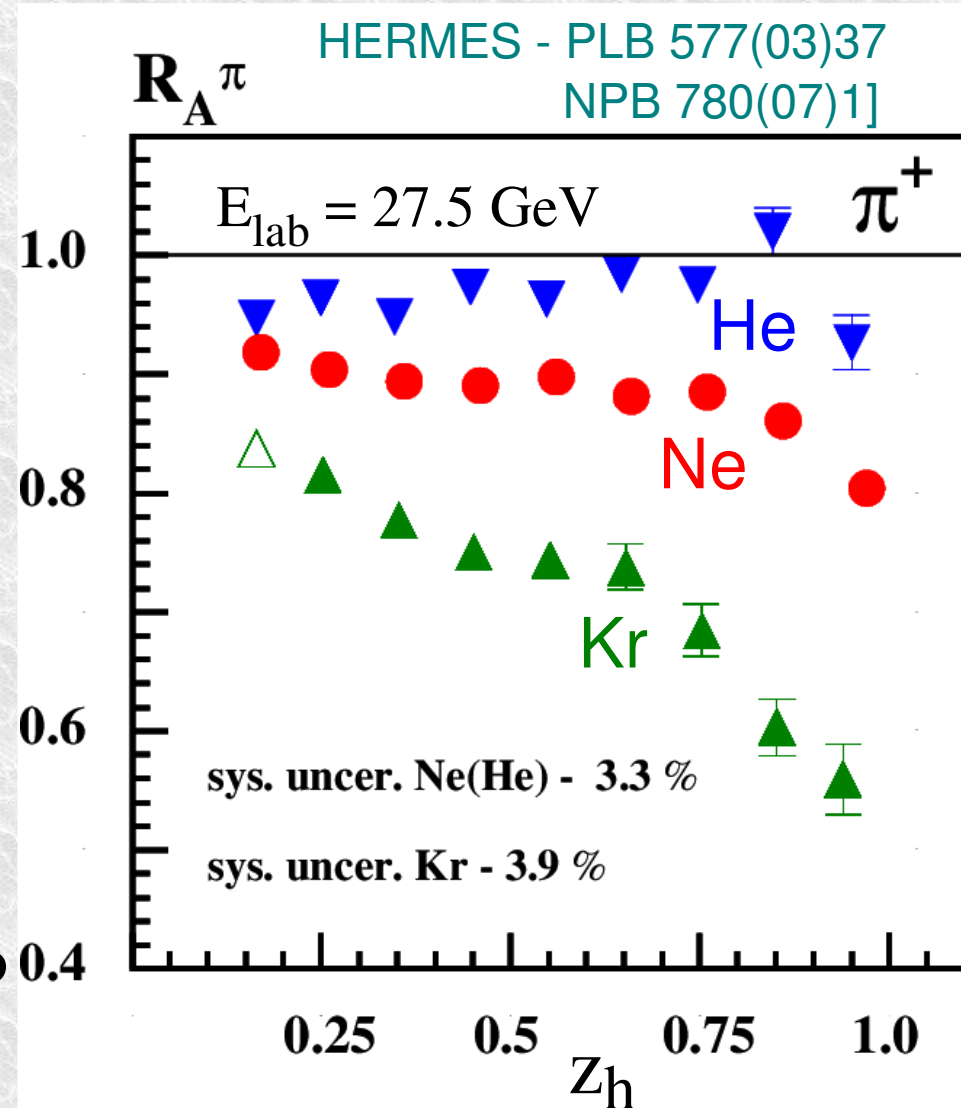 - Hadron attenuation corrections for ν-oscillation experiments
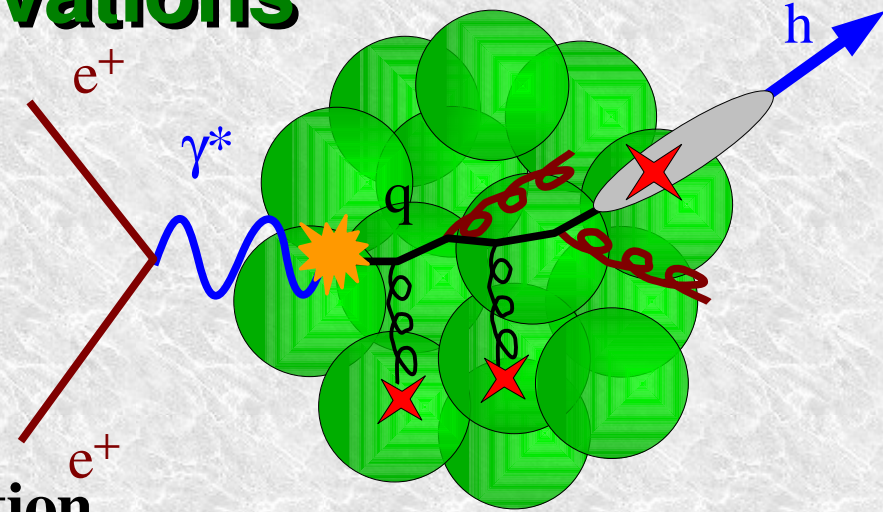
Nuclear collisions 1 - nDIS

$$R_M^h(z_h) = \frac{\dfrac{1}{N_A^{\mathrm{DIS}}}\dfrac{dN_A^h(z_h)}{dz_h}}{\dfrac{1}{N_D^{\mathrm{DIS}}}\dfrac{dN_D^h(z_h)}{dz_h}} \approx \frac{D_A(z)}{D_D(z)}$$

Cold
QCD matter

HERMES - PLB 577(03)37
NPB 780(07)1]

$E_{lab} = 27.5$ GeV

R_A^π

π^+

He

Ne

Kr

sys. uncer. Ne(He) - 3.3 %

sys. uncer. Kr - 3.9 %

🔹 Nuclear effects on PDF "cancel" in ratio
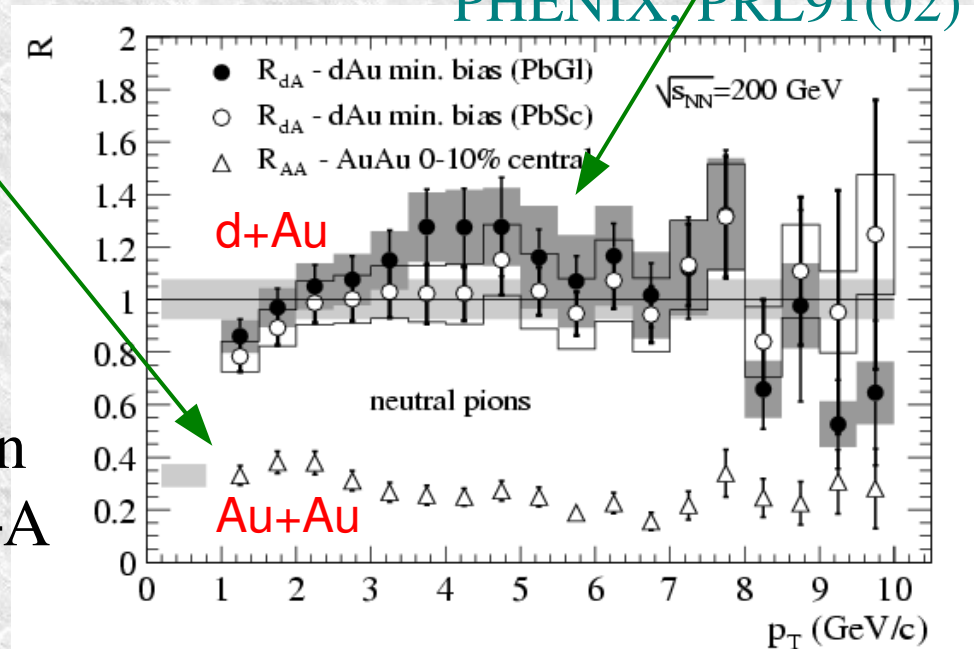🔹 Exposes modifications of hadronization

$R_M < 1 \Rightarrow$ hadron attenuation in cold nuclear matter
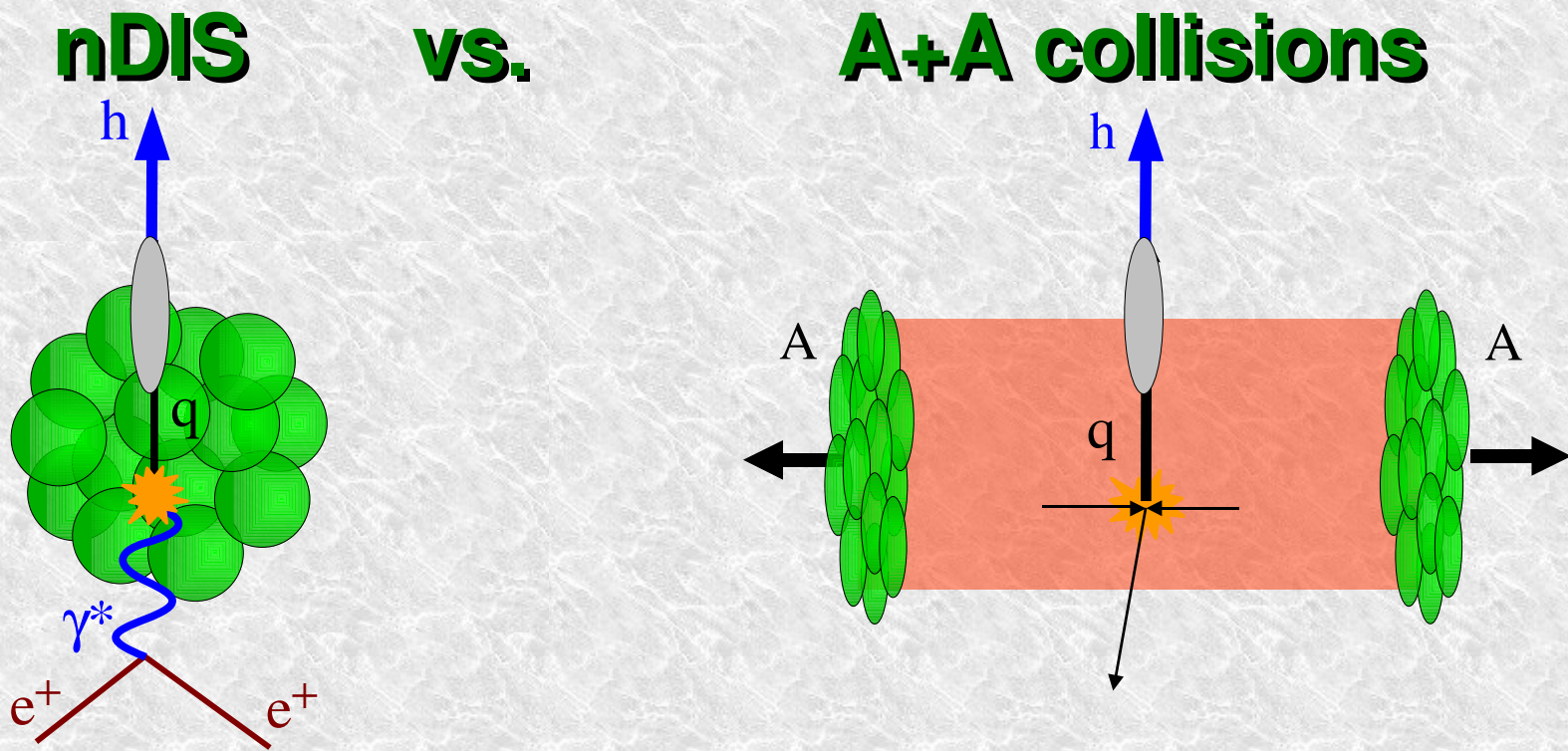
Nuclear collisions 2 – Heavy ion collisions

Hot QCD matter
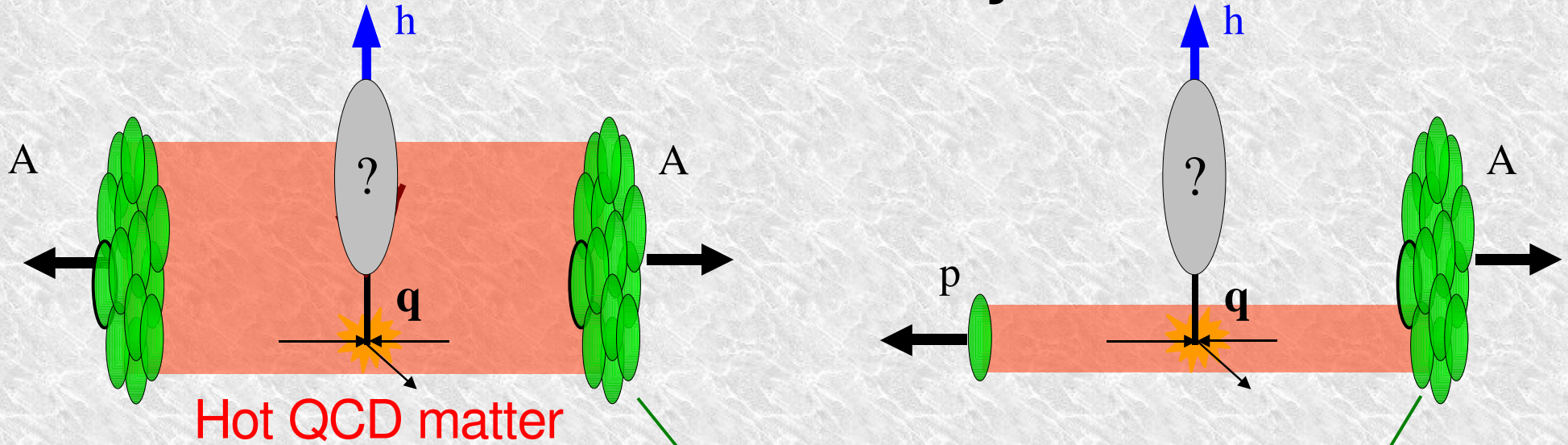
PHENIX, PRL91(02)

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

◆ 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

nDIS   vs.   A+A collisions

nDIS is a clean environment for

(1) **space-time evolution of hadronization**
- nucleons as femto-detectors
- medium rather well known

(2) **Cold nuclear matter effects**
- quark energy loss
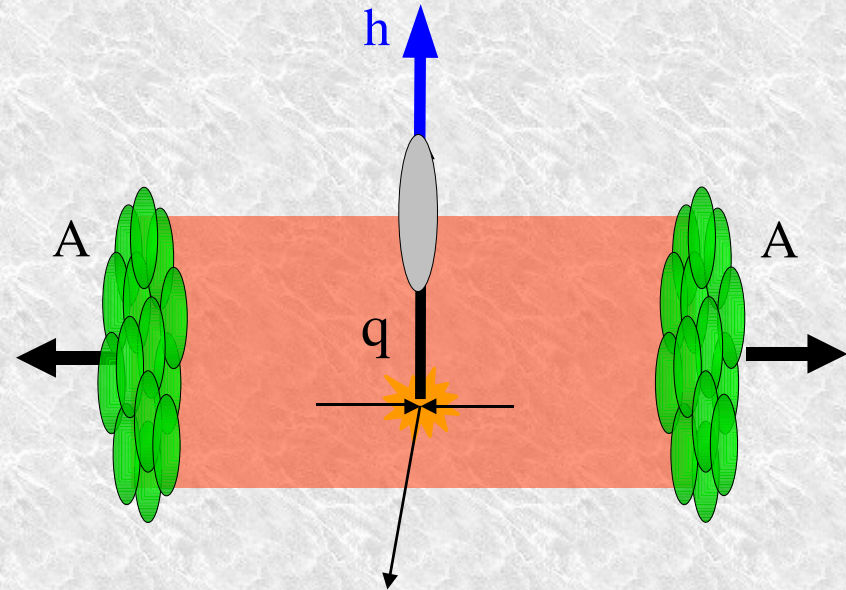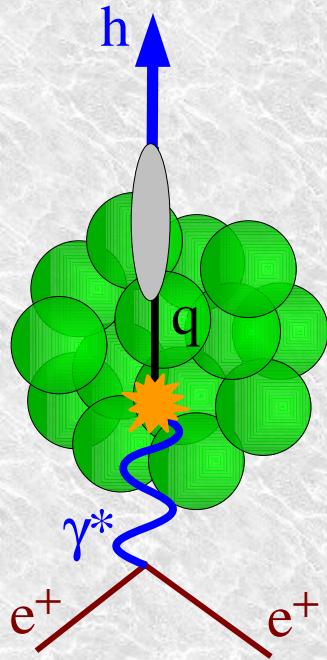- nuclear modifications of FF
- parton showers

Jet-quenching in A+A

⇓

properties of hot nuclear matter

nDIS   vs.   A+A collisions

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

at HERMES/Jlab

$E_h = z_h \nu \approx$ **2 - 20 GeV**

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

$E_q = p_{Th} / z$

$E_h = p_{Th} \approx$ **2 - 20 GeV**

$Q^2 \propto E_q^2 = (p_T/z)^2$ is not

HERMES/JLAB is relevant to RHIC mid-rapidity

...but beware the virtuality: ≈ 2 GeV^2 vs. $O(100)$ GeV^2 !!

Parton propagation and fragmentation

see:
– <u>A.A.</u>, EPJC 2007, mini review
– <u>A.A.</u> **et al, full review soon to appear**
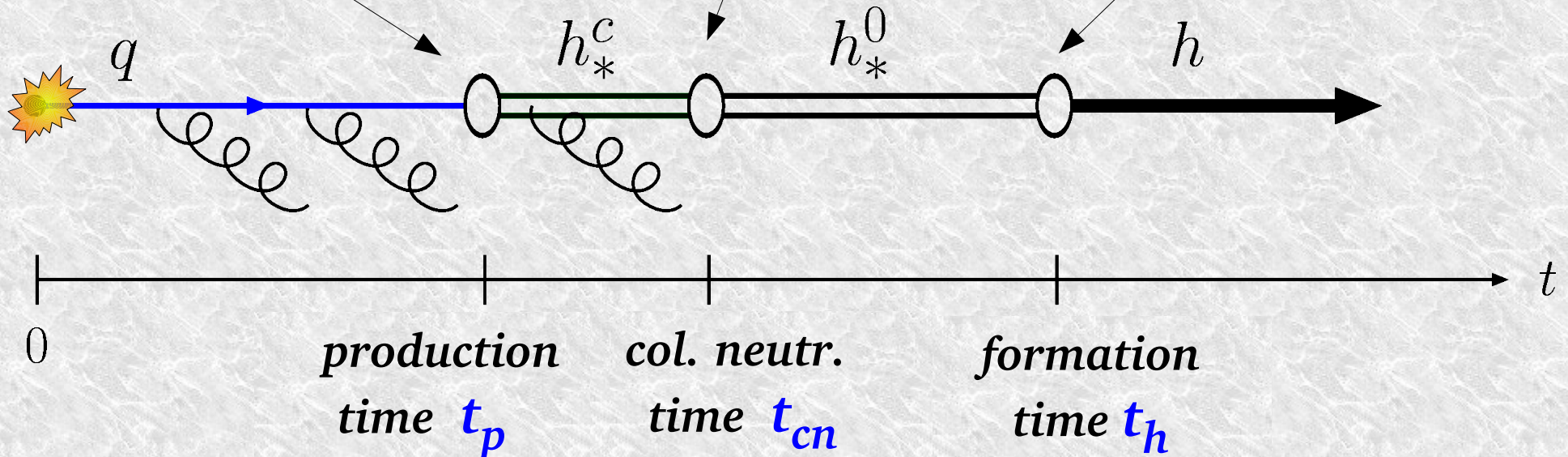
The (naïve) framework : quark, prehadron, hadron

◆ Hadronization is non perturbative $\Rightarrow$ (many) models

◆ General features:

Colored "prehadron":
large inelastic cross-sect.

Color neutralization:
gluon radiation stops

prehadron collapses on
hadron's h wavefunction

$q \quad h_*^c \quad h_*^0 \quad h$

$0 \qquad$ *production* $\qquad$ *col. neutr.* $\qquad$ *formation*
$\qquad$ *time* t_p $\qquad$ *time* t_{cn} $\qquad$ *time* t_h $\qquad t$

◆ *Caveats:*

➡ It's tricky to define t_p, t_{cn}, t_h: working tools – simplify: $t_p = t_{cn}$

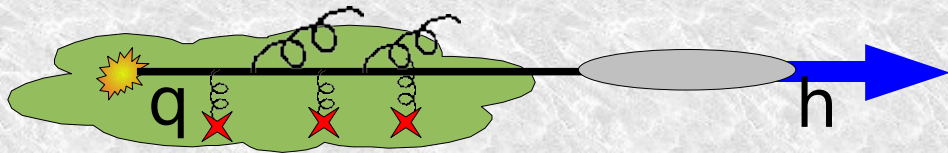➡ Leading-order pQCD mindset ($\gamma^* + q \rightarrow q$), but NLO may be large

Hadron attenuation in nDIS

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

Energy loss (gluon bremsstrahlung)
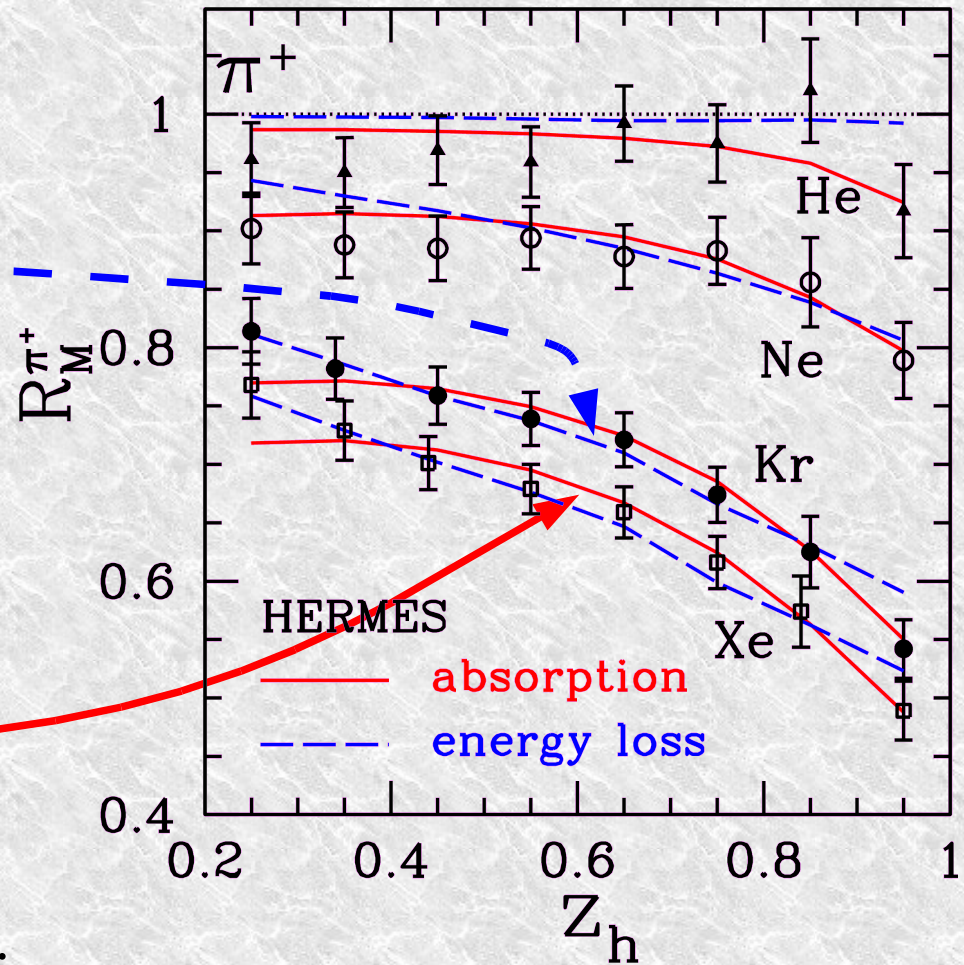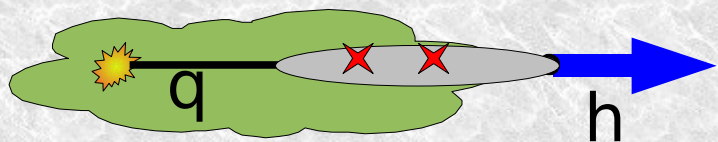
[Arleo; Wang *et al.*; Accardi]

➡ 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
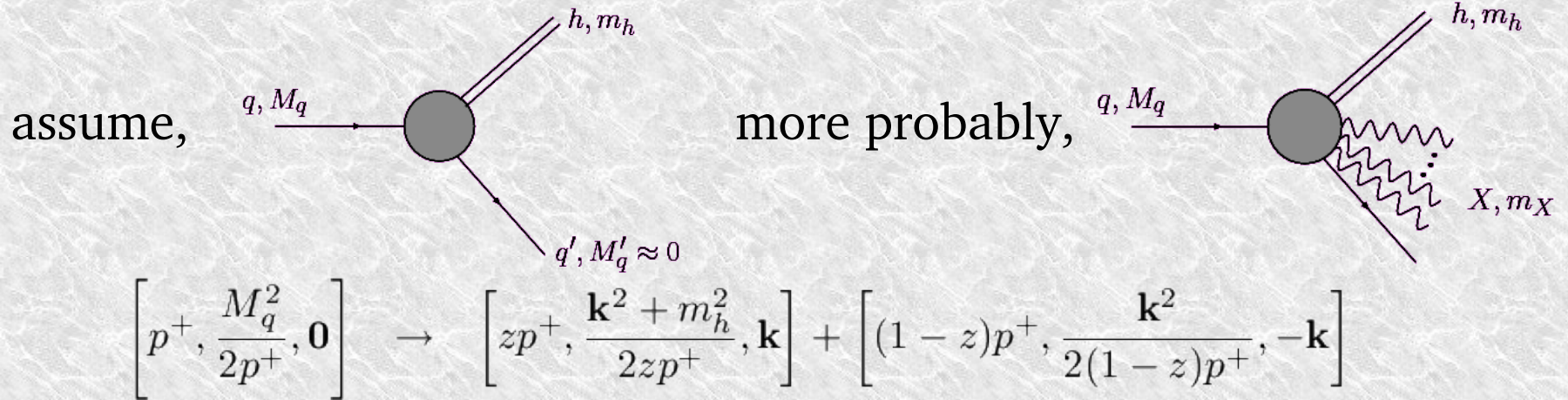
➡ prehadron-nucleon scatterings

π^+

He
Ne
Kr
Xe

HERMES
— absorption
-- energy loss

[A.A., et al., NPA 761(05)67]
[A.A., Acta.Phys.Hung. '06 & PRC '07]

Parton lifetime 1 – pQCD estimate

- pQCD estimate [see Vitev, Adil '07]

assume, q, M_q $\to$ h, m_h ; $q', M_q' \approx 0$

more probably, $q, M_q \to h, m_h$; X, m_X

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

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

	π	K	η	p	D	B
HERMES ($\nu \sim 13$ GeV, $z \sim 0.5$)	28 fm	9 fm	7 fm	3 fm	0.8 fm	0.1 fm
RHIC ($p_T^h \sim 7$ GeV $z \sim 0.7$)	18 fm	7 fm	6 fm	3 fm	0.8 fm	0.1 fm

~ inside the medium !!

- Large π formation time, used in en. loss models to justify assumptions

Parton lifetime 2 – Lund model

* Inside-out cascade [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 computable

$$\begin{cases} \langle t_p \rangle = f(z_h)(1-z_h)\dfrac{z_h\nu}{\kappa} \\ \langle t_h \rangle = \langle t_p \rangle + \dfrac{z_h\nu}{\kappa} \end{cases}$$
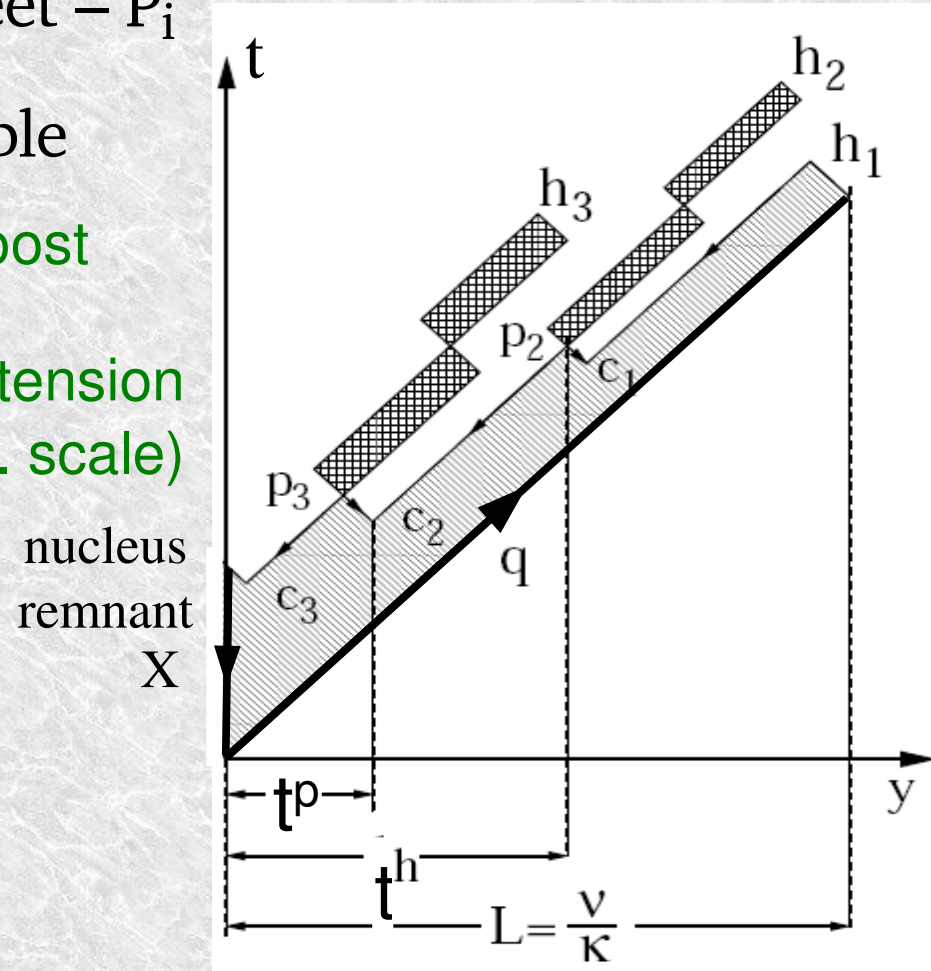
boost ←

string-tension (non pert. scale)

energy conservation

nucleus remnant X

- <u>At large z → 1</u>
  $E_h \to \nu \Rightarrow$ string breaks early to leave all energy to the hadron: $\langle t_p \rangle \to 0$

- <u>At small z → 0</u>
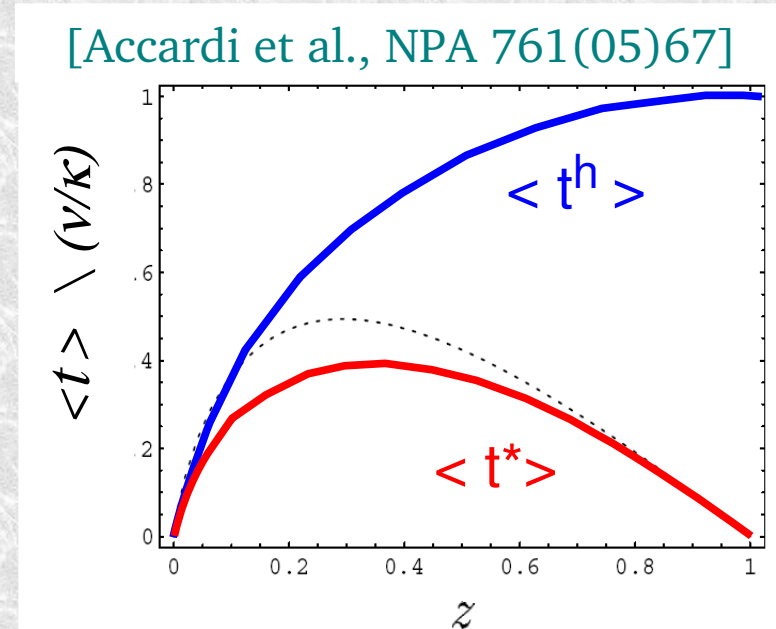 hadron created at high rank after many string breakings: $\langle t_p \rangle \to 0$

(see also GiBUU model later on in the talk)

Formation time estimates 2 – Lund model

$$
\begin{cases}
\langle t_p \rangle = f(z_h)(1 - z_h)\dfrac{z_h \nu}{\kappa} \\[2ex]
\langle t_h \rangle = \langle t_p \rangle + \dfrac{z_h \nu}{\kappa}
\end{cases}
$$

[Accardi et al., NPA 761(05)67]

- ✱ For a $\nu = 14$ GeV pion at Hermes,

$$
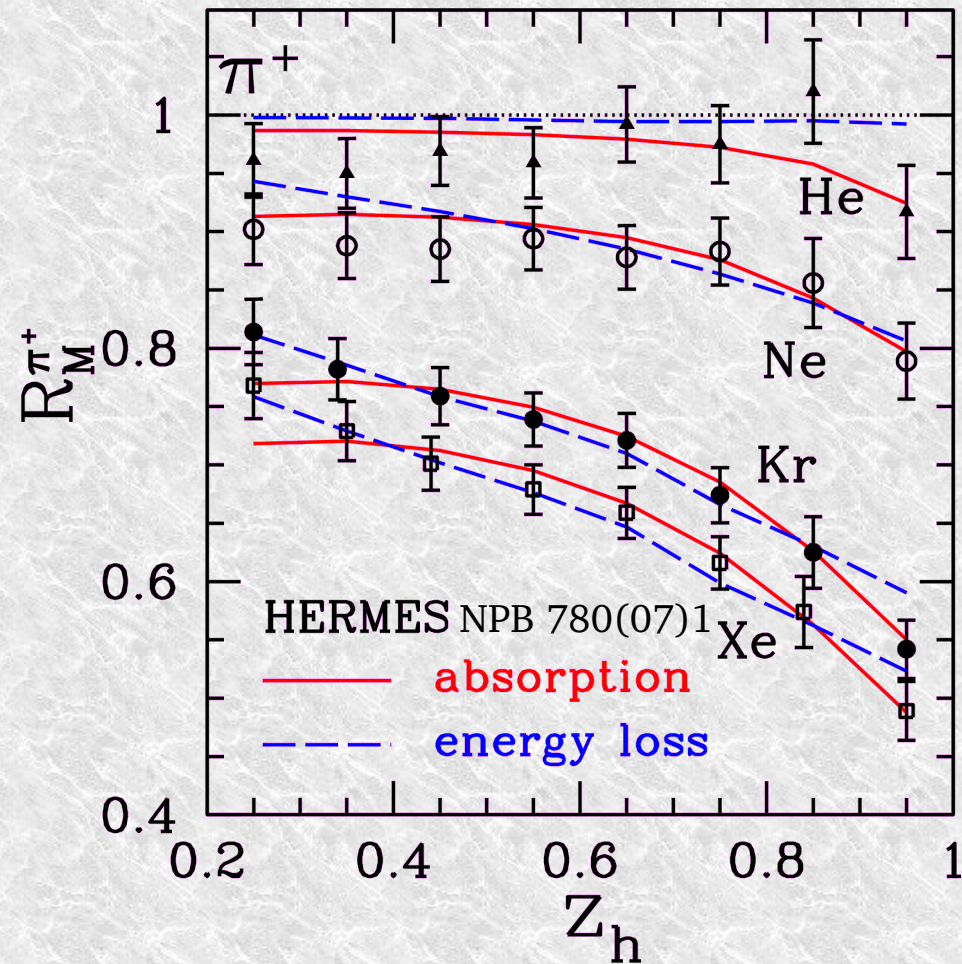\langle t_p \rangle \lesssim 5 \text{ fm} \quad \langle t_h \rangle \sim 10 \text{ fm} > R_A
$$

- ➜ **shorter time scales than in pQCD estimates**

- ✱ Full fledged hadrons behave as expected: $\langle t_h \rangle \sim \dfrac{R_h}{m_h} z_h \nu$

(see also GiBUU model later on in the talk)

How long is the quark lifetime?

1) Hadron quenching vs. z_h

Red: absorption model
$$(\sigma_p = 0.65\,\sigma_h)$$
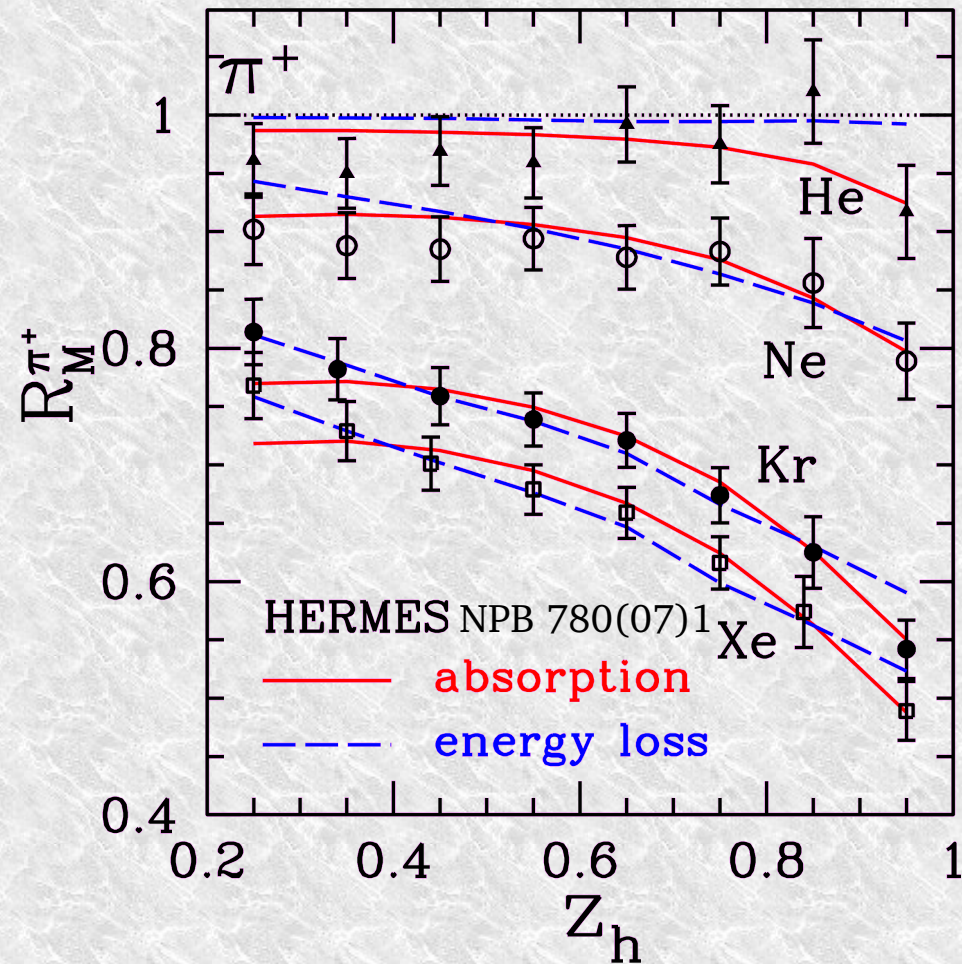
[A.A., et al., NPA 761(05)67]

Blue: energy loss model
with SW quenching weights
$$(\hat{q} = 0.6\ \text{GeV}^2/\text{fm})$$

[A.A., Acta.Phys.Hung. '06 & PRC '07]

**Both describe the data:
no info on parton lifetime**

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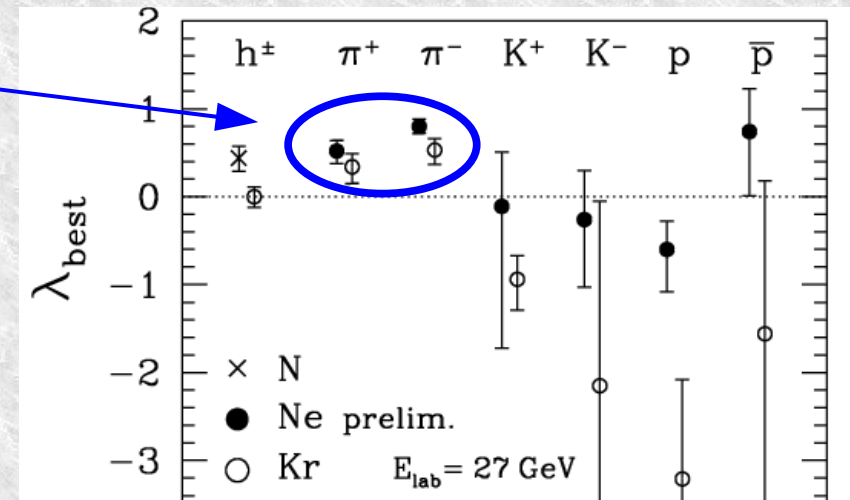# 2) Scaling of R_M [A.A., PLB B649 (07) 384]

⬥ $\mathbf{R_M}$ should scale with $\boldsymbol{\tau = \tau(z_h, \nu)}$ not with z and ν separately

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

⬥ "Scaling exponent" λ can distinguish absorption and energy-loss

absorption models: $\lambda > 0$
[short hadron formation time]

energy loss models: $\lambda \lesssim 0$
[from energy conservation]

Hadronization starts inside the nucleus!

3) p_T – broadening [A.A., nucl-th/0808.0656]

$$\Delta\langle p_T^2\rangle = \langle p_T^2\rangle_A - \langle p_T^2\rangle_D$$

Assume very long production times: pure energy loss models

$$\langle\Delta p_T^2\rangle \approx \hat{q}L \approx \hat{q}\times\frac{3}{4}R_A$$

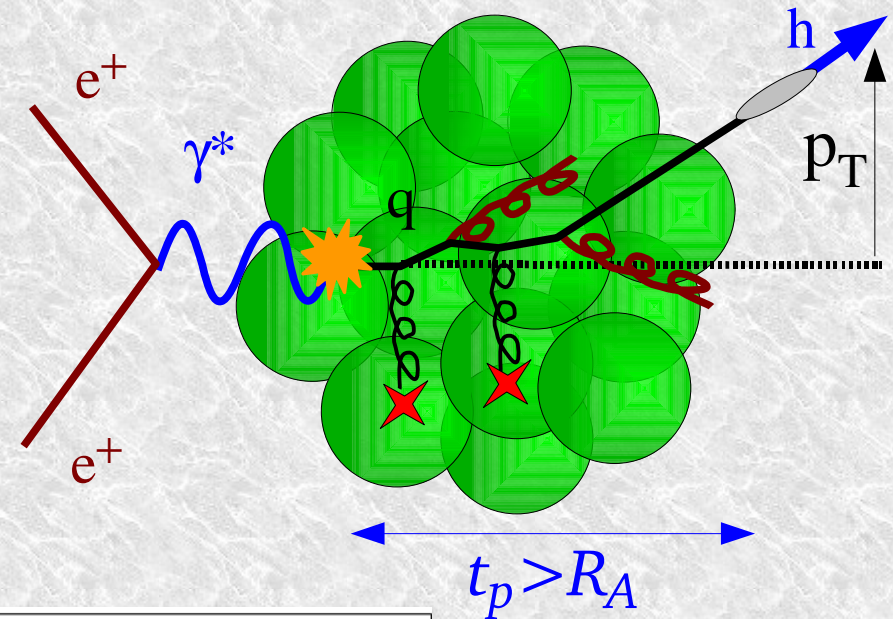Use the extracted

$$\hat{q} = 0.6 \text{ GeV}^2/\text{fm}$$

e^+

γ^*

q

h

p_T

$t_p > R_A$

Obtain too large broadening!!

	$\langle\Delta p_T^2\rangle$
Ne	1.4 GeV^2
Kr	2.2 GeV^2
Xe	2.6 GeV^2

HERMES preliminary

π^+
π^-
K^+

Ne, Kr, Xe

$\Delta\langle p_t^2\rangle$ (GeV^2)

$A^{1/3}$
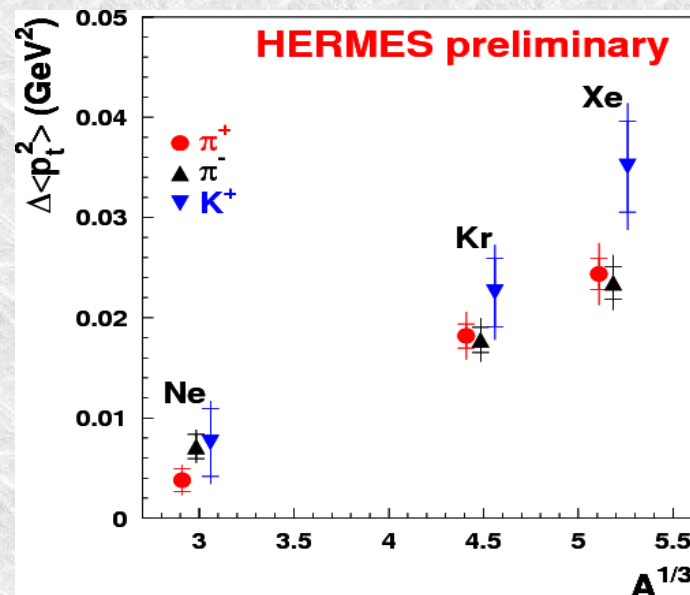
3) p_T − broadening [A.A., nucl-th/0808.0656]

Assume short t_p and no energy loss:

- In prehadron stage, no broadening: elastic scattering very small
- Incoherent partonic scattering: $\Delta\langle p_T^2\rangle$ linear in quark in-medium path

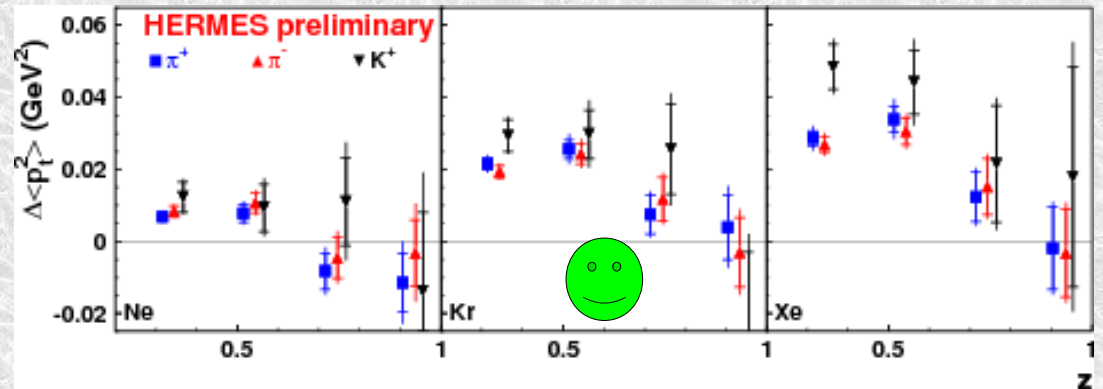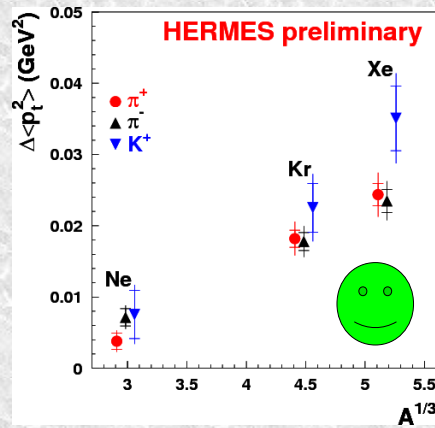$$\Delta\langle p_T^2\rangle \propto \langle t_p\rangle \approx C\, z_h^{0.5}(1-z_h)\nu$$

$$\Delta\langle p_T^2\rangle = \langle p_T^2\rangle_A - \langle p_T^2\rangle_D$$

$t_p < R_A$

- p_T-broadening should:
  1) rise with $A^{1/3}$ until $\langle t_p\rangle \sim R_A$, then level off
  2) decrease as $z_h \to 1$
  3) rise with ν, then level off
  4) possibly, decrease with Q^2 if $\langle t_p\rangle \propto \nu/Q^2$
     as claimed by Kopeliovich et al., NPA 740(04)211
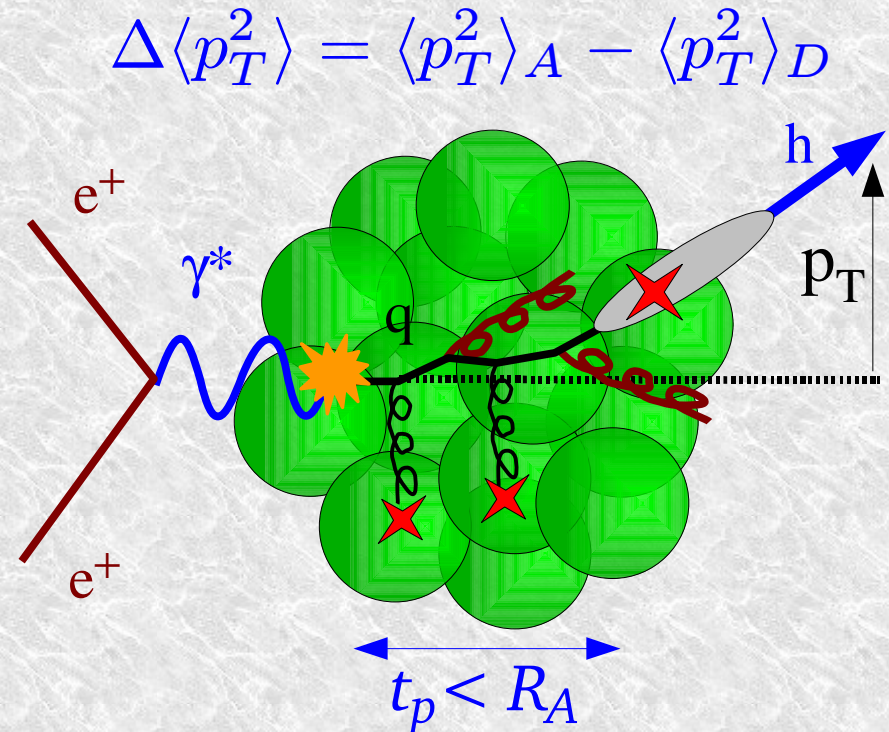
3) p_T – broadening [A.A., nucl-th/0808.0656]

◆ **Assume short t_p and no energy loss**: $\Delta\langle p_T^2\rangle \propto \langle t_p\rangle \approx C\, z_h^{0.5}(1-z_h)\,\nu$

◆ Let's assume: $\langle t_p\rangle \approx \dfrac{4}{3}R_{\mathrm{Xe}}$ at $z_h = 0.4$ $\nu = 14$ GeV

$$\Delta\langle p_T^2\rangle \propto \langle t_p\rangle \approx (0.8~\mathrm{GeV}) \times z_h^{0.5}(1-z_h)\,\nu$$

	$\langle Q^2\rangle$ [GeV^2]	ν [GeV]	$\langle z_h\rangle$	$\langle t_p\rangle$ [fm]
$\langle\Delta p_{Th}^2\rangle$ vs A				
Ne (2.3 fm)	2.4	13.7	0.42	4.2
Kr (3.7 fm)	2.4	13.9	0.41	4.2
Xe (4.3 fm)	2.4	14.0	0.41	4.3
$\langle\Delta p_{Th}^2\rangle$ vs z	2.4	14.6	0.30	4.5
	2.4	13.3	0.53	3.7
	2.3	12.6	0.74	2.3
	2.2	10.8	0.92	0.7

3) p_T – broadening [A.A., nucl-th/0808.0656]

Assume short t_p and no energy loss:

$$\Delta\langle p_T^2 \rangle \propto \langle t_p \rangle \approx 0.8\, z_h^{0.5}(1-z_h)\,\nu$$

It should:
1) rise with $A^{1/3}$, then level off ☺
2) decrease as $z_h \to 1$ ☺
3) rise with ν, then level off ❓❓
4) possibly, decrease with Q^2
   (if $p_T^2 \propto 1/Q^2$) 🚫
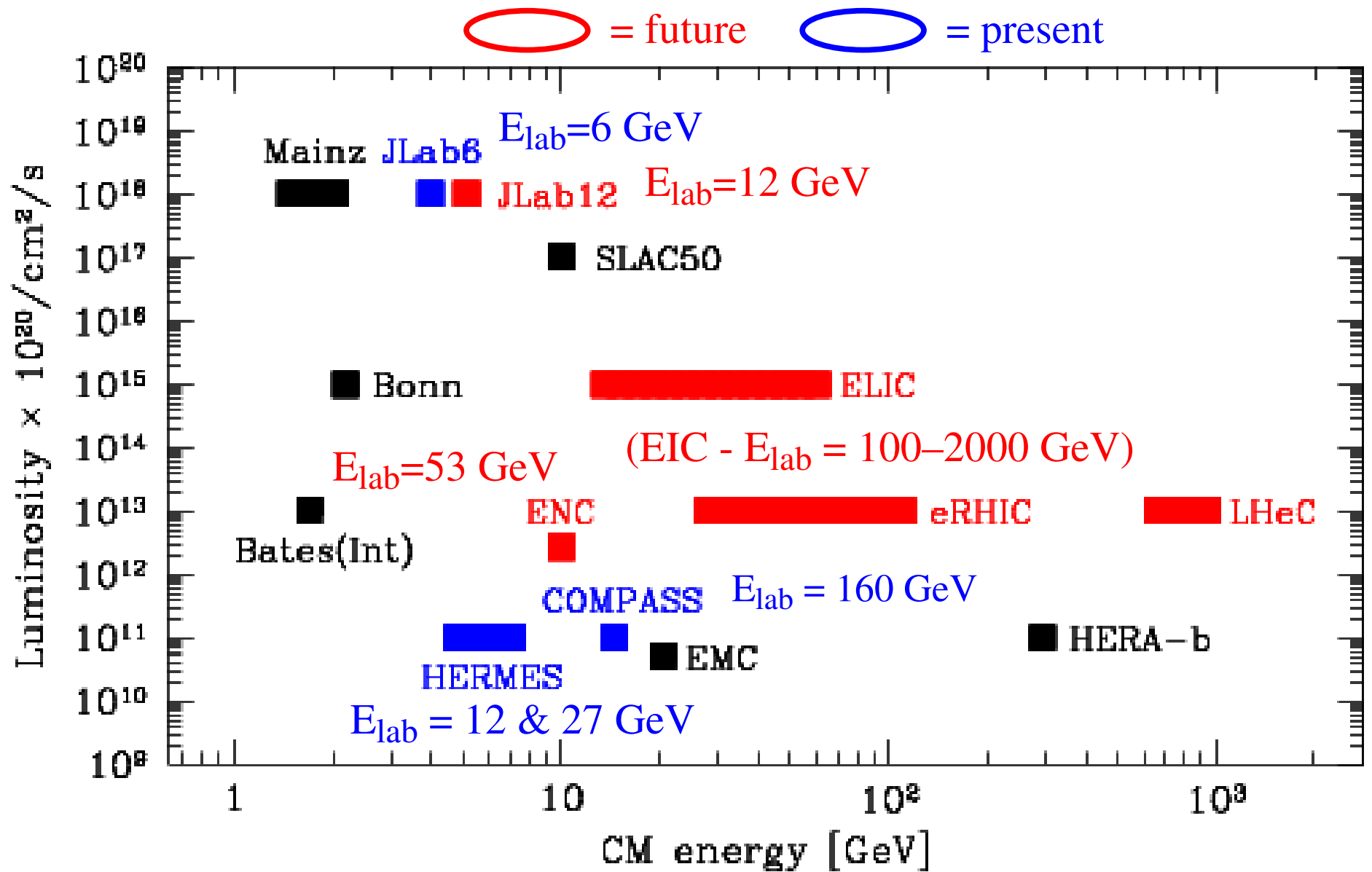
at strong variance with Kopeliovich et al.
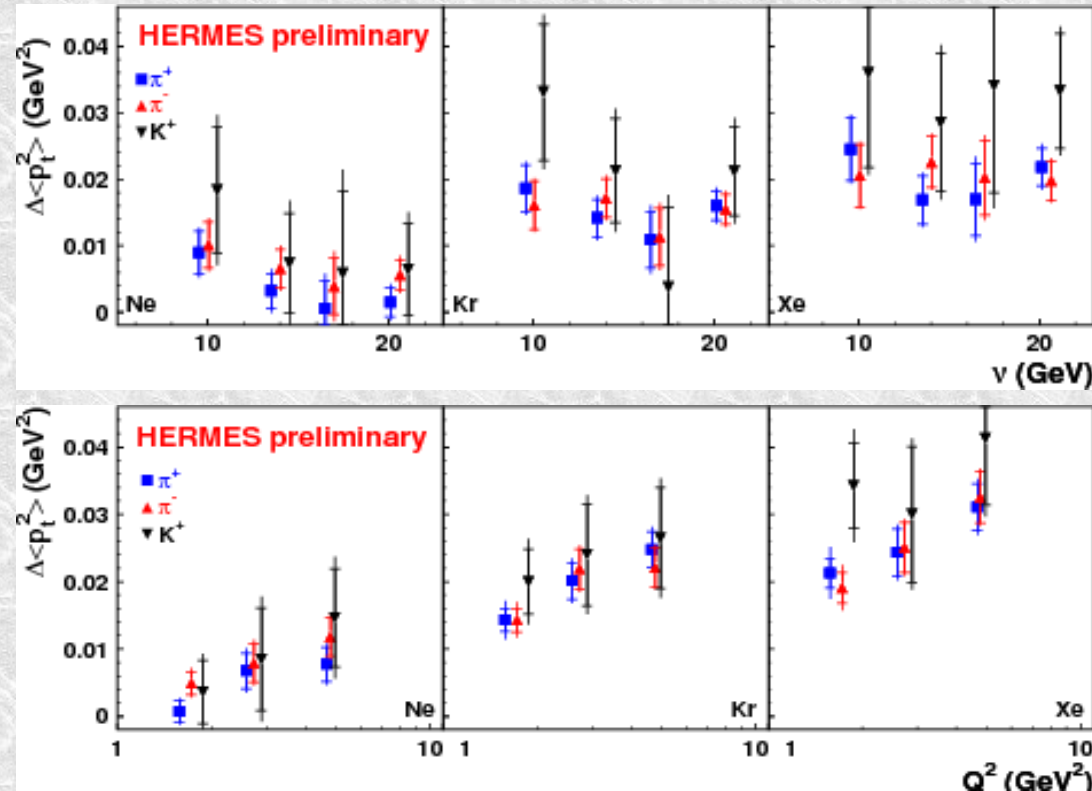
Partonic dynamics beyond production time & multi-scattering
  - modified DGLAP evolution ?
  - NLO effects ? colored dipoles ?
  - Role of virtuality ?

Perspectives

Present and future e+A facilities

EIC

The EIC

Q² (GeV²)

Polarized DIS
— Fixed target μ-DIS
---- Fixed target e-DIS
▨ EIC

(a)

X
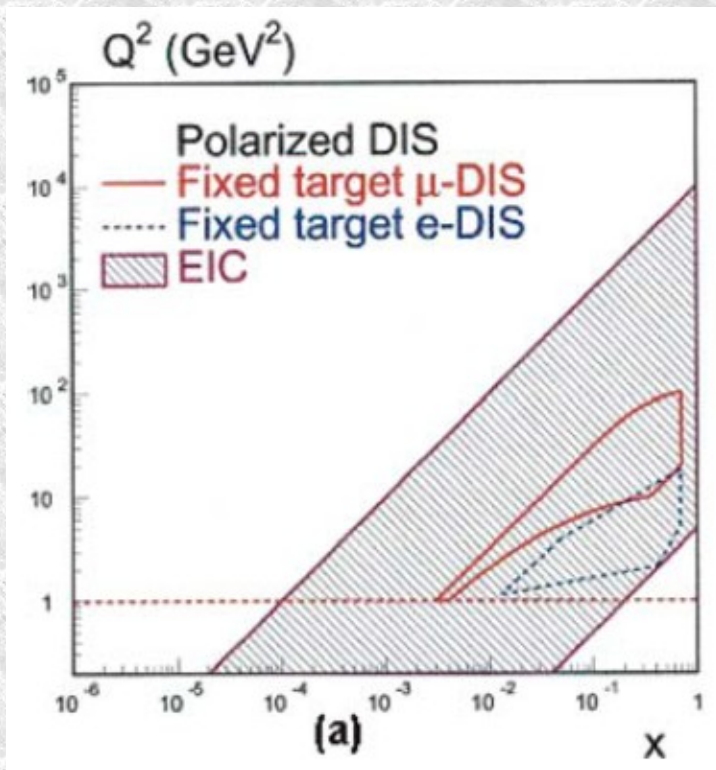
- high luminosity $\approx 10^2\text{-}10^4 \times$ HERMES

- small x, large ν, large Q^2 reach

- **Test /extend HERMES**
  - cross-check results
  - multi-differential observables
  - 2-particle correlation (h-h, γ-h, …)

- **Unique:**
  - **tests of parton dynamics**
  - **heavy flavors, jets, …**

EIC

	ENC		s-eRHIC		eRHIC		ELIC		LHeC	
	Ca	e	Au	e	Au	e	Ca	e	Pb	e
E [GeV/A or GeV]	7.5	3	100	2	100	20	75	7	2750	70
L_{peak} [10^{33} cm^{-2}s^{-1}]		1		0.1		1		100		1.0

The EIC – large ν, Q^2, W^2

- **Large ν-range:** $10 < \nu < 1600$ GeV
  - hadrons formed well outside of the nuclear medium
  - in-medium parton dynamics can be experimentally isolated

- **Large Q^2:** role of virtuality in hadron attenuation

- **New access to p_T-broadening studies**
  - fundamental tests of pQCD energy loss
  - study medium modification of DGLAP evolution
  - test parton shower algorithms in Monte-Carlo generators (!!)

- **Heavy flavors:**
  - radiative vs. collisional parton energy loss
  - J/psi "normal" absorption in clean environment, ...

- **Plus:**
  - Jet shape modifications, dijets, γ+jet, dihadron correlations, ...
  - η vs. π, baryon fragmentation, small-x & CGC, ...

EIC vs. HERMES

[Accardi, Dupré, Hafidi, EIC e+A note]

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

- ◆ Simulation with PYTHIA 6.4.19
  - ➡ no nuclear effect yet
  - ➡ 10 weeks of beam at eRHIC

- ◆ <u>High statistics</u>:
  - ➡ from 2D to 5D distributions

- ◆ <u>Large reach in p_T and Q^2</u> (x_B)

- ◆ <u>Large range in ν</u>
  - ➡ small ν – hadronization inside A
  - ➡ large ν – precision tests of QCD en. loss, DGLAP evolution, parton showers

(Simulations by R.Dupré)

charged pions
eRHIC 20+100 GeV
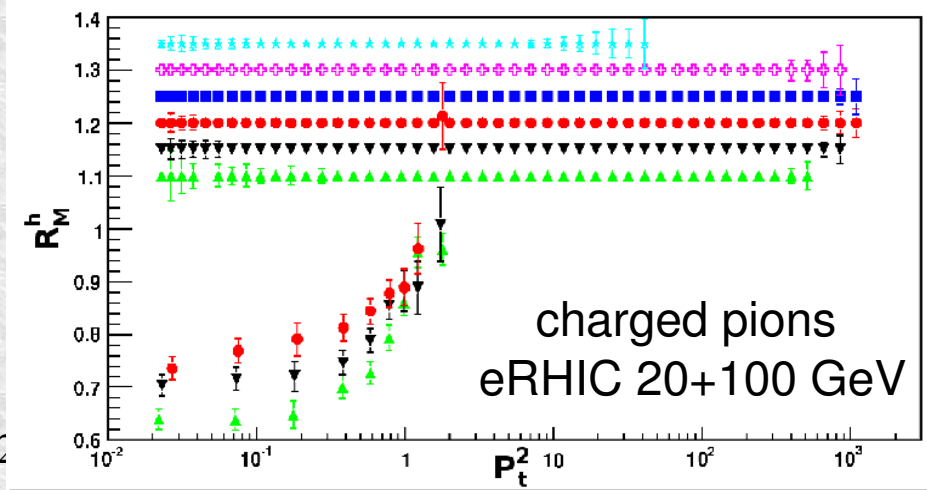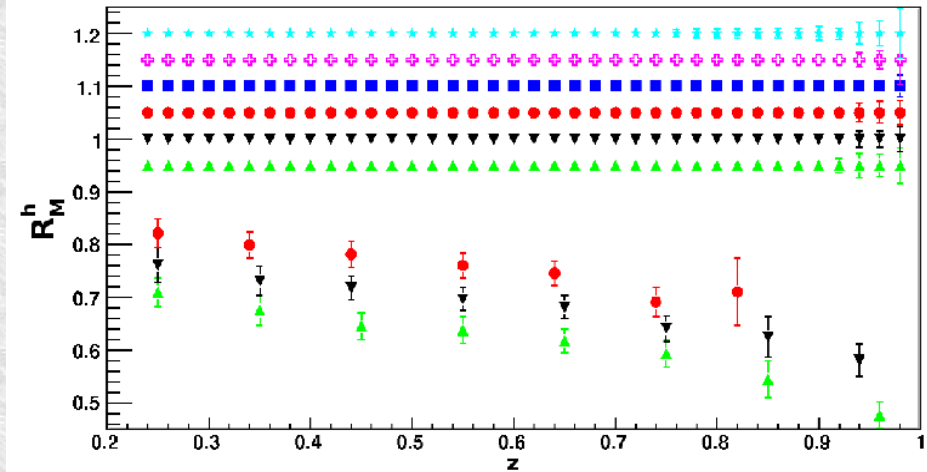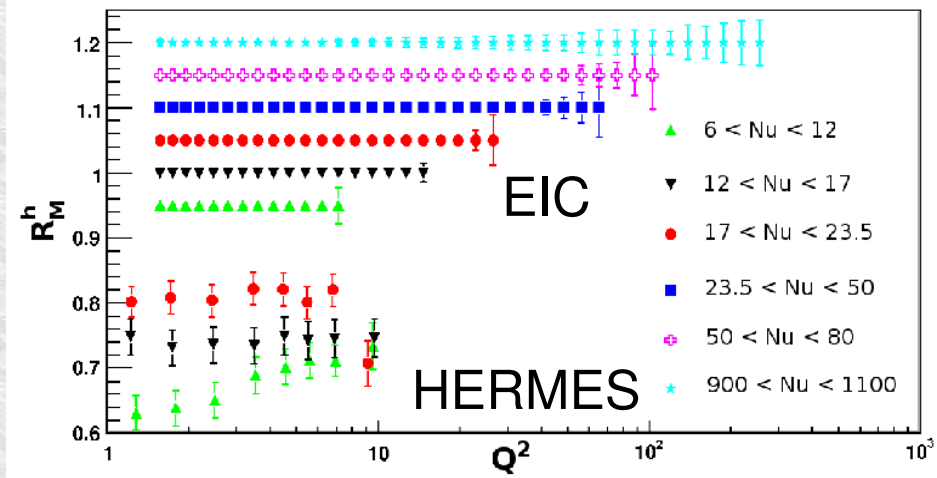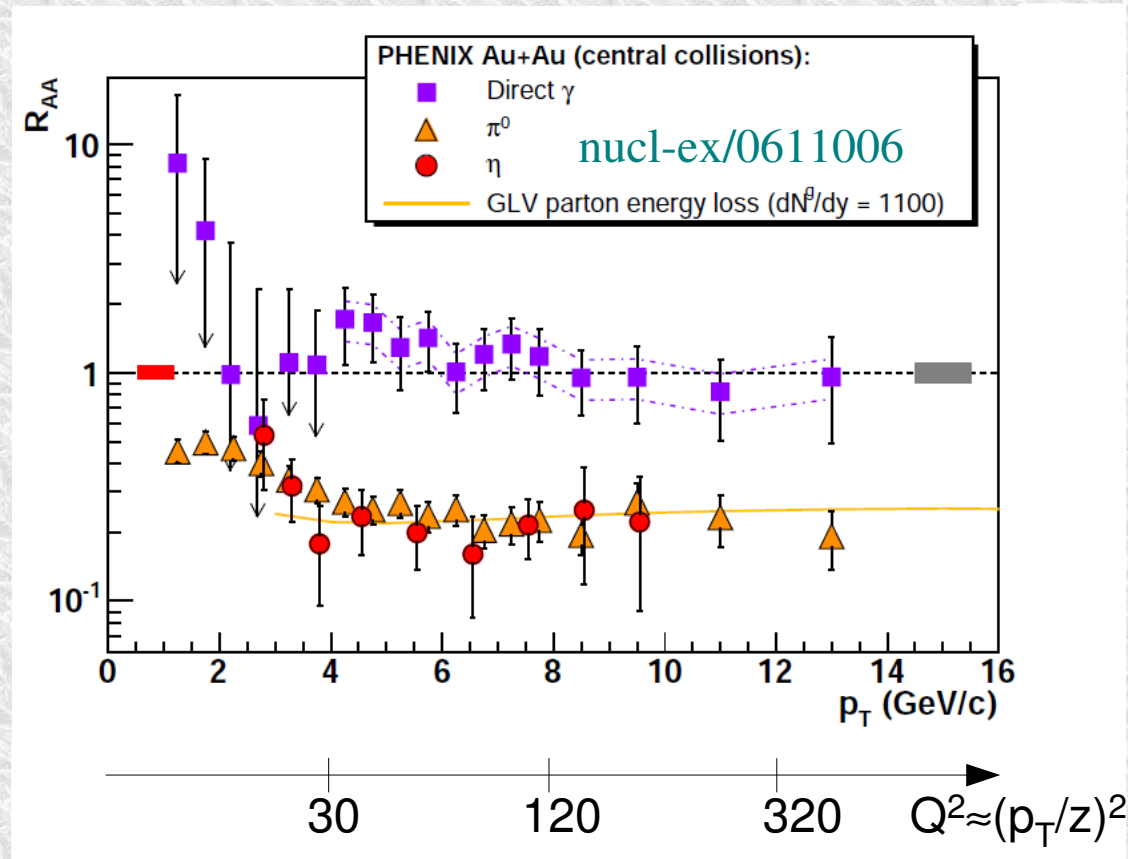
π^0 vs. η in hot nuclear matter

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

- **Is it so also in nDIS?** [η is heavier $\Rightarrow$ hadronizes earlier, smaller x-sect.]
  - measurement possible at CLAS (low Q^2), EIC (high Q^2)

π⁰ vs. η at EIC – attenuation

◆ Can precisely test if $R_M(\pi^0) \approx R_M(\eta)$ as seen in the QGP at RHIC

$$R_M^h(z_h) = \frac{1}{N_A^{DIS}} \frac{dN_A^h(z_h)}{dz_h} \bigg/ \frac{1}{N_D^{DIS}} \frac{dN_D^h(z_h)}{dz_h}$$

EIC π^0

EIC η

$\langle \nu \rangle = 14$ GeV

$\langle z_h \rangle = 0.4$

HERMES π^0
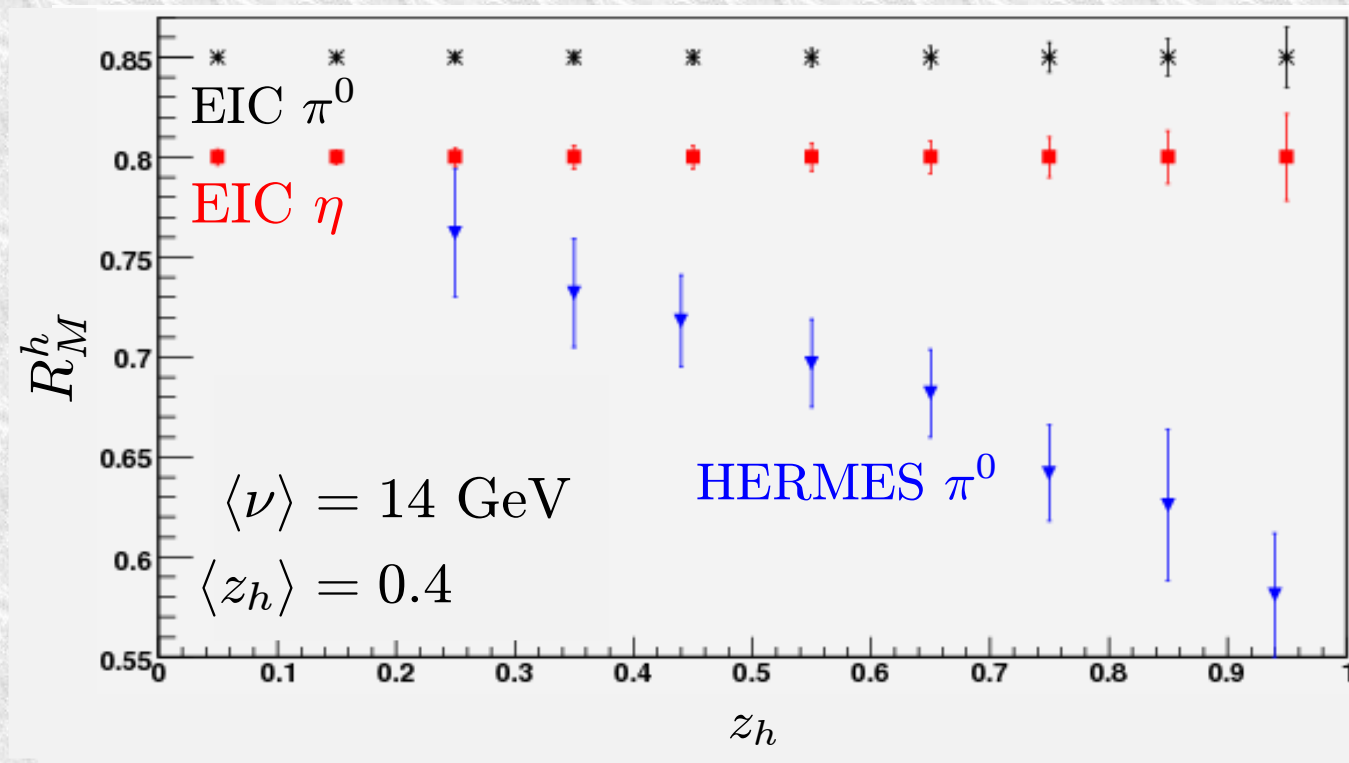
(Simulations by R.Dupré)

π^0 vs. η at EIC – p_T-broadening

[Accardi, Dupré, Hafidi, EIC e+A note]

◆ Can detect different π / η dynamics, if any

◆ Tests role of virtuality in detail
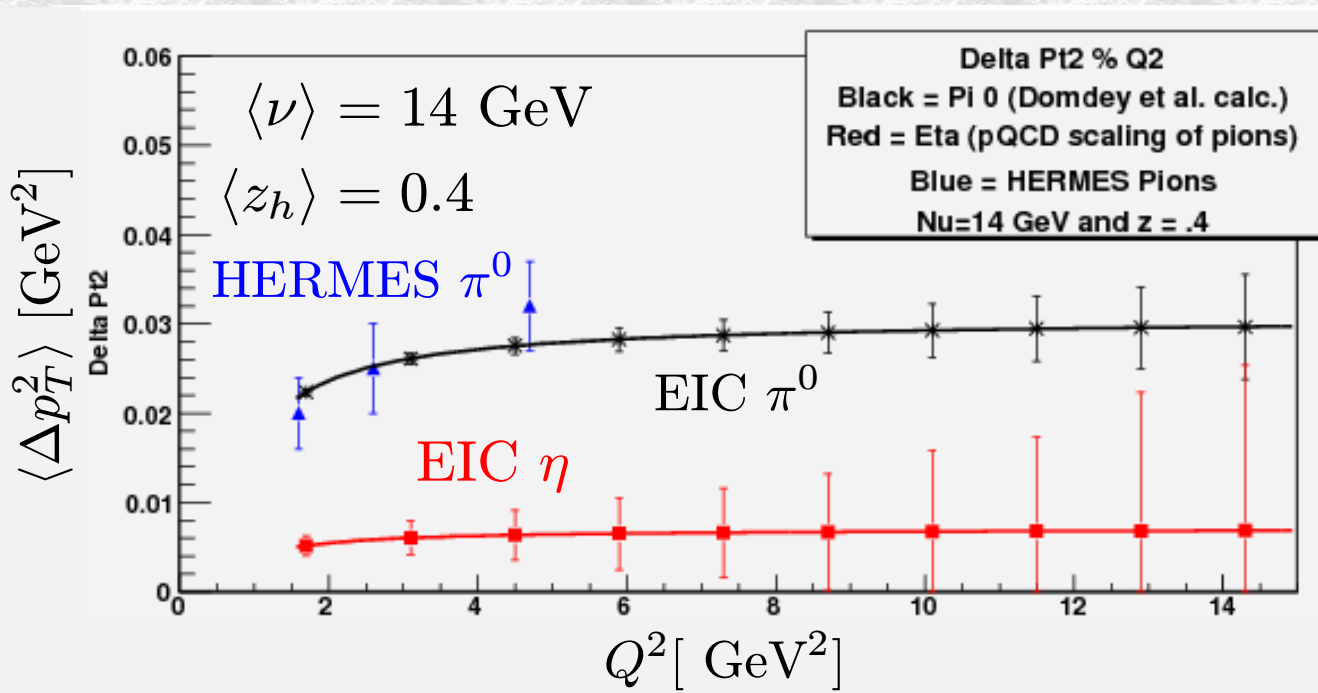
$$\Delta\langle p_T^2\rangle = \langle p_T^2\rangle_A - \langle p_T^2\rangle_D$$

medium-modified DGLAP
(Domdey et al.)

pQCD scaling of pions
(slide 14)

(Simulations by R.Dupré)

Large ν, light vs heavy

- At large ν
  - formation times are very long
  - attenuation disappears
  - pT-broadening little affected $\Rightarrow$ ideal test of pQCD energy loss

π^0

η

D

B

$\langle \Delta p_T^2 \rangle$ [GeV^2]

EIC

$\langle \nu \rangle = 1000$ GeV

$\langle z_h \rangle = 0.4$

Q^2 [GeV^2]

NOTE: pT-broadening values are arbitrary
2% acceptance for heavy flavors

(Simulations by R.Dupré)

Large ν, light vs heavy

[Accardi, Dupré, Hafidi, EIC e+A note]

- At large ν
  - formation times are very long
  - attenuation disappears
  - pT-broadening little affected $\Rightarrow$ ideal test of pQCD energy loss
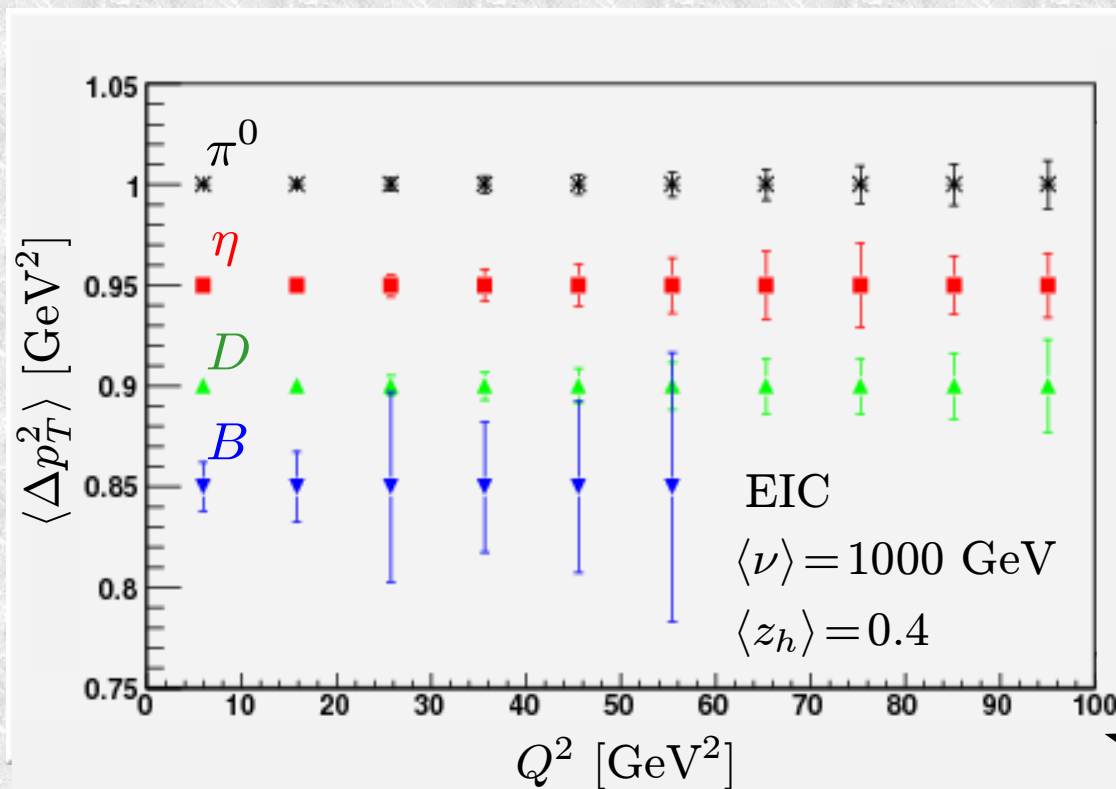
NOTE: pT-broadening values are arbitrary
         2% acceptance for heavy flavors

Q^2 range relevant to A+A

(Simulations by R.Dupré)

Large ν – light vs heavy flavors

[Accardi, Dupré, Hafidi, EIC e+A note]

- At large ν
  - formation times are very long
  - attenuation disappears
  - pT-broadening little affected ⇒ ideal test of pQCD energy loss

EIC
$\langle \nu \rangle = 1000$ GeV
$\langle z_h \rangle = 0.4$
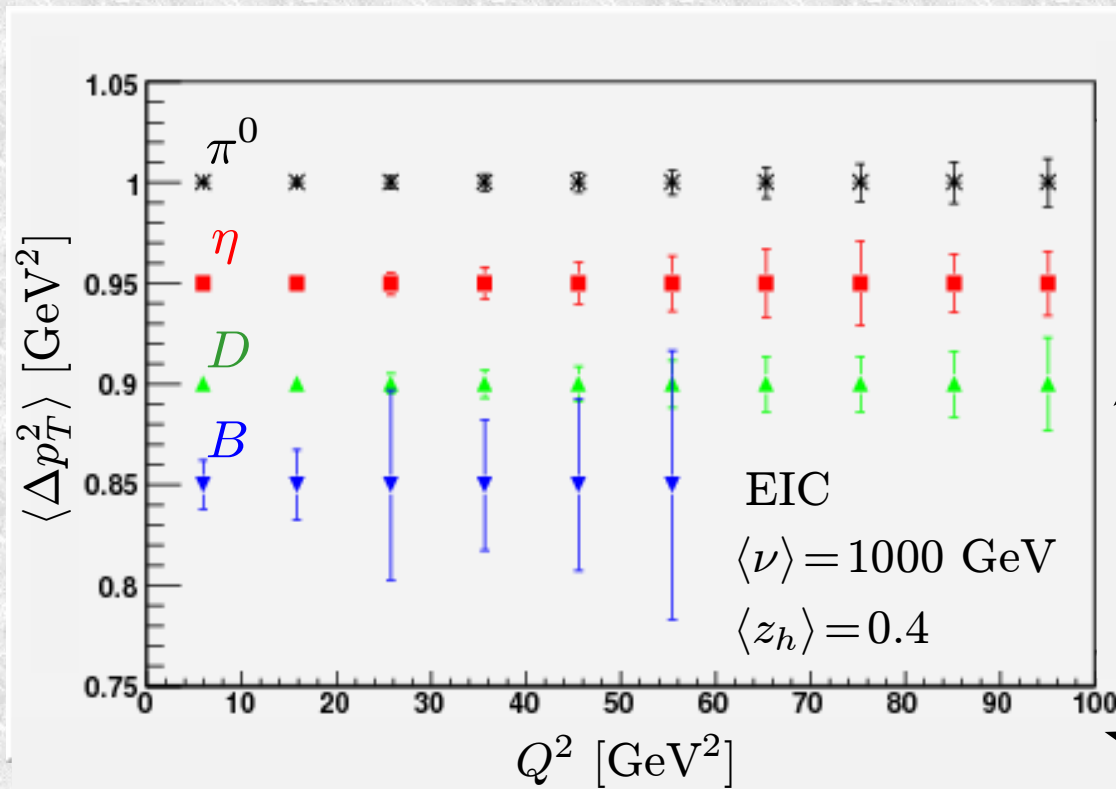
NOTE: pT-broadening values are arbitrary
2% acceptance for heavy flavors

Can solve RHIC's "heavy-flavor puzzle"

Wicks et al., nucl-th/0512076
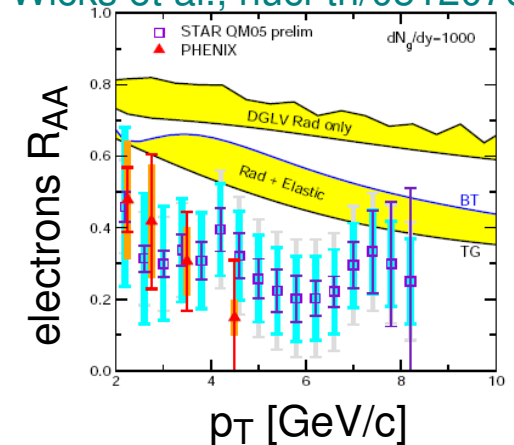
Q² range relevant to A+A

(Simulations by R.Dupré)

Heavy quarks identification

- D and B particles have a non negligible life time ($c\tau \sim 100~\mu m$)

- High precision vertex tracking used or planned in a lot of experiments (ALICE, CMS – STAR, PHENIX – ZEUS ...):
  - Silicon strip detector
  - Pixel detector
  - ...

- Needs spatial resolution

$$\Delta x \lesssim 100~\mu m$$

but more studies are needed

[A.Bruell, EIC MC Group Meeting @ Boulder, Nov. 04]

hadrons

D

τ = M/slope = (123+-2) μm

PDG = 123.4+-0.8 μm

100 μm
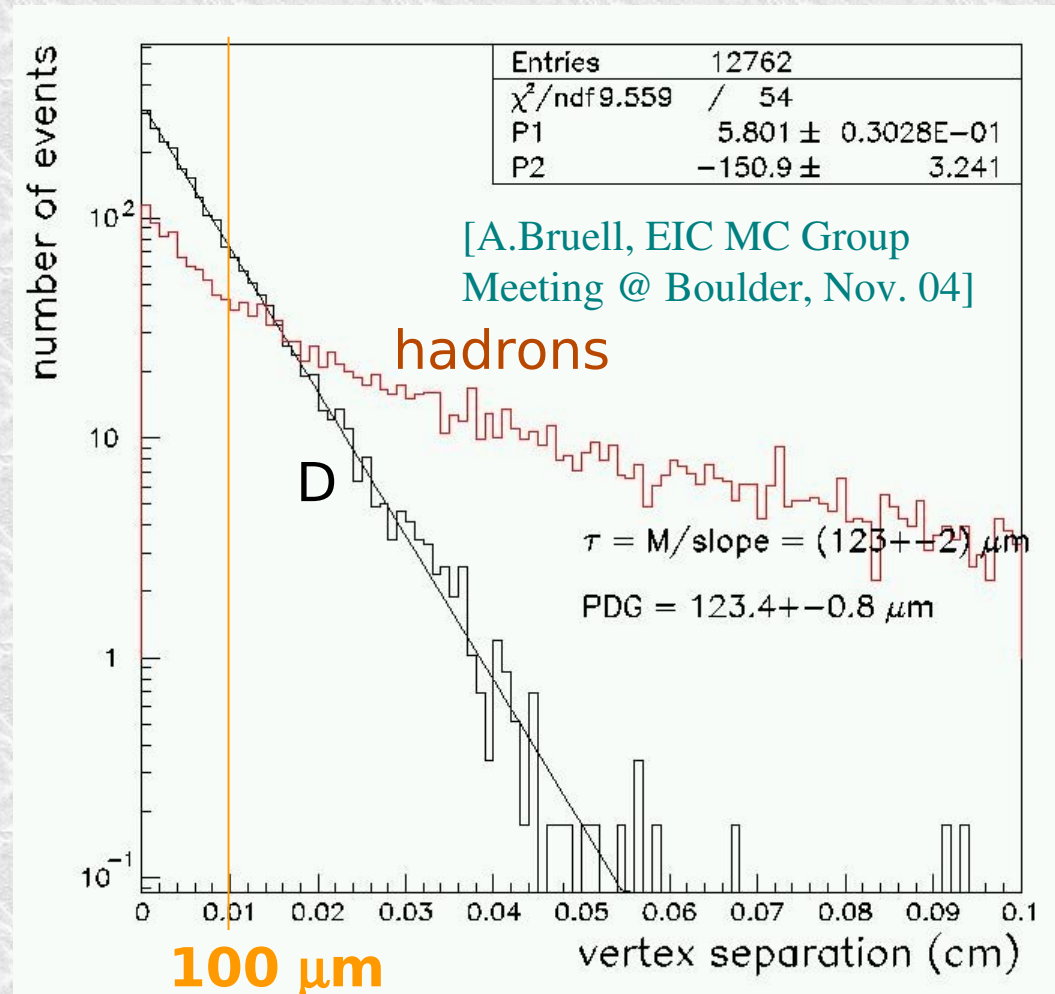
COMPASS

Perspectives at COMPASS
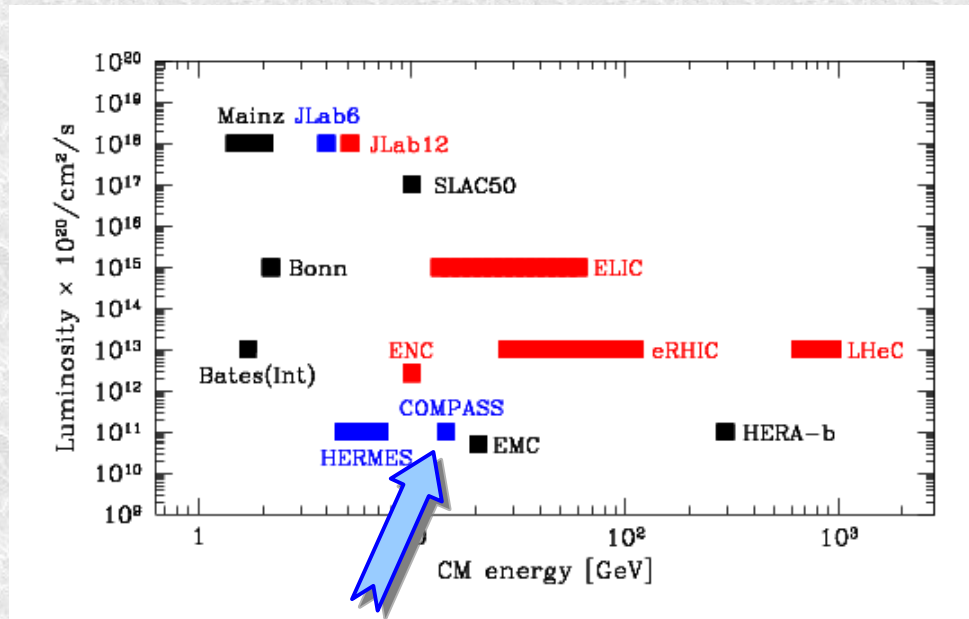
➢ **Nuclear targets are possible**
[Abbon et al., Nucl. Instrum. Meth. A577 (2007) 455]

➢ **Larger ν than HERMES (<150 GeV)**
➡ pure parton energy loss studies
➡ DGLAP evolution

before the EIC !

➢ **π vs. *e* beams**
➡ energy loss in DY compared to DIS

ENC

Perspectives at the ENC
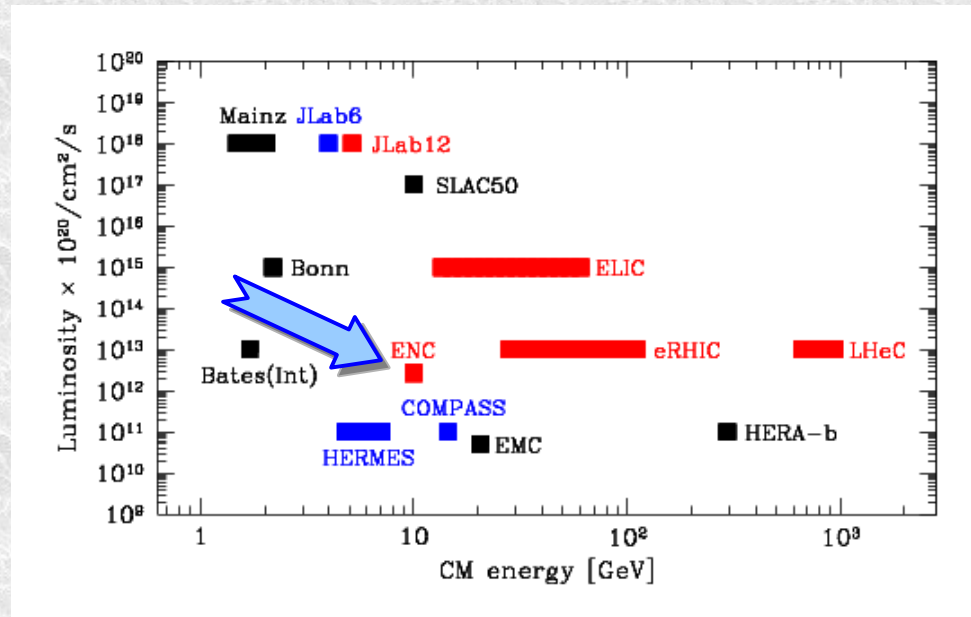
- Energy between HERMES and COMPASS
  - $\nu < 50$ GeV
  - hadronization not completely outside the nucleus ??

- Higher luminosity
  - multi-differential observables
  - η, Λ, ... – heavy flavors (?)

- Collider mode
  - target vs. current fragmentation

Conclusions

* **Quark lifetime:**
  - rather short in cold matter seems, $O(R_A)$
  - but long in hot matter at RHIC – a QGP signal ???

* **In nDIS, p_T-broadening is next theoretical challenge**
  - test of space-time evolution of hadronization
  - best place to test: pQCD energy loss, DGLAP, parton showers
  - role of virtuality in hadron attenuation

* **At the EIC:**
  - many new channels (jets, heavy flavors, ...)
  - long parton lifetimes: precision study of en.loss, DGLAP
  - opportunities for theoretical developments

* **Open question: perspectives at the ENC, COMPASS**

Conclusions

* **Quark lifetime:**
  + rather short in cold matter seems, $O(R_A)$
  + but long in hot matter at RHIC – a QGP signal ???

* **In nDIS, p_T-broadening is next theoretical challenge**
  + test of space-time evolution of hadronization
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  + role of virtuality in hadron attenuation

* **At the EIC:**
  + many new channels (jets, heavy flavors, ...)
  + long parton lifetimes: precision study of en.loss, DGLAP
  + opportunities for theoretical developments

* **Open question: perspectives at the ENC, COMPASS**

need
good PID,
vertex detector

The end

Backup slides

Parton lifetime
in hot QCD matter

π^0 vs. η

◆ **Why is η as much suppressed as π in Au+Au ?**
  ➡ points towards **long lived quark**
  ➡ but nDIS analysis suggests π formed on short time scales

◆ **Is it so also in nDIS?** [η is heavier $\Rightarrow$ hadronizes earlier, smaller x-sect.]
  ➡ measurement possible at CLAS (low Q^2), EIC (high Q^2)

From nDIS to heavy-ion collisions

GiBUU absorption model:

[Falter et al. PRC '04, Gallmeister, Mosel NPA '08]

Formation times: t_p from PITHYA (Lund model)

Cross sections: leading h: $\sigma_* = f(t)\,\sigma_h$

subleading h: $\sigma_* = 0$

$$f(t) \propto \begin{cases} \text{const.} \\ t & \text{(linear, or quantum diffusion)} \\ t^2 & \text{(color transparency)} \end{cases}$$
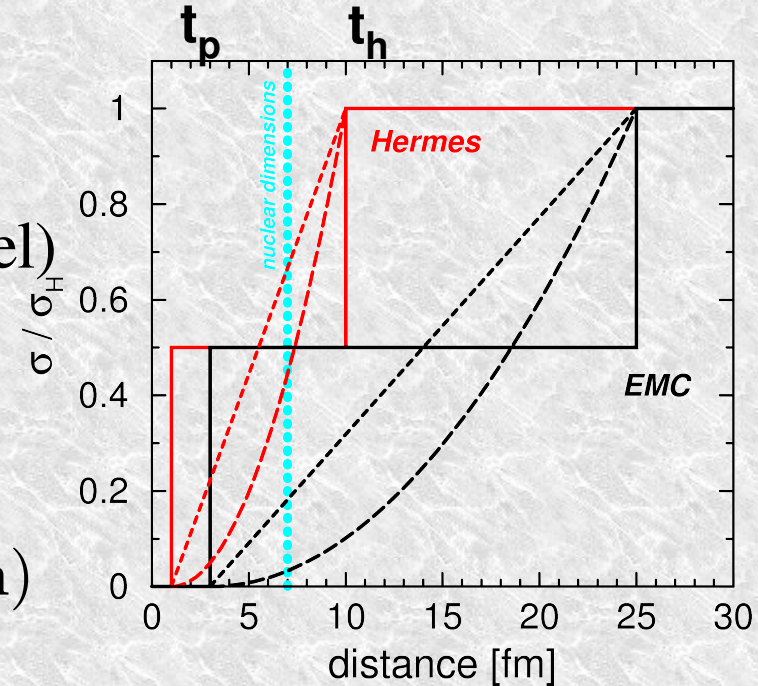
Consistency of HERMES + EMC data selects linear $f(t) \sim t$

[Gallmeister, Mosel NPA'08]
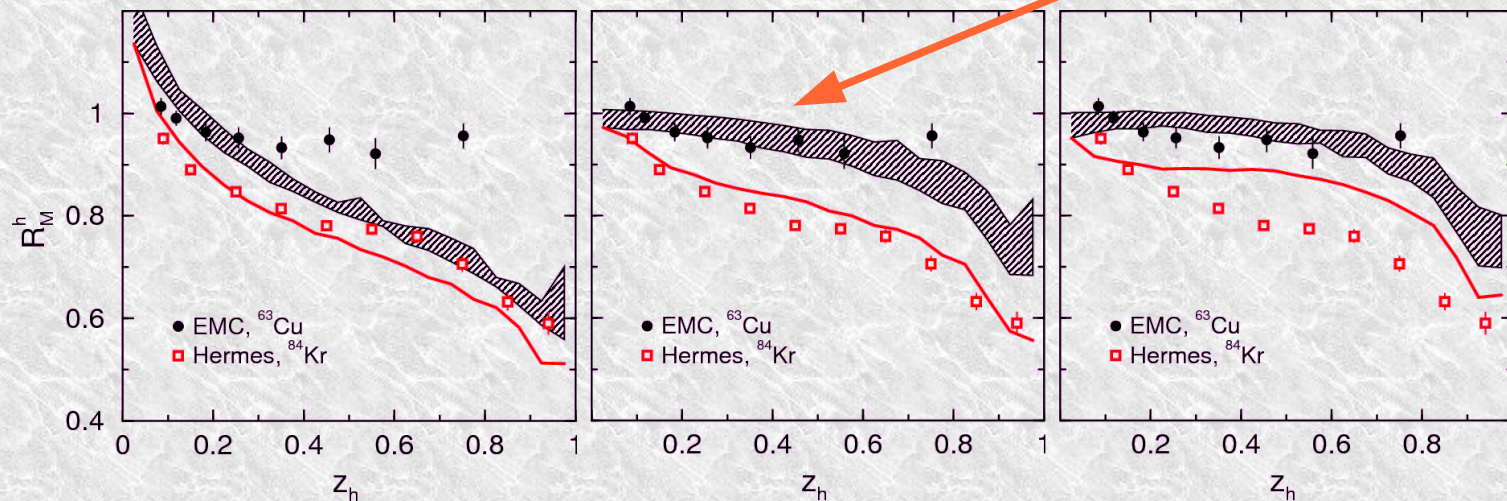
Parton lifetime in hot QCD matter – 2

◆ Apply it to Au+Au collisions at RHIC:
[Cassing, Gallmeister,Greiner NPA '04; Cassing, Gallmeister NPA '05]
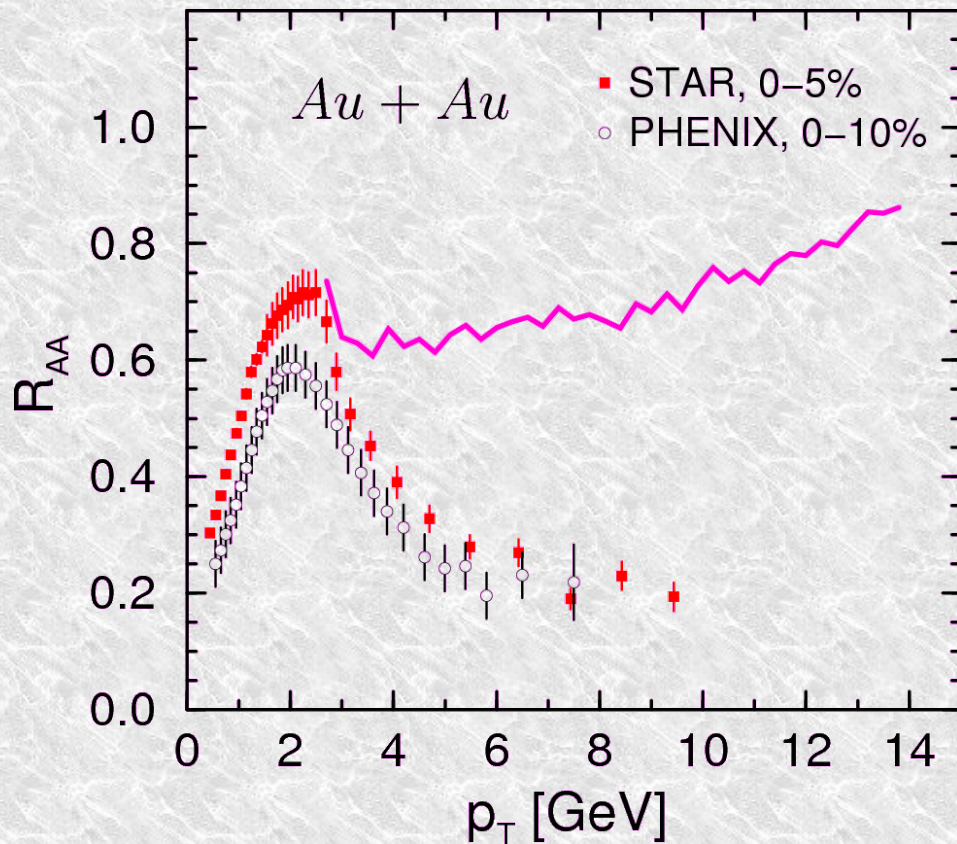
Way too little suppression:
long lived partons in QGP?

Why do partons seem short lived in cold QCD matter, but long lived in hot QCD matter?

Short review of e+A data

For the latest data see:

1) HERMES, NPB 780 (2007) 1

2) Trento Fragmentation Workshop, Feb 2008
   http://arleo.web.cern.ch/arleo/ff_vacuum_medium_ect08/

Measurements at HERMES @ HERA

◆ HERMES: fixed target, $E_{lab} = 27.5$ GeV and 12 GeV

◆ Hadron attenuation versus
→ ν = virtual γ energy
→ $z_h = E_h/\nu$
   (hadron's fractional energy)
→ Q^2 = photon virtuality
→ p_T = hadron transv. momentum
→ hadron flavor = $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$
→ A = target mass number

◆ Hadron p_T-broadening

◆ Dihadron correlations

◆ 2-dimensional binning (!)

[HERMES, NPB 780 (2007) 1]
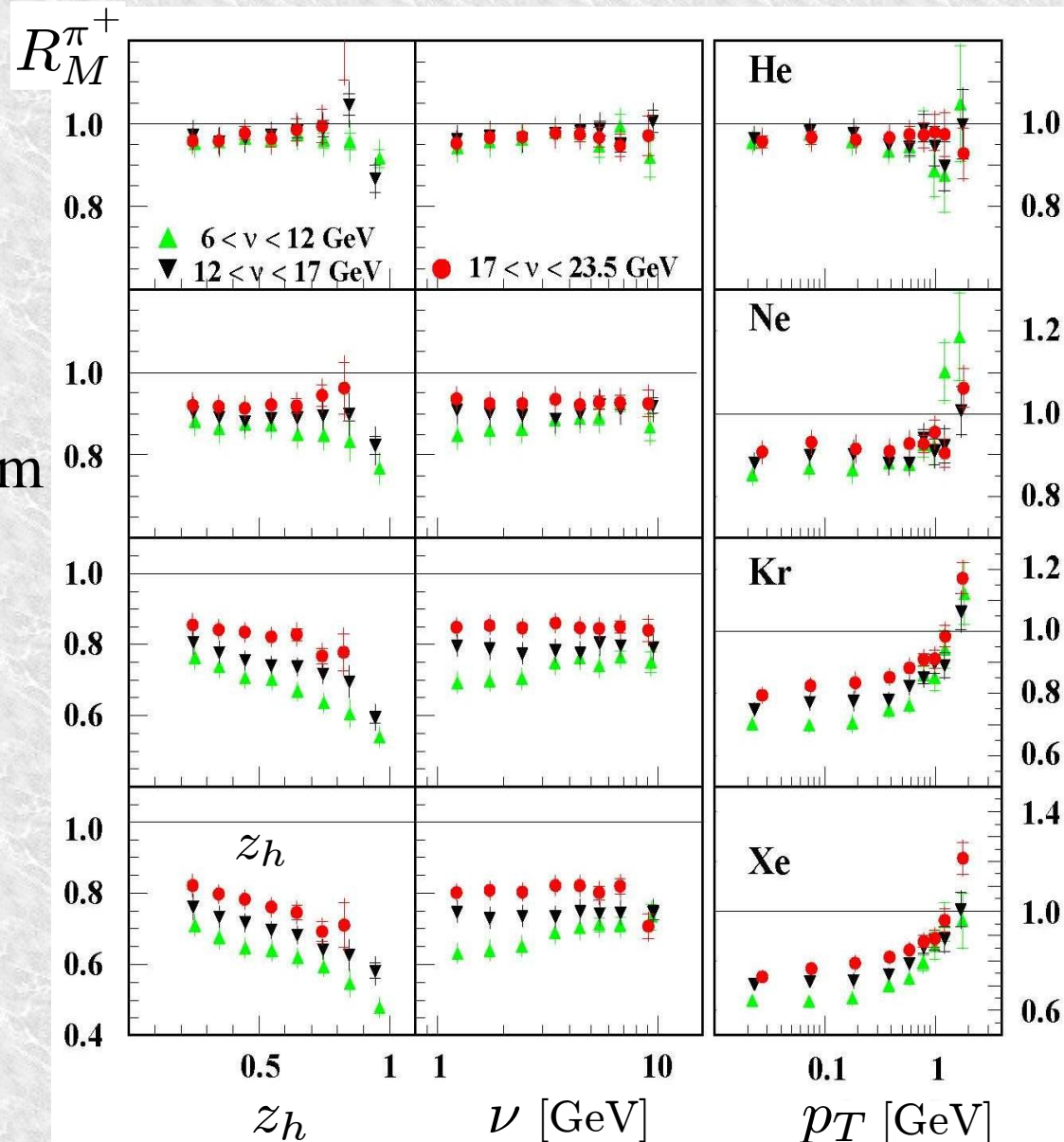
Preliminary results at CLAS @ Jefferson Lab

2.20<ν<3.00 1.00<Q²<1.25 | π⁺

$R_M \pi+$

E_{lab} = 5 GeV
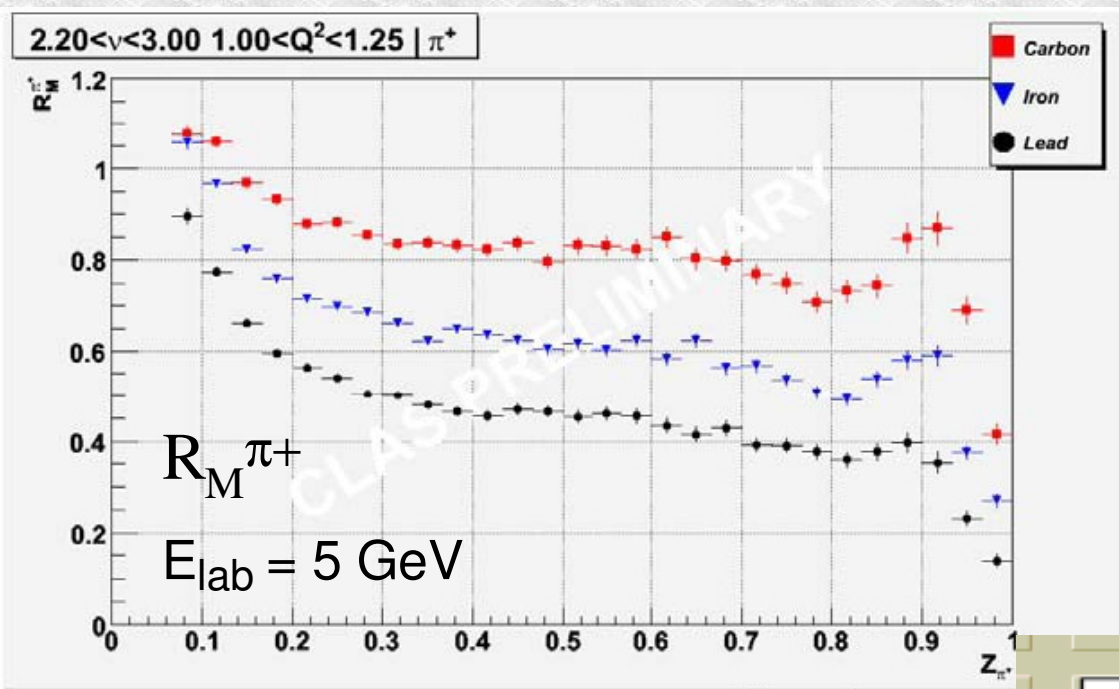
- 6 (12) GeV beam
- huge luminosity
  - multi-differential binning !!
  - γ+h correlations
  - and much more...

K.Hafidi, nucl-ex/0609005

Brooks, Hicks, talks at Trento Workshop

Cronin effect for Iron

$0.45<Z_h<0.55$

$0.65<Z_h<0.75$

p_T broadening

$1<Q^2<2 \ 0.5<Z_{\pi^+}<0.6 \ | \ \pi^+ \ |$

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

E_{lab} = 5 GeV

Struck quark energy (GeV)
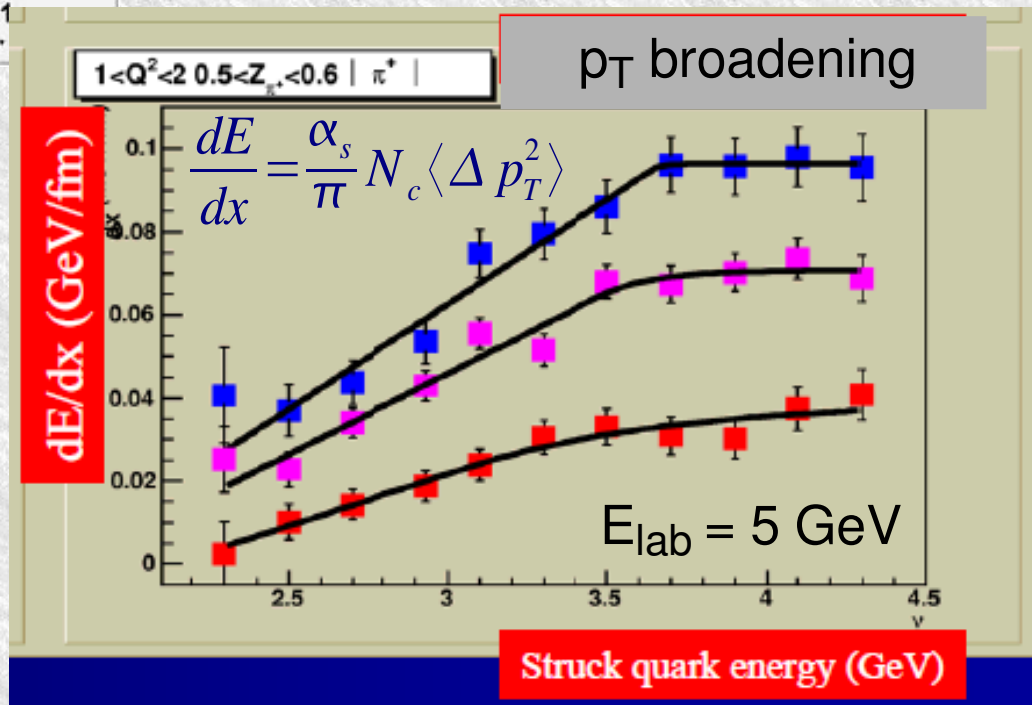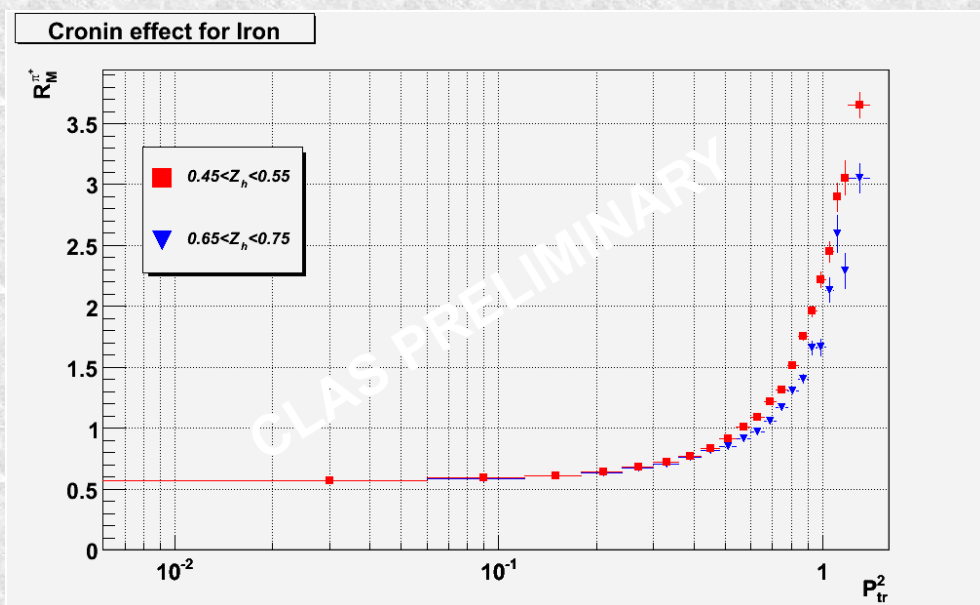
Proton anomaly also in cold matter!

HERMES E_{lab}=27 GeV - Phys.Lett.B577(03)37
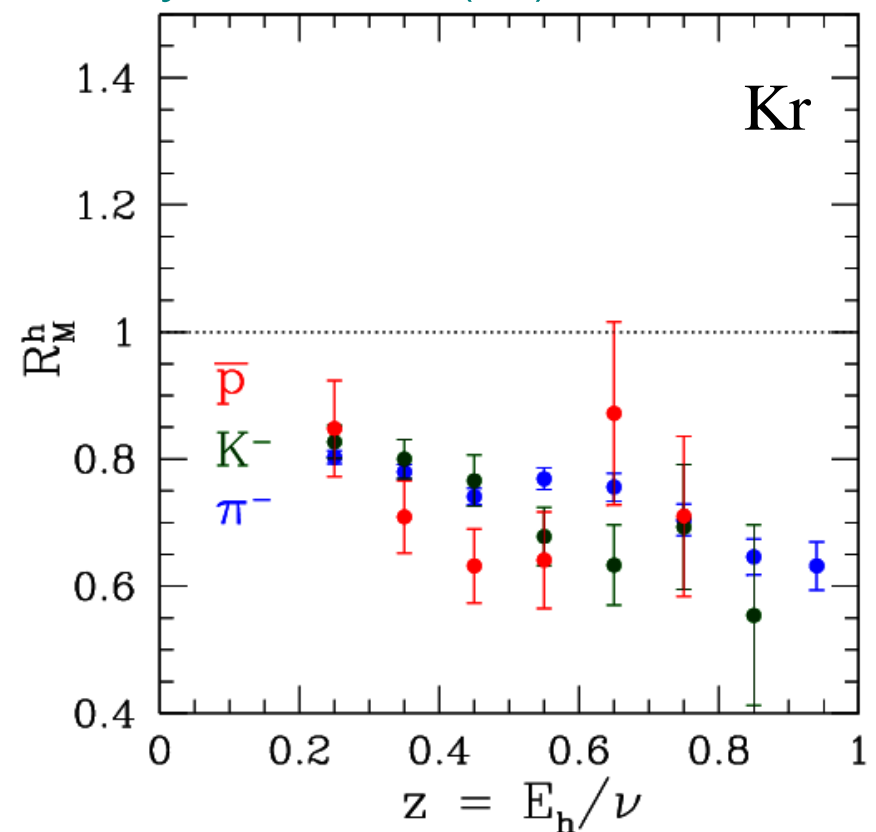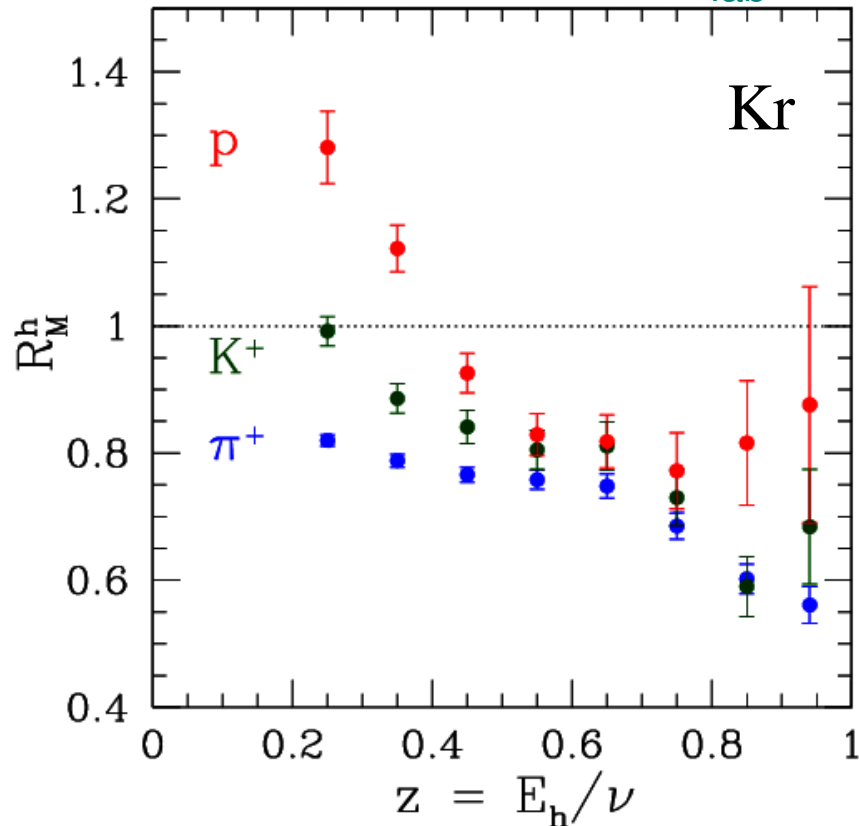
- ◆ **proton anomaly!** ...but anti-protons are normal...
- ◆ analogous to "baryon/meson anomaly" in p+p, p+A and A+A
  - ➡ what do they have in common, if anything?
  - ➡ What about "Higher-Twist" baryon production ?

Hadronization in elementary collisions
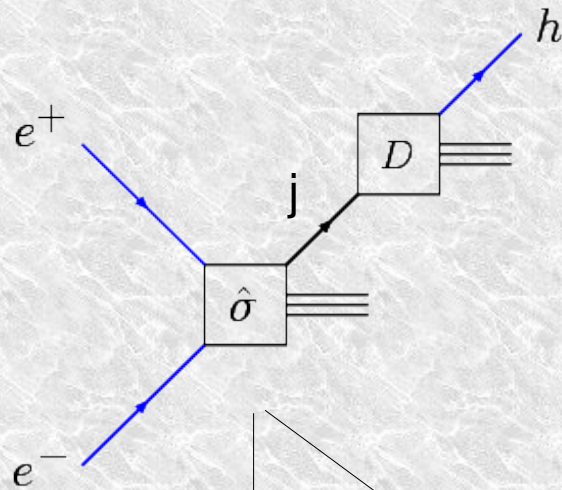
- **perturbative QCD factorization**
  of short and long distance physics

$$d\sigma_{\text{hadron}} = \sum_{ij} \phi_i \otimes \hat{\sigma}^{ij}_{\text{parton}} \otimes D_{j|h}$$

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 $p+p \to h+X$
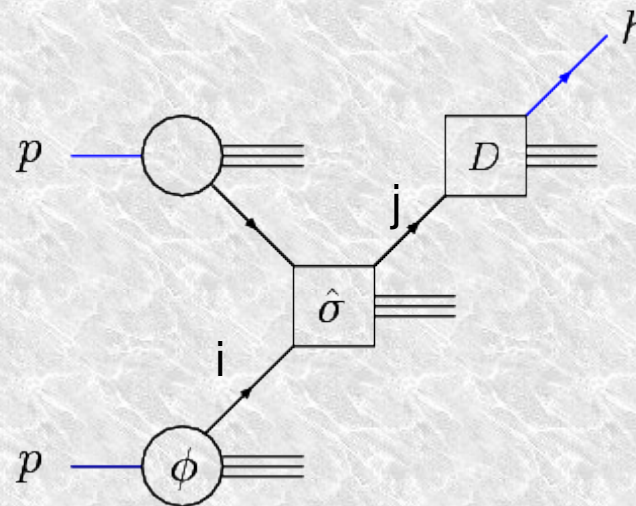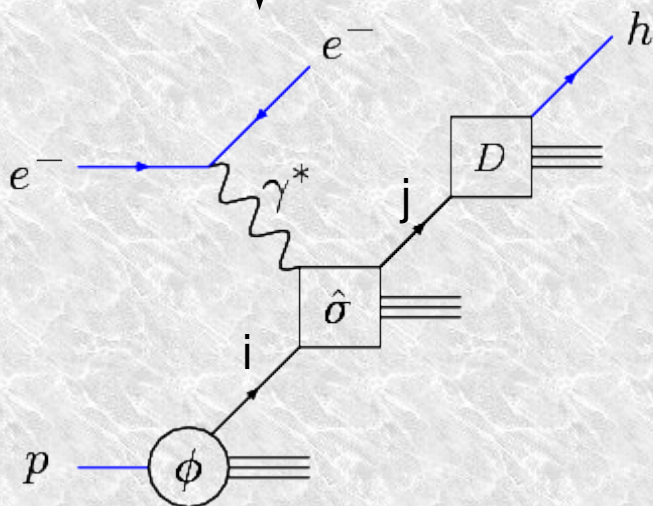
The collider point of view

h (p_{Th}, y_1)

$x_e = E_e/\sqrt{s}$

A

e^+, x_e

q, x

A

$e^+ (p_T, y_2)$

h (p_{Th}, y_1)

A

q_2, x_2

q, x

A

q (p_T, y_2)
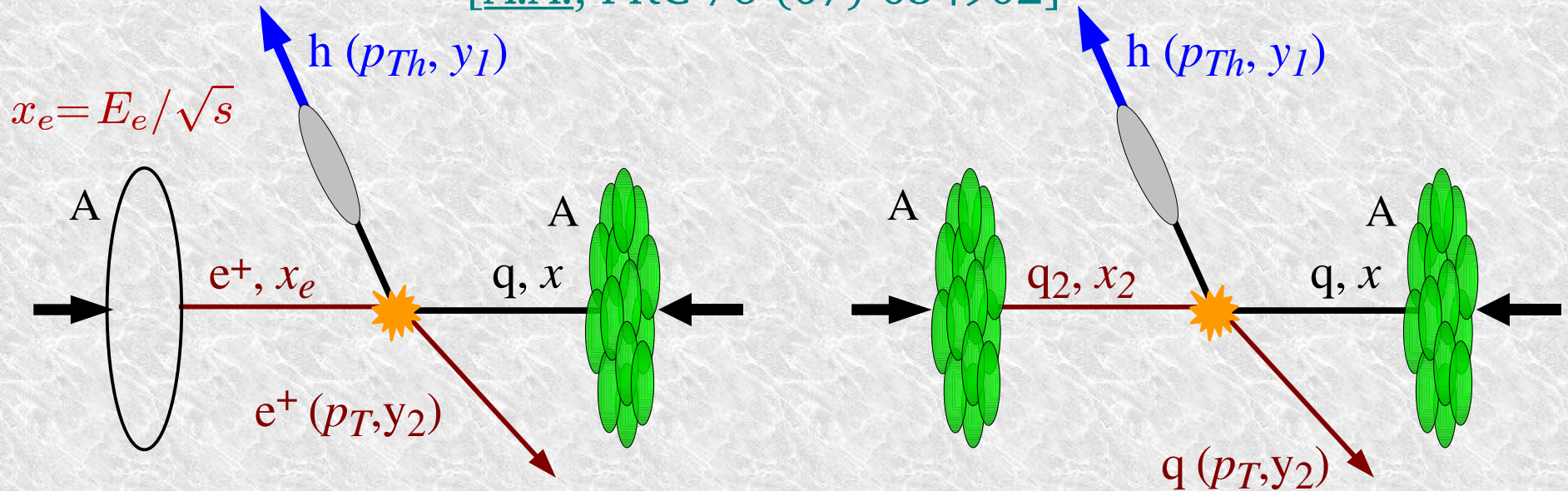
In LO kinematics:

$$Q^2 = p_T^2(1 + e^{y_1 - y_2})$$

$$\nu = \frac{p_T\sqrt{s}}{2M}e^{y_1}$$

$$y = \frac{1}{1 + e^{y_2 - y_1}}$$

$$z_h = z$$
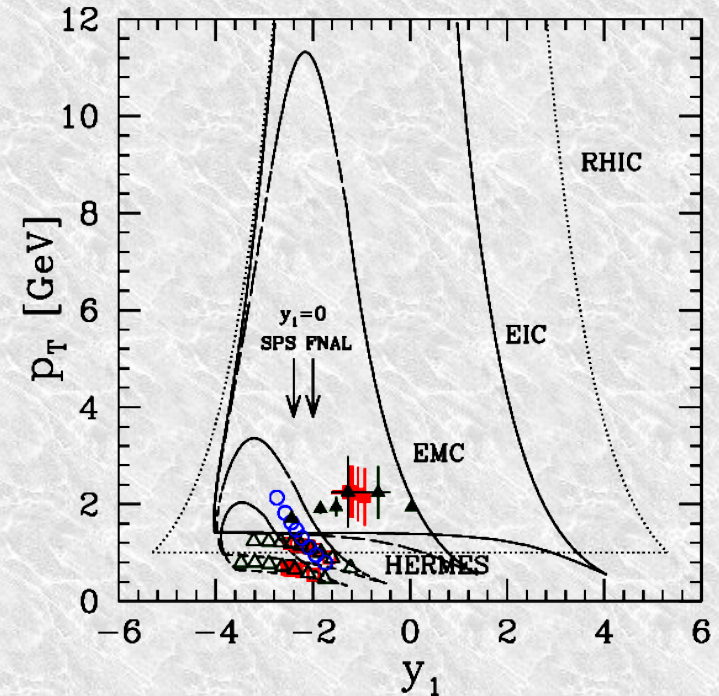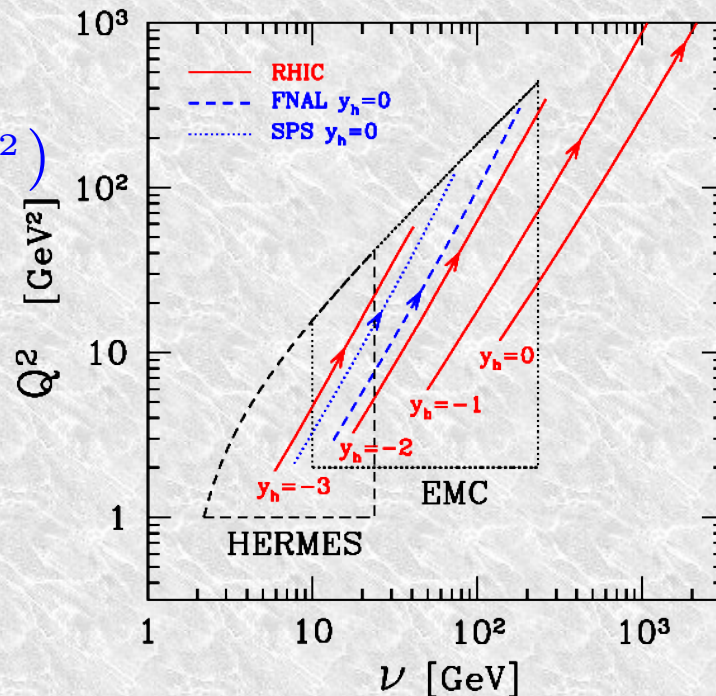
Cold quenching in p+A and A+A collisions

🔶 At low $\sqrt{s}$, or negative η, a parton travels slowly through the target nucleus, when seen in the nucleus rest frame.
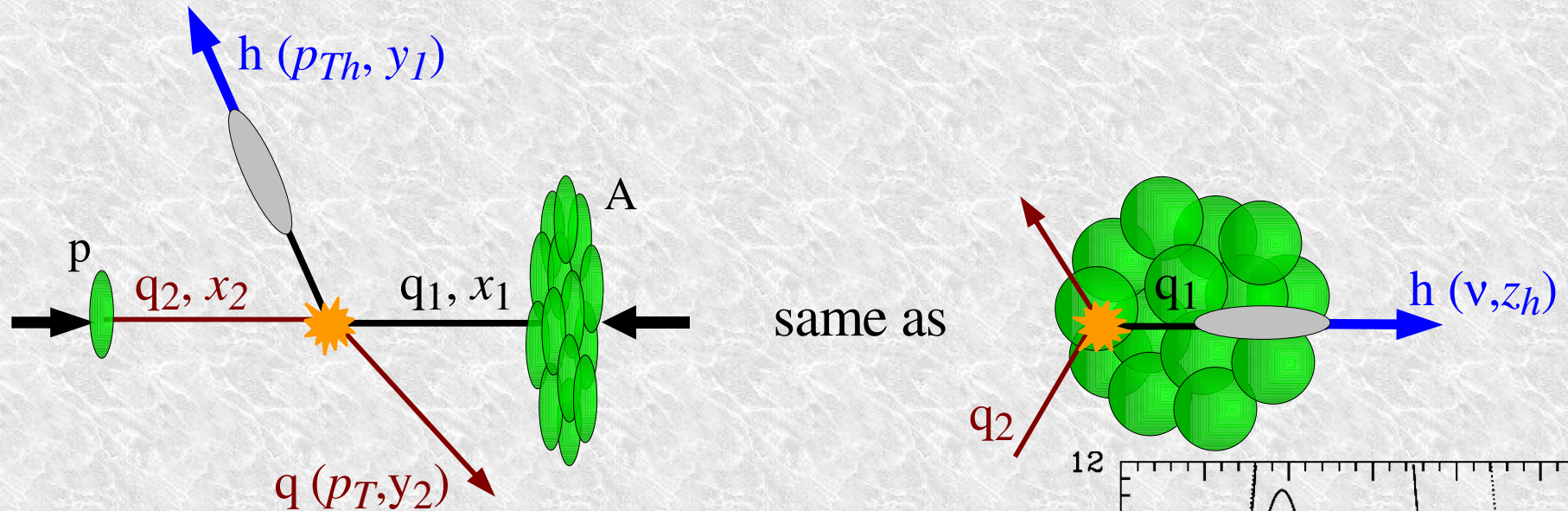
At LO:

$$Q^2 = p_T^2(1 + e^{y_1 - y_2}) \qquad \nu = \frac{p_T \sqrt{s}}{2M} e^{y_1} \qquad z_h = z$$

🔶 If parton slow enough (small ν) the hadron will be quenched in the cold nucleus by the same mechanism that quenches it in nDIS.
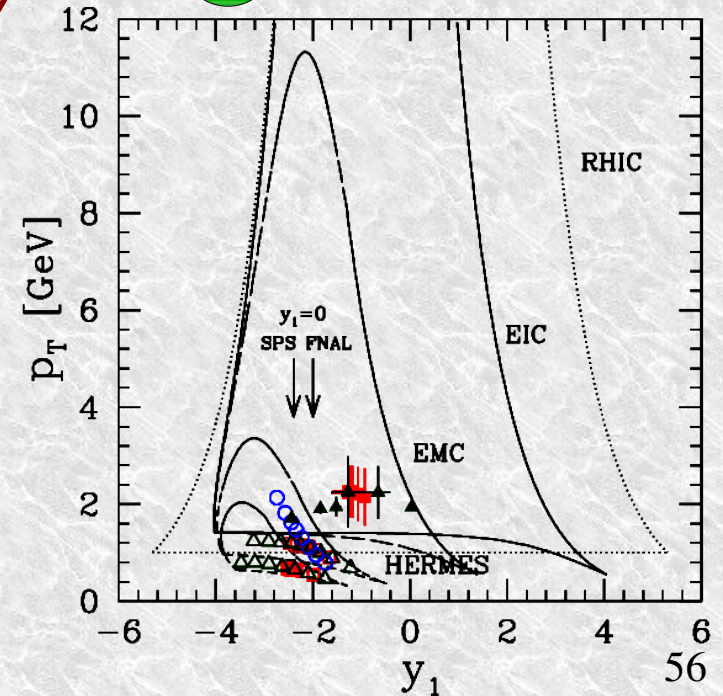
Cold quenching in p+A and A+A collisions

⬧ Use $Q^2 = p_T^2(1 + e^{y_1 - y_2})$ $\nu = \dfrac{p_T\sqrt{s}}{2M}e^{y_1}$ $z_h = z$

in any hadron quenching model validated by HERMES R_M data

➡ e.g., energy loss with SW quenching weights [AA, ...]
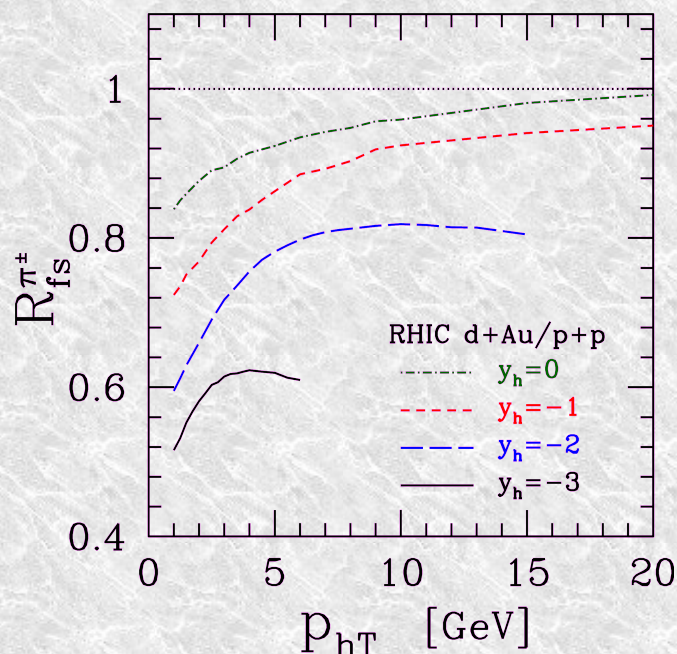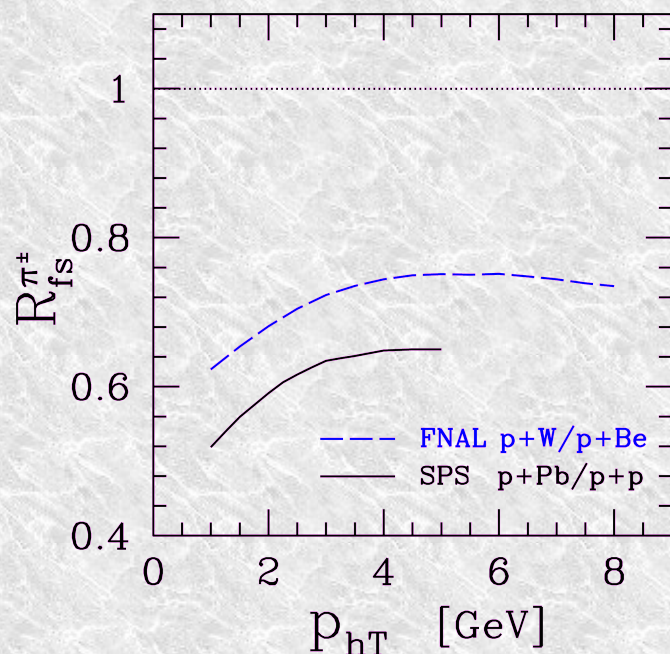
⬧ For **A+A at $\eta = 0$**, suppression comes from both nuclei $\Rightarrow$ ~ squared:

> **Cold quenching in target nuclei not negligible in A+A at SPS: easily competes with quenching from hot medium**
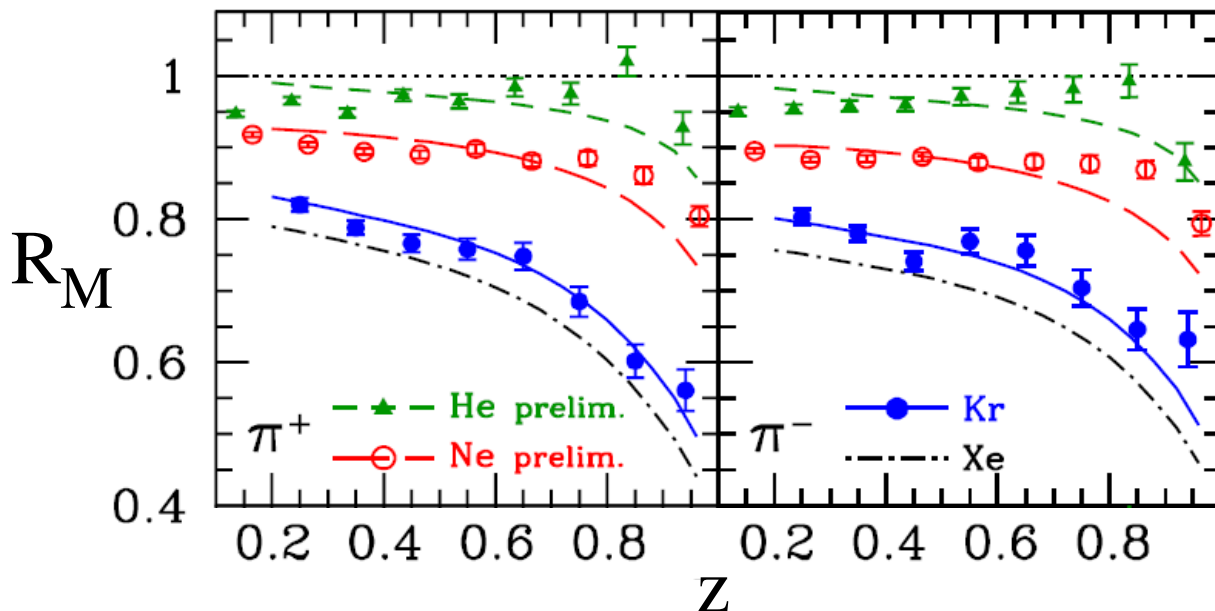
Formation time estimates 2 – Lund model

$$\begin{cases} \langle t_p \rangle = f(z_h)(1 - z_h)\dfrac{z_h \nu}{\kappa} \\[2mm] \langle t_h \rangle = \langle t_p \rangle + \dfrac{z_h \nu}{\kappa} \end{cases}$$
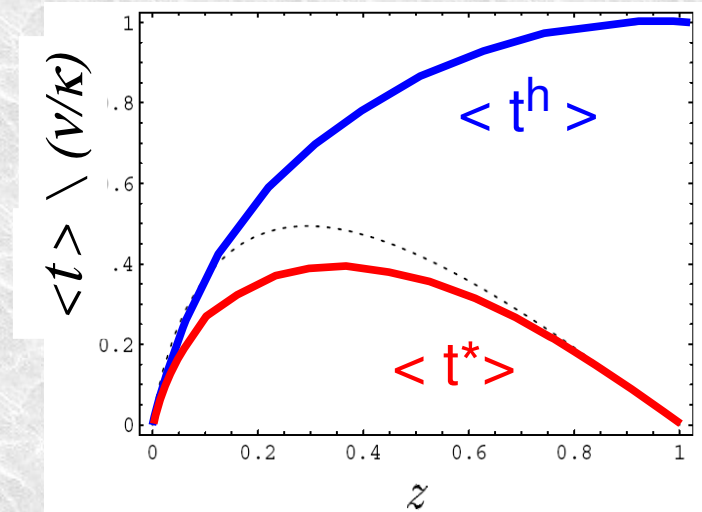
✷ For a $\nu = 14$ GeV pion at Hermes,

$$\langle t_p \rangle \lesssim 5 \text{ fm} \quad \langle t_h \rangle \sim 10 \text{ fm} > R_A$$

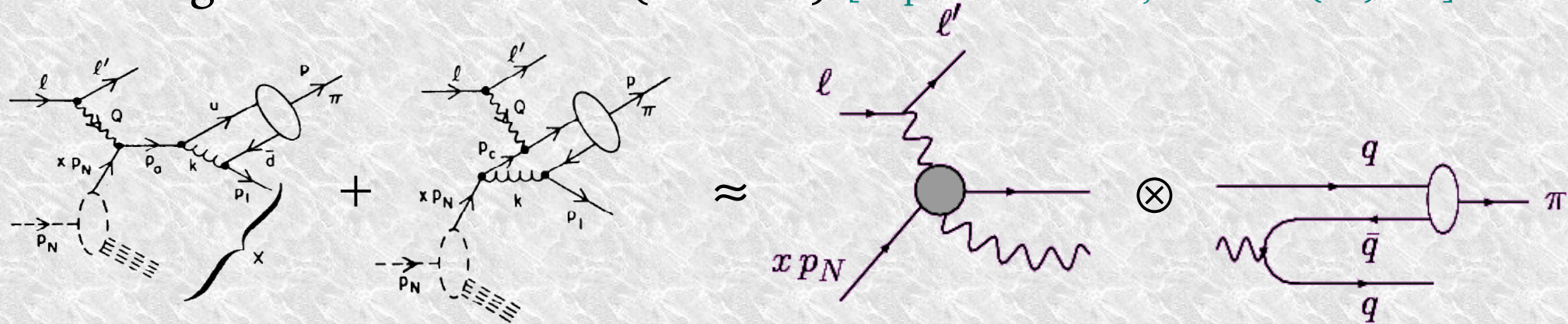✷ Prehadron absorption with this estimate [A.A. et al., NPA 761(05)67]

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

Formation time estimates 3 – Dipole model

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

* Prehadron production time t_p
  = time at which gluon becomes decoherent with parent quark
* At large z → 1, E_h → ν ⟹ quark must be short-lived
  (or radiates too much energy)

$$\langle t_p \rangle \propto (1 - z_h) \frac{z_h \nu}{Q^2}$$

boost

energy conservation

virtuality (perturbative scale)

* Evolution to hadron by path-integral formalism
  → usually $\langle t_p \rangle < R_A$ $\langle t_h \rangle \gg R_A$

3) p_T − broadening [A.A., nucl-th/0808.0656]

HERMES preliminary
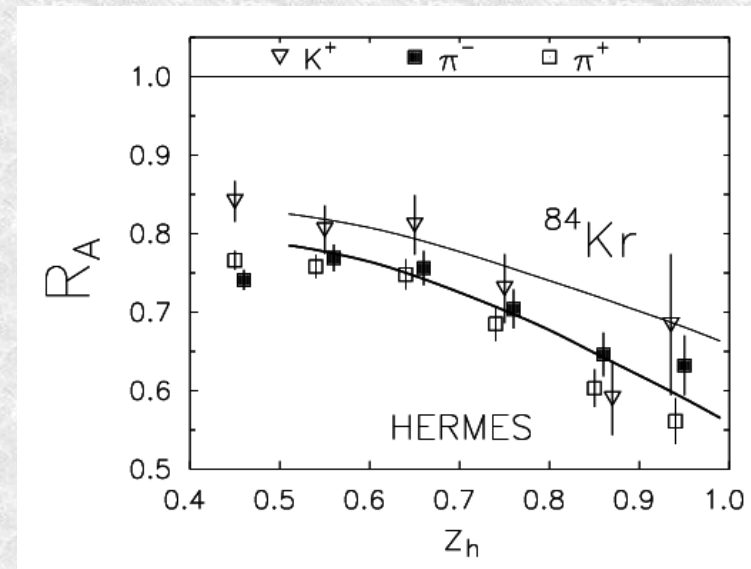
Let's assume no energy loss for a moment:

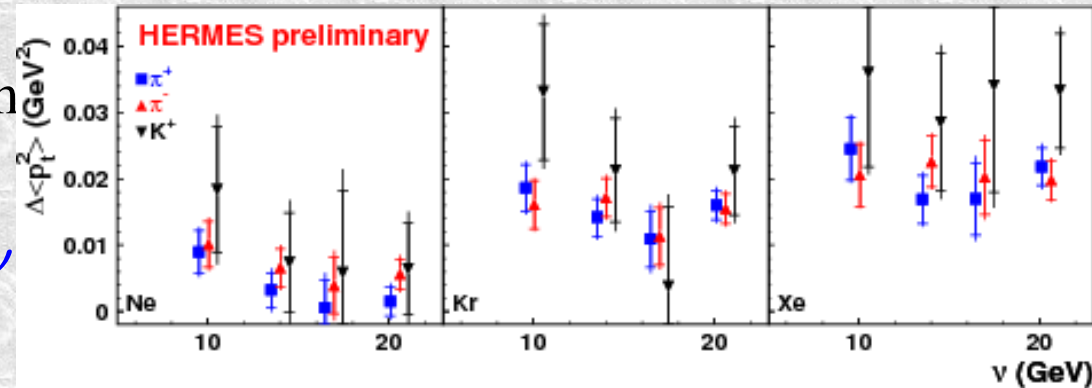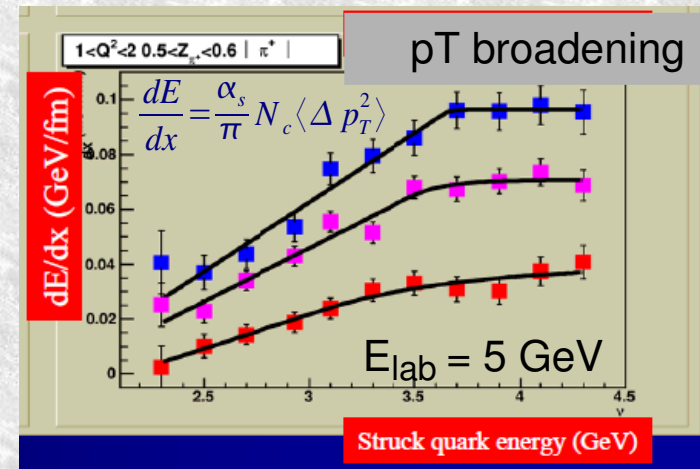$$\Delta\langle p_T^2 \rangle \propto \langle t_p \rangle \approx C\, z_h^{0.5}(1-z_h)\,\nu$$

It should:
1) rise with A$^{1/3}$, then level off 🙂

$$\Delta\langle p_T^2 \rangle = D\left[(A/2)^{1/3}-1\right]$$

E866

E772

JLab/CLAS preliminary

HERMES Preliminary, see E.Aschenaur talk

JLAB preliminary, Will Brooks, Trento workshop

3) p_T – broadening [A.A., nucl-th/0808.0656]
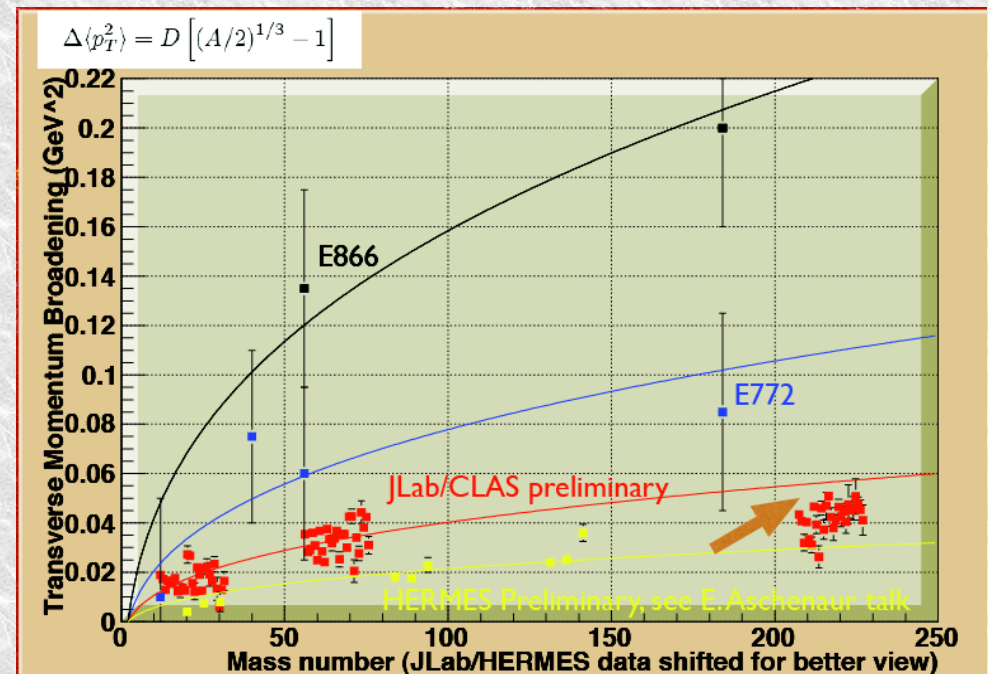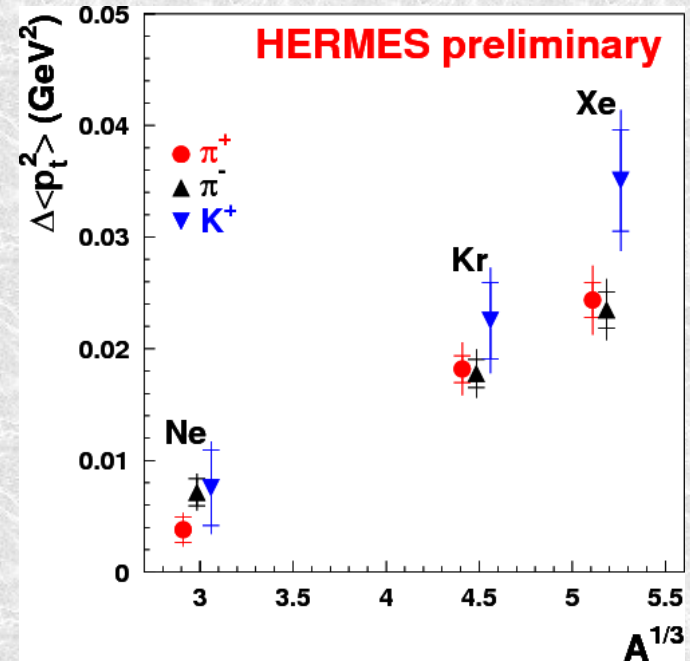
HERMES preliminary

- Let's assume no energy loss for a mom...

$$\Delta\langle p_T^2\rangle \propto \langle t_p\rangle \approx C\, z_h^{0.5}(1-z_h)\,\nu$$

- It should:
  1) rise with $A^{1/3}$, then level off 🙂
  2) decrease as $z_h \to 1$ 🙂
  3) rise with ν, then level off ❓❓

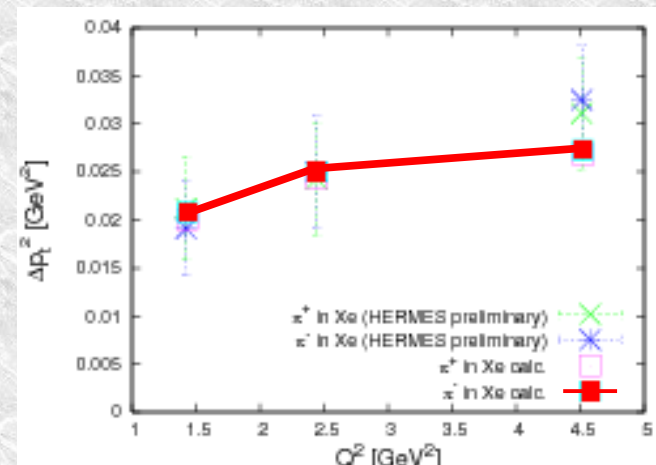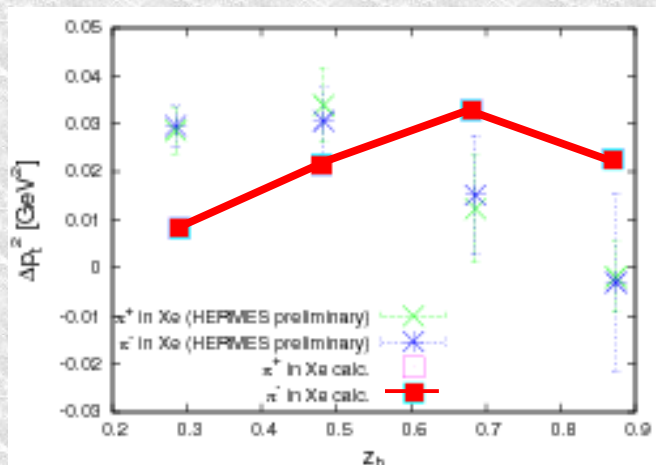pT broadening

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

E_{lab} = 5 GeV

Struck quark energy (GeV)

HERMES prelim.	$\langle Q^2\rangle$ [GeV^2]	ν [GeV]	$\langle z_h\rangle$	$\langle t_p\rangle$ [fm]
$\langle \Delta p_{Th}^2\rangle$ vs ν	2.1	8.1	0.48	2.4
	2.5	12.0	0.42	3.7
	2.6	15.0	0.40	4.6
	2.4	18.6	0.36	5.8

3) p_T – broadening [A.A., nucl-th/0808.0656]
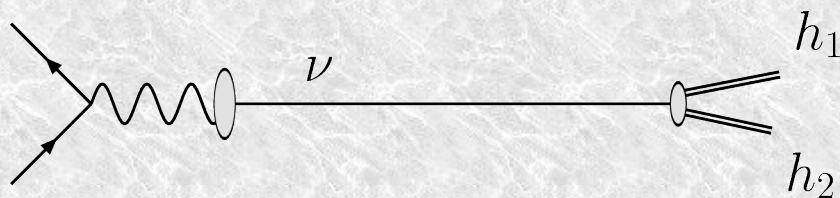
◆ **Medium-enhanced DGLAP evolution?**   (see talk by K.Zapp)

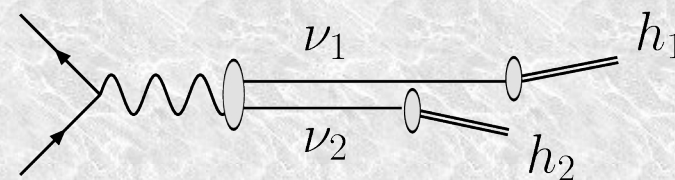[Ceccopieri et al. PLB'08; Armesto et al. JHEP'08; Domdey et al. arXiv:0802.3282]

$$(\Delta p_{\perp}^2)_h(Q^2) = (\Delta p_{\perp}^2)_h(Q^2) + z_h^2 \, \nu \, \rho_0 \, \langle \sigma q_{\perp}^2 \rangle \left(\frac{1}{\bar{Q}^2} - \frac{1}{Q^2} \right)$$ [Domdey et al., arXiv:0812.2838]

◆ **NLO effects ?**

struck q at large x_B (large Q^2)   struck $q\bar{q}$ at small x_B (small Q^2)

◆ **Colored dipoles with t_p~0 t_{cn}~(1-z)ν ??**

4) Correlations between x_B and Q^2

[A.A., nucl-th/0808.0656]

◆ For example: if Lund string model for $\langle t_p \rangle$ is valid,

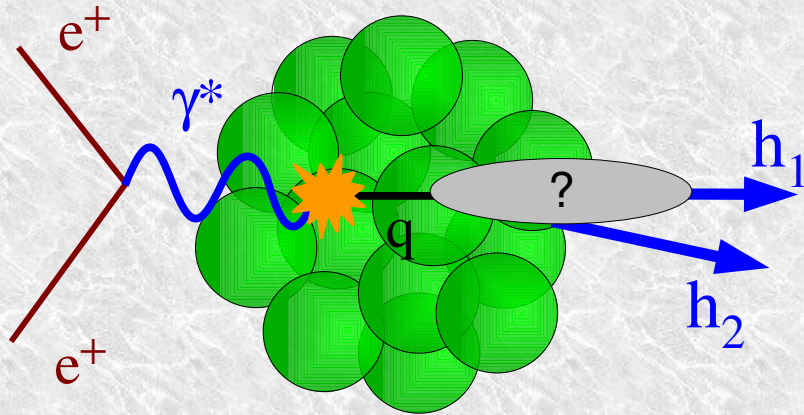$$Q^{-2}\Delta\langle p_T^2 \rangle_{x_B\text{-bins}} \approx \text{const.}$$

$$x_B\Delta\langle p_T^2 \rangle_{Q^2\text{-bins}} \approx \text{const.}$$

◆ Deviations from such scaling are going to expose the underlying physics:

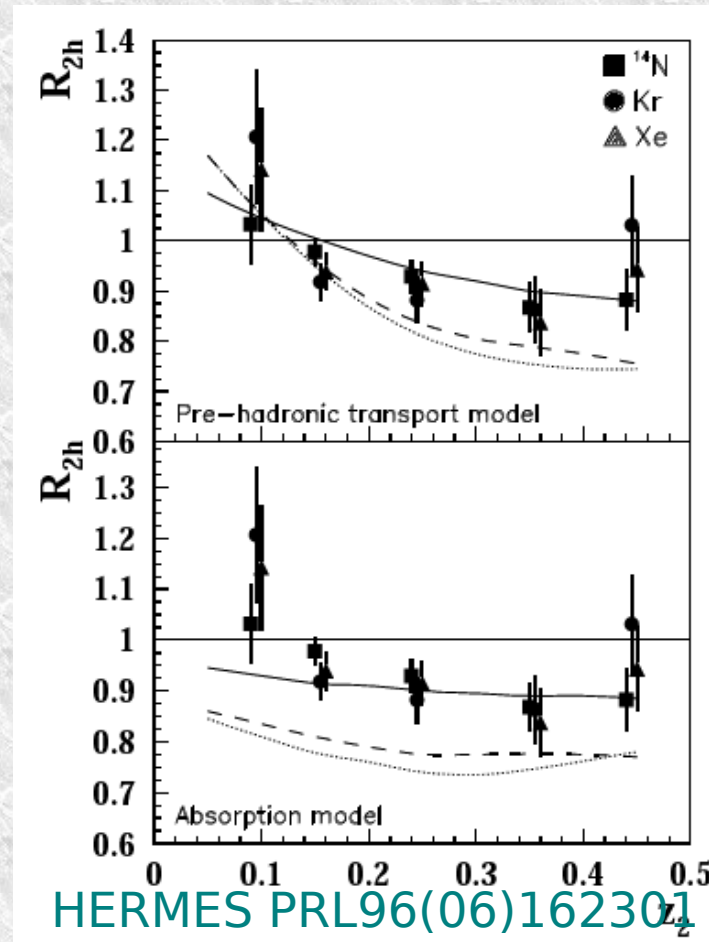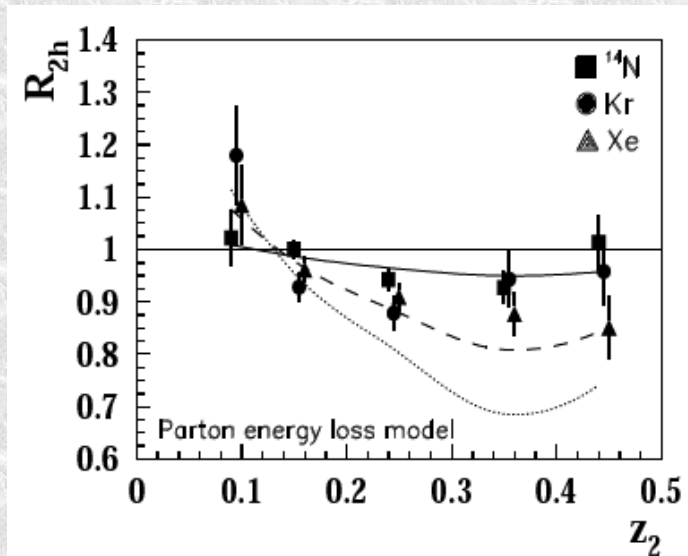|	model	$Q^{-2}\Delta\langle p_T^2 \rangle_{x_B}$ vs. Q^2	$x_B\Delta\langle p_T^2 \rangle_{Q^2}$ vs. x_B
$t_p \propto \nu/\kappa$	LO	$\leftrightarrow$	$\leftrightarrow$
	mDGLAP (1)	$\uparrow$	$\leftrightarrow$
	NLO vs. LO (2)	$\leftrightarrow$	$\uparrow$
	colored h_c^* (3)	$\uparrow$	$\leftrightarrow$
$t_p \propto \nu/Q^2$	color dipole [11]	$\downarrow$	$\leftrightarrow$

Two-particle correlations at HERMES

🔶 **Double hadron attenuation** R_2

🔶 in A+A = "same-side correlations",
(akin to jet yield on top of ridge)
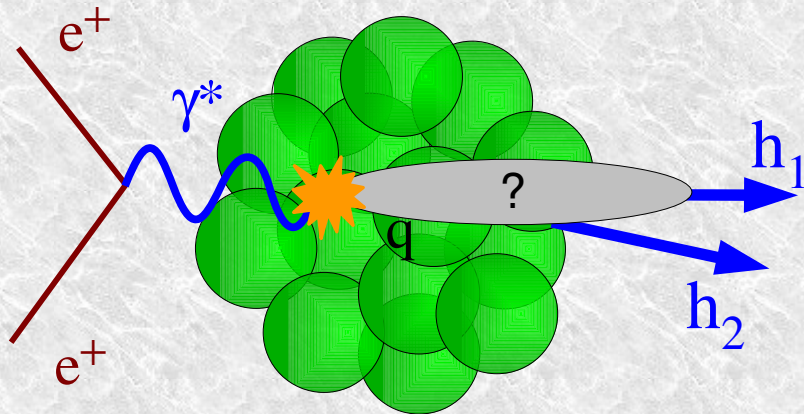
$$R_2(z_2) = \frac{\left.\frac{N_2(z_2)}{N_1}\right|_A}{\left.\frac{N_2(z_2)}{N_1}\right|_D}$$
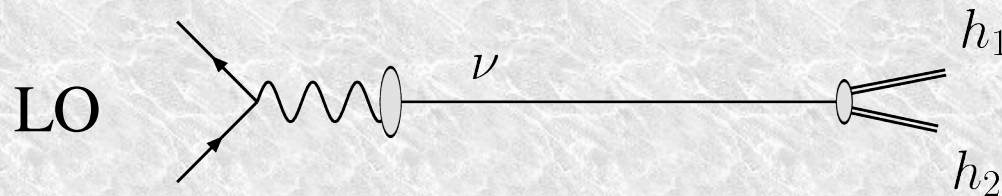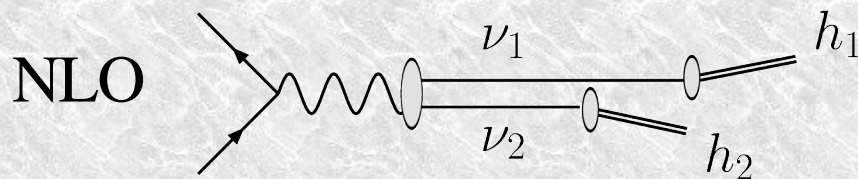
$$z_2 \leq z_1 \ ; \ z_1 \geq 0.5$$

HERMES PRL96(06)162301

Two-particle correlations at HERMES

◆ Small A-depence: surface bias?

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

$$z_2 \le z_1 \; ; \; z_1 \ge 0.5$$

◆ E.g., NLO hard scattering

LO

$$z_i^{\mathrm{LO}} = E_i^h / \nu$$

NLO

$$z_i^{\mathrm{NLO}} = E_i^h / \nu_i > z_i^{\mathrm{LO}}$$

more absorption: hard scattering for *observed h* is close to surface

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

➤ Old thinking: the A$^{2/3}$ law

  ➤ Energy loss (LPM effect in QCD): $1 - R_M \sim \langle \Delta z \rangle \sim L^2 \sim A^{2/3}$

  ➤ Hadron absorption: $1 - R_M \sim \langle$ no. of nucleons seen $\rangle \sim L \sim A^{1/3}$

WRONG!

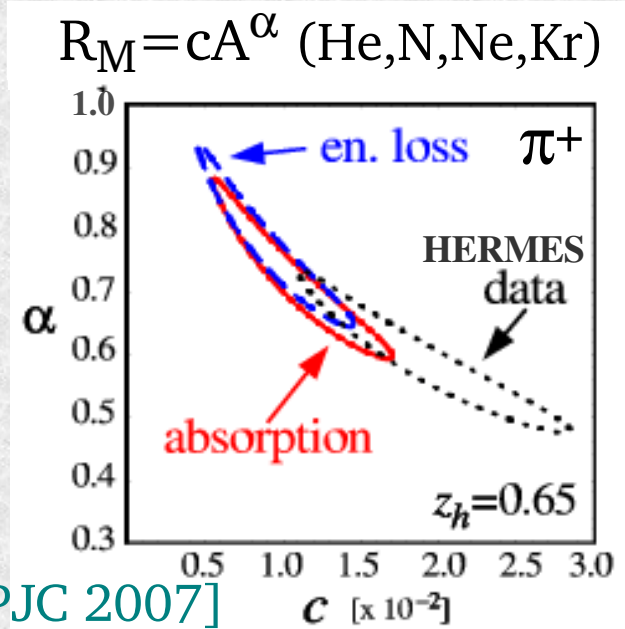➤ A$^{2/3}$ also for absorption models!
[A.A., et al., NPA 761(2005)67]

  ➤ additional dimensionful scale: prehadron production length $\langle t_p \rangle$

  ➤ neutralize it $\Rightarrow$ additional power of A

$$1 - R_M \propto A^{1/3}(R_A/\langle t_p \rangle)^n = A^{(1+n)/3}$$
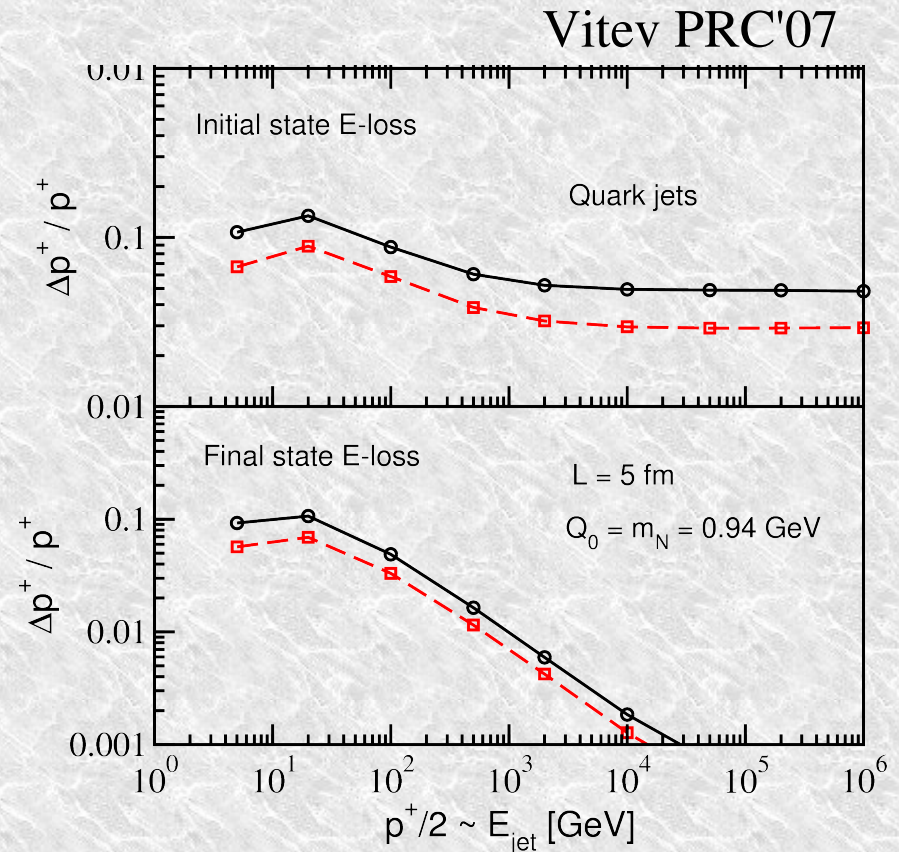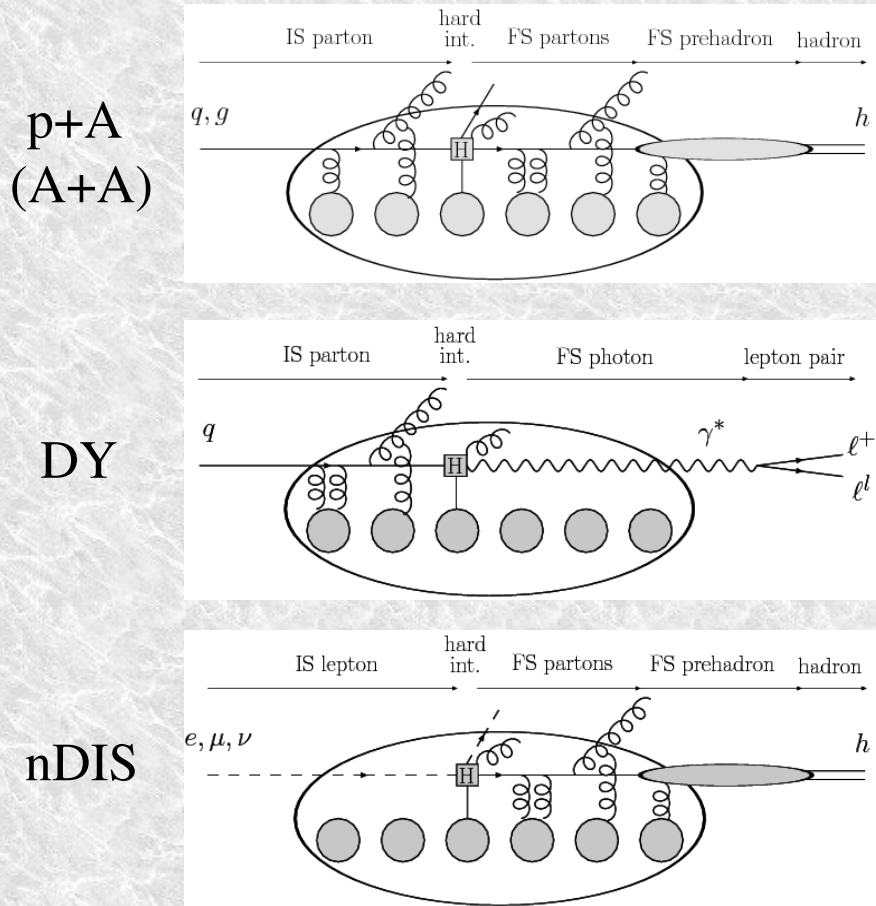
  ➤ typically A$^{2/3}$!!

$R_M = cA^\alpha$ (He,N,Ne,Kr)

en. loss   π$^+$

HERMES data

absorption

$z_h = 0.65$

α c [x 10^{-2}]

[A.A.,EPJC 2007]

A-dependence of R$_M$ does not test dominance of partonic or prehadronic physics: no info on parton lifetime

Initial state parton energy loss in p+A / A+A

🔶 Initial & final state cold energy loss in p+A / A+A :
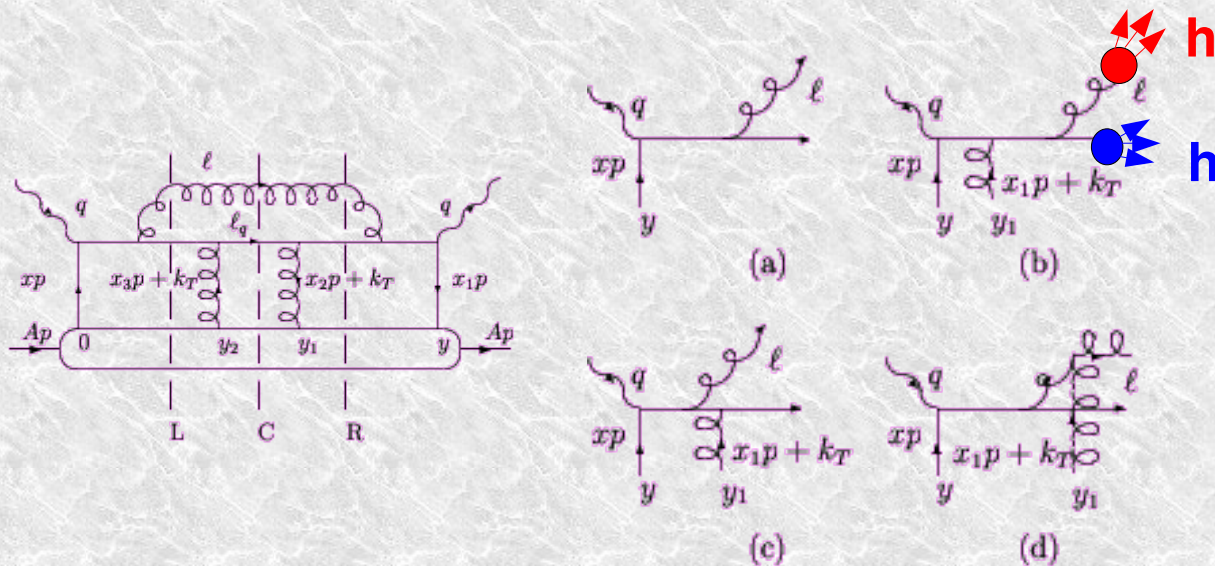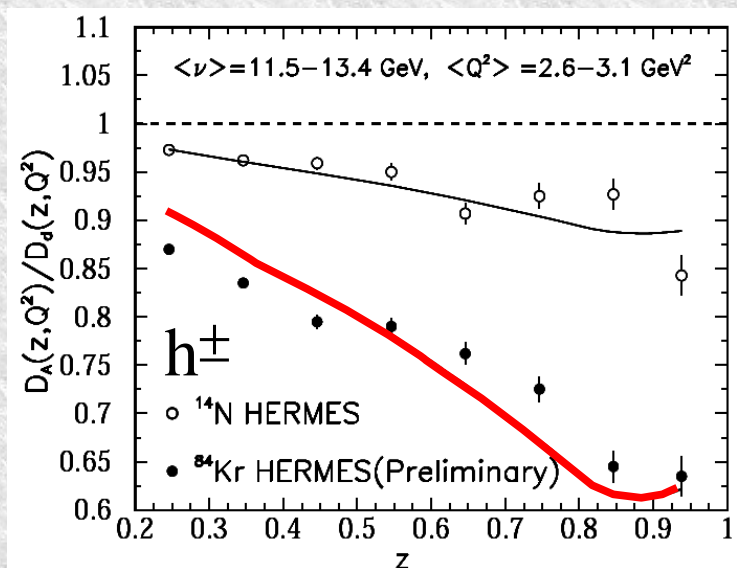
p+A
(A+A)

DY

nDIS

Vitev PRC'07

🔶 Initial state energy loss can be large [Vitev PRC'07]

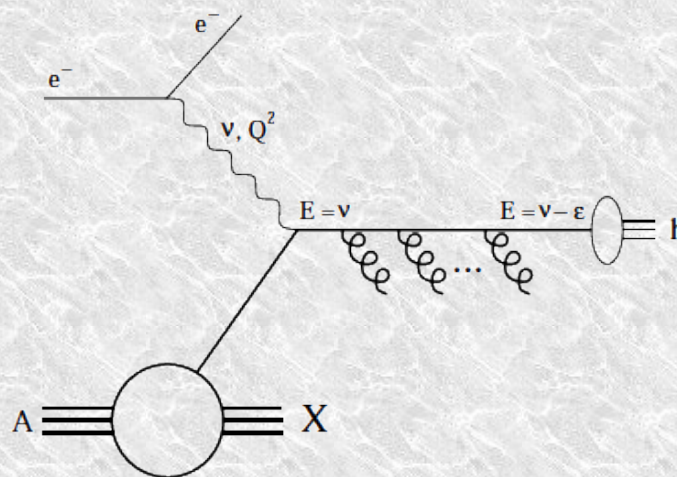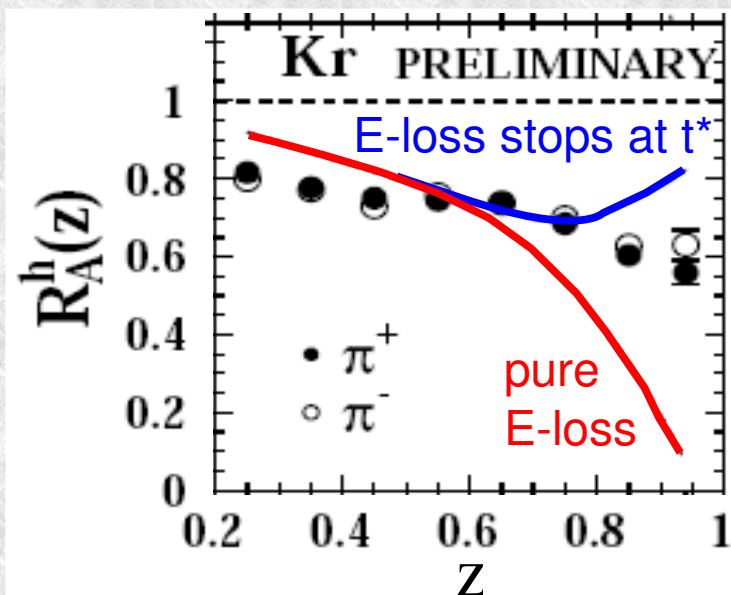➡ test models against DY data (but beware nuclear effects in target w.f.)

Needs unified energy loss formalism for DY, nDIS, h+A

Formation time estimates 1 – energy loss models

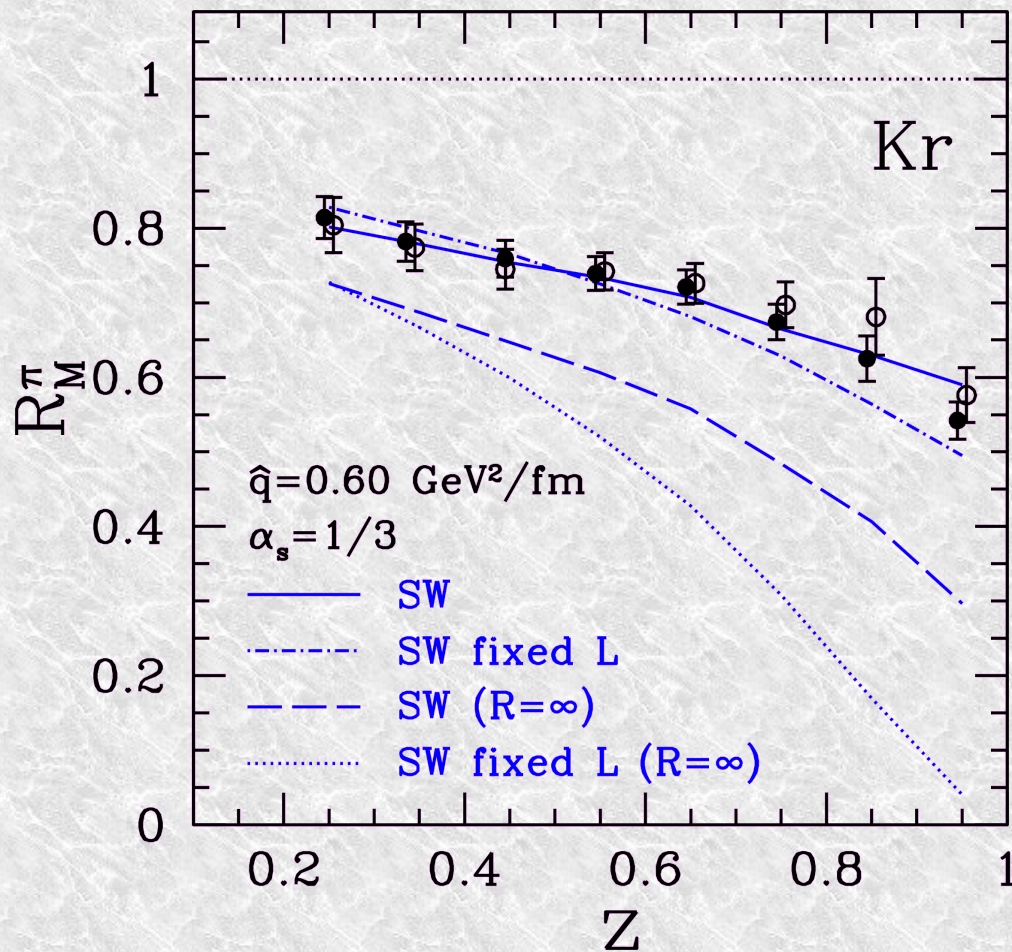◆ Twist-4 modified Fragmentation Fns. [Wang&Guo '00, Wang & Wang '02]

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

Effect of medium geometry approximations

◆ Example: energy loss model with SW quenching weights

Kr

$\hat{q} = 0.60$ GeV²/fm
$\alpha_s = 1/3$

— SW
—·— SW fixed L
— — SW (R=∞)
········ SW fixed L (R=∞)

R_M^π

Z

Fixed vs. variable path length:
⇒ change in slope
⇒ variable p.l. describes data,
    fixed L too steep
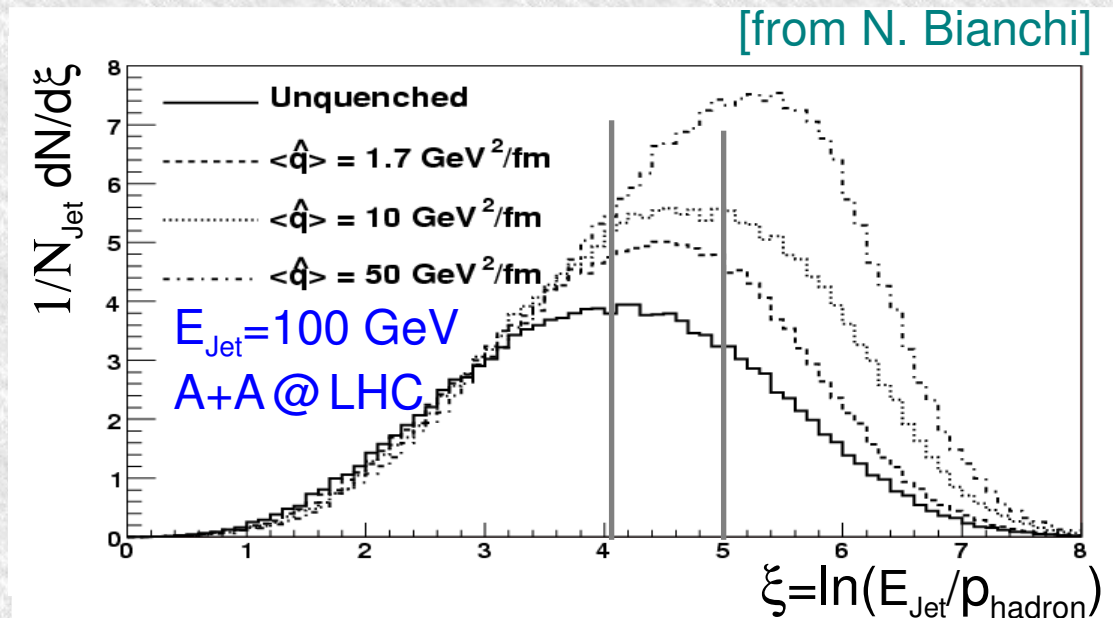
Thick vs. finite size medium:

⇒ changes $\hat{q}$
⇒ thick: $\hat{q} \approx 0.2$ GeV²/fm
⇒ f.s.: $\hat{q} \approx 0.6$ GeV²/fm

◆ **Correct geometry needed at qualitative & quantitative levels**

The EIC – jet physics

* First time for jet physics in e+A
  - map out observables as a function of parton energy

* Tests of energy loss models:
  - e.g., modification of jet shapes in cold nuclear matter
    [Borghini, Wiedemann, '06]

[from N. Bianchi]

Unquenched
$\langle\hat{q}\rangle$ = 1.7 GeV^2/fm
$\langle\hat{q}\rangle$ = 10 GeV^2/fm
$\langle\hat{q}\rangle$ = 50 GeV^2/fm

E_{Jet}=100 GeV
A+A @ LHC

$\xi = \ln(E_{Jet}/p_{hadron})$

  - light-quark jets vs. heavy-quark jets vs. gluon jets
  - dijets, γ-jet correlations, ...

The EIC – small x

- Increased production of heavy flavors

- heavy quarks $\Rightarrow$ D, B mesons
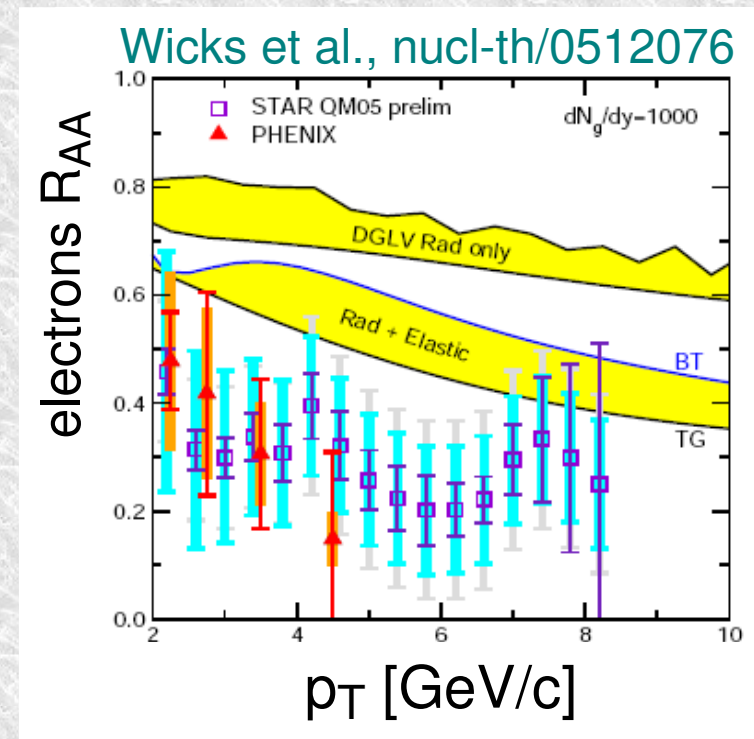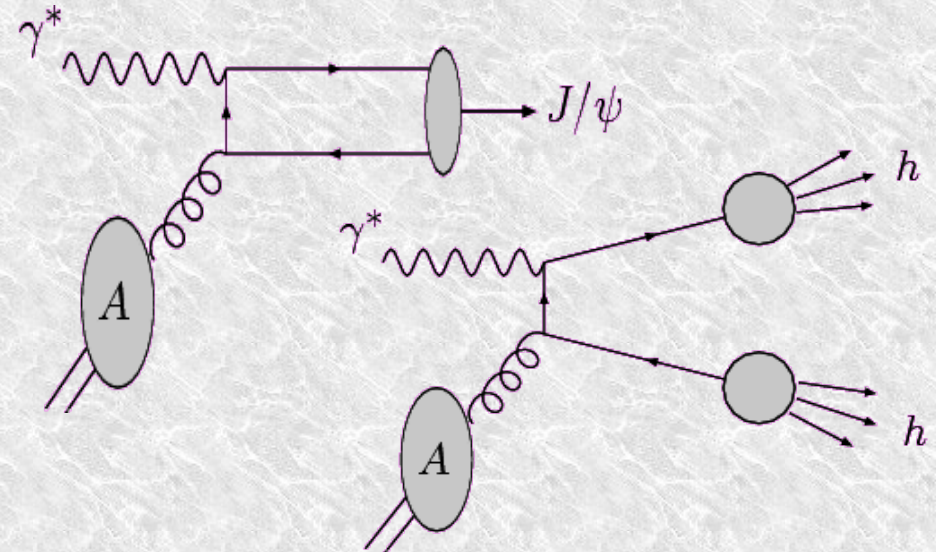 - "heavy quark puzzle" at RHIC

- J/ψ "normal suppression"
  - J/ψ, ψ', χ suppression pattern
  - theoretically and experimentally cleaner in e+A

- back-to-back partons
  - "away-side" correlations: hadron-hadron, γ-hadron

Wicks et al., nucl-th/0512076

The EIC – large Q^2 range

* Access to true perturbative QCD regime

* Color transparency

* Q^2 dependence of mentioned observables
  * is p_T-broadening going to plateau at large Q^2 ?

* Super fast quarks in nuclei:
  * DIS regime at $x_B \gg 1$
  * exotic mechanisms
    * short-range nucleon correlations
    * 6-, 9-, ..., n-quark bags
    * ...

CLAS, PRL96(2006)

Quasi-elastic regime
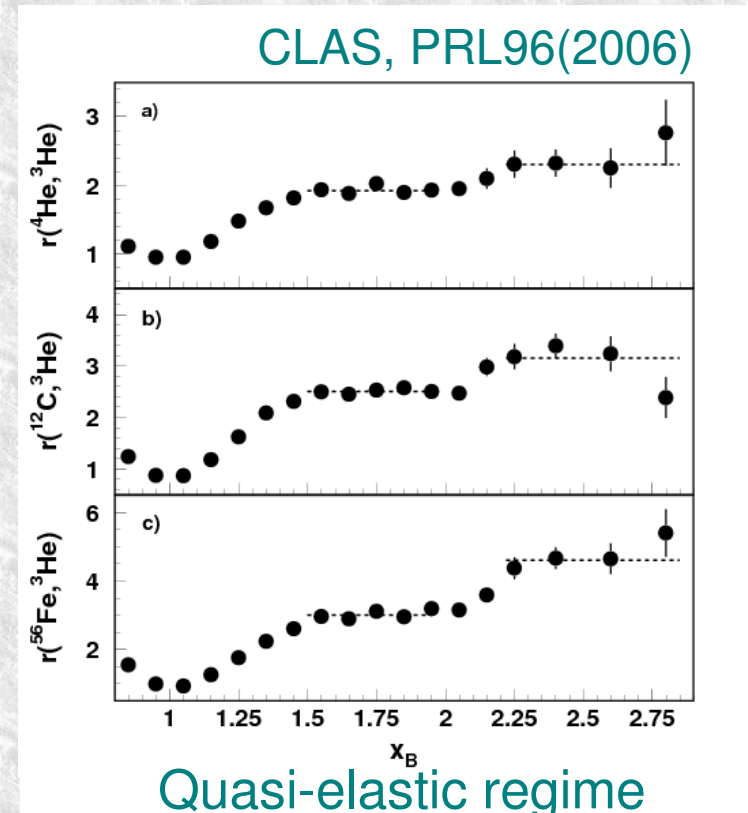
The EIC – large W²

★ Heavy mesons from fragmentation, large rate

  ➡ η vs. π attenuation (no difference at RHIC)

    ● low-ν ⟹ η is heavier, hadronizes earlier

    ● high-ν ⟹ same valence,
               same partonic effects?

    ● role of Q^2 (at RHIC, $Q^2 \sim$ 10-50 GeV²)

  ➡ extend to strange / charm sector

★ Baryons from fragmentation

  ➡ study baryon transport

  ➡ investigate baryon anomaly
    seen in fixed-target e+A,
    in p+p through A+A

  ➡ needs a good variety of baryons
    p, Λ, strange and charmed, ...

PHENIX, PRC75(2007)
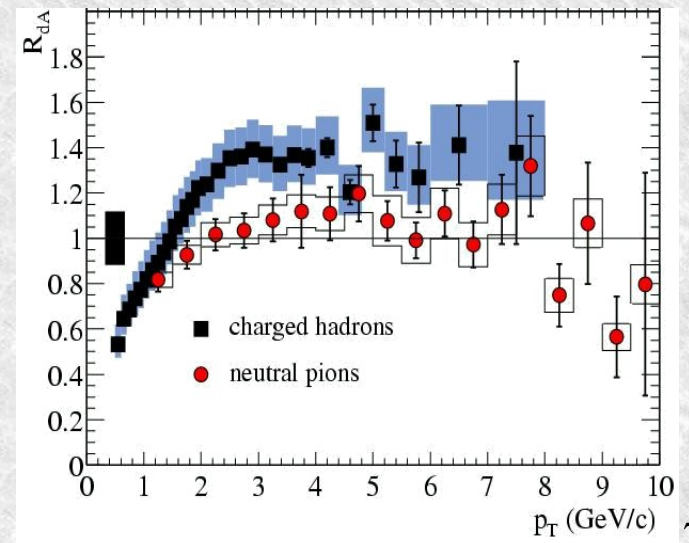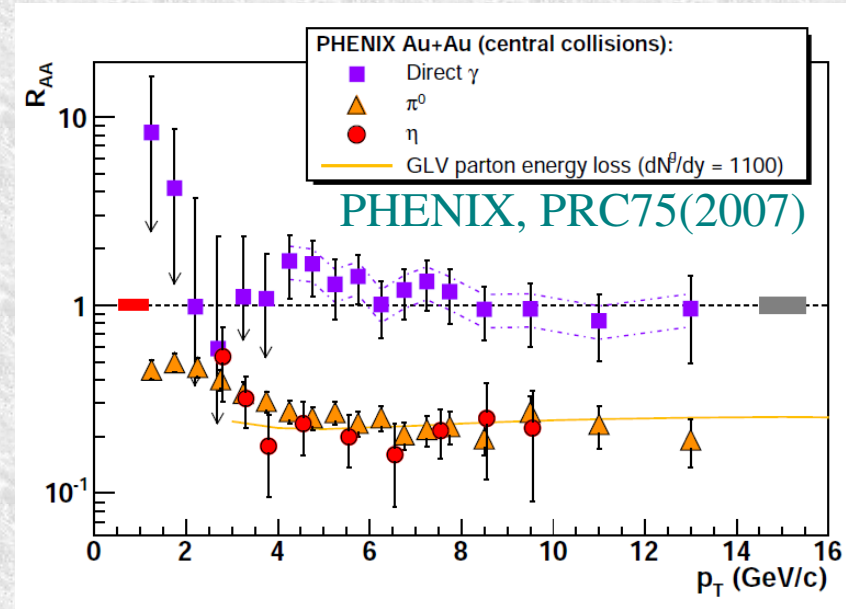
The EIC – large W²

* Heavy-quark energy loss and hadronization of D, B mesons in the spotlight at RHIC, big deal at LHC
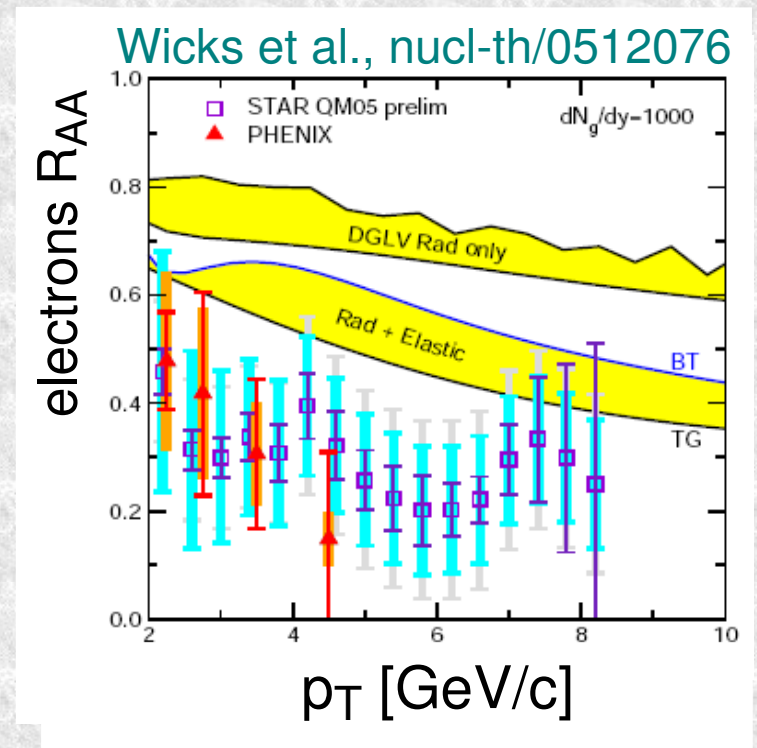 * measure D, B in e+A !

* At HERMES
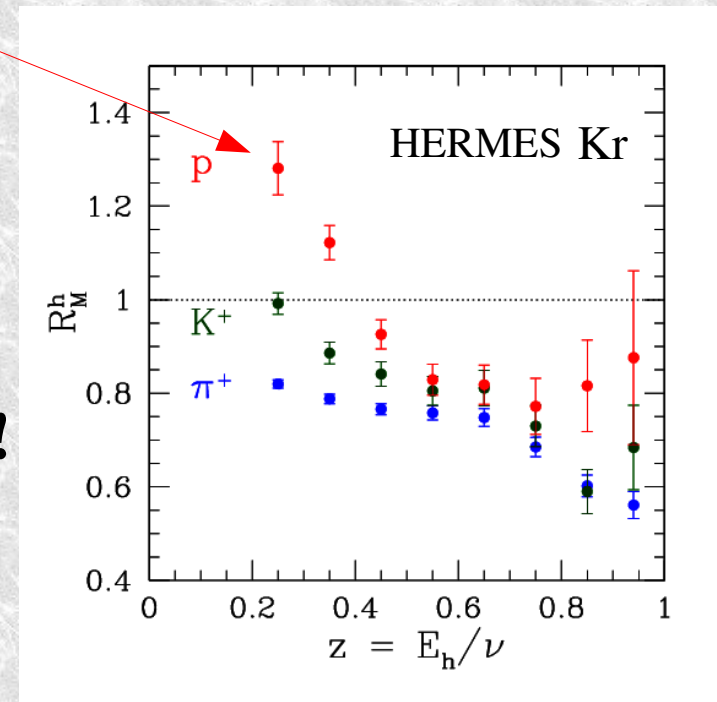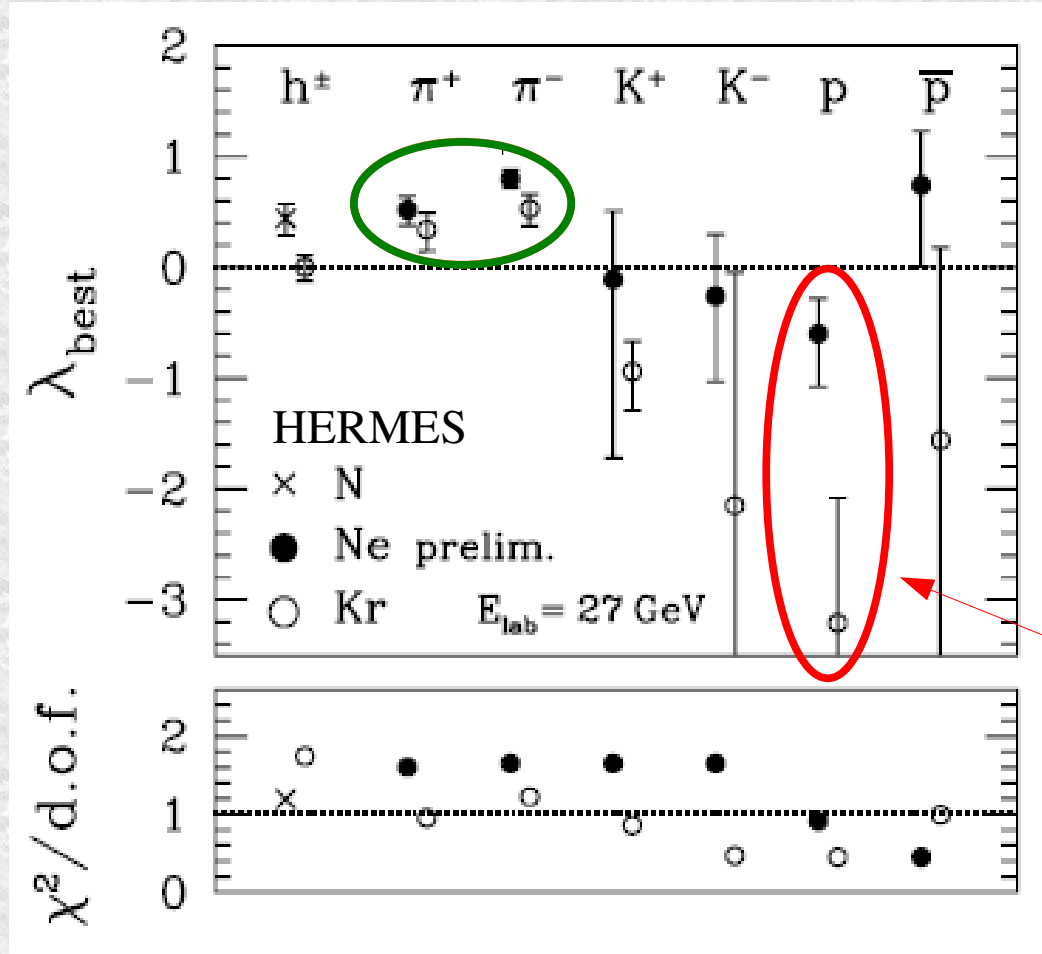 * luminosity is too low for D meson

* 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

Wicks et al., nucl-th/0512076

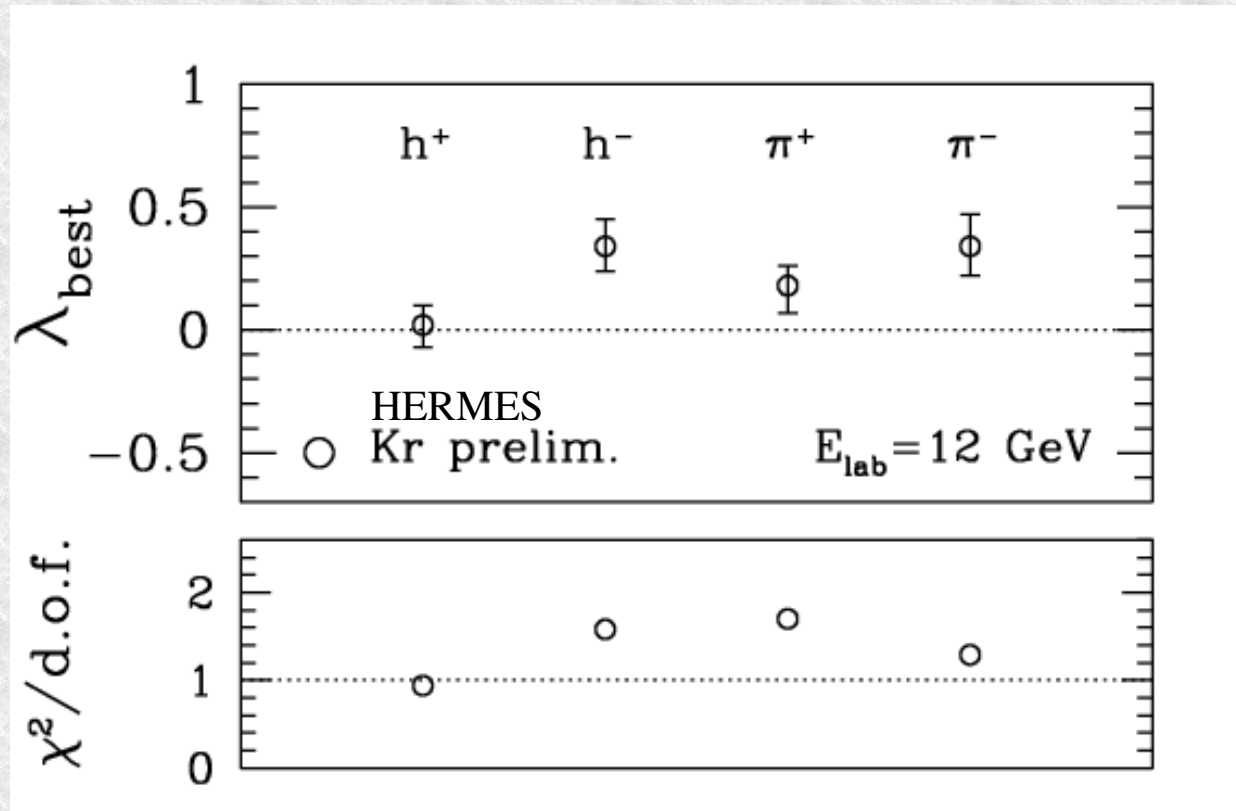* Needs an Electron-Ion Collider!

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

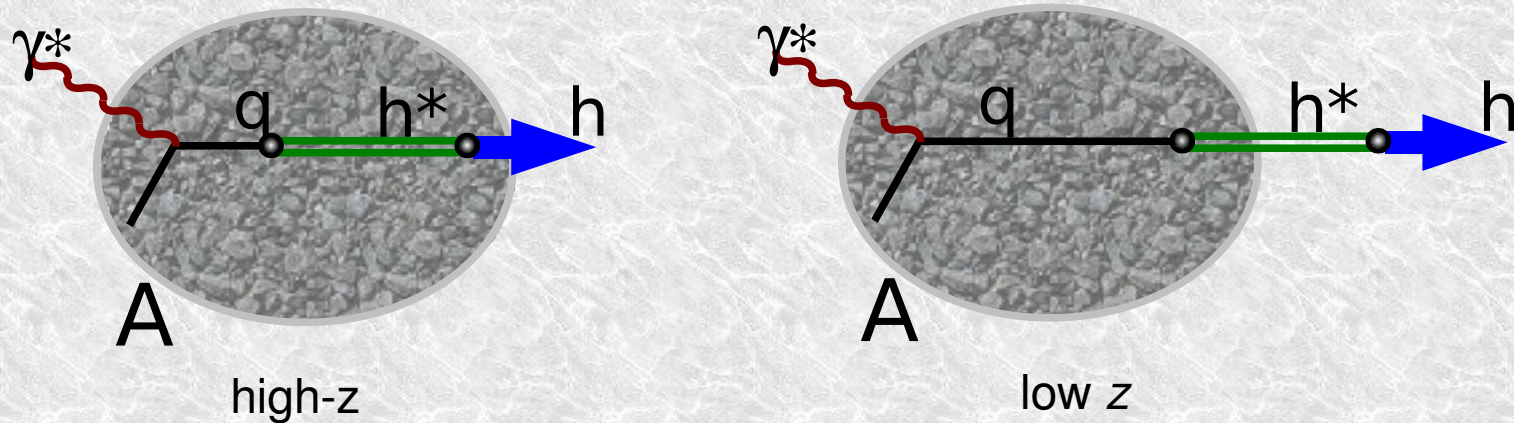# 2) Scaling analysis - example

A.A., PLB B649 (07) 384
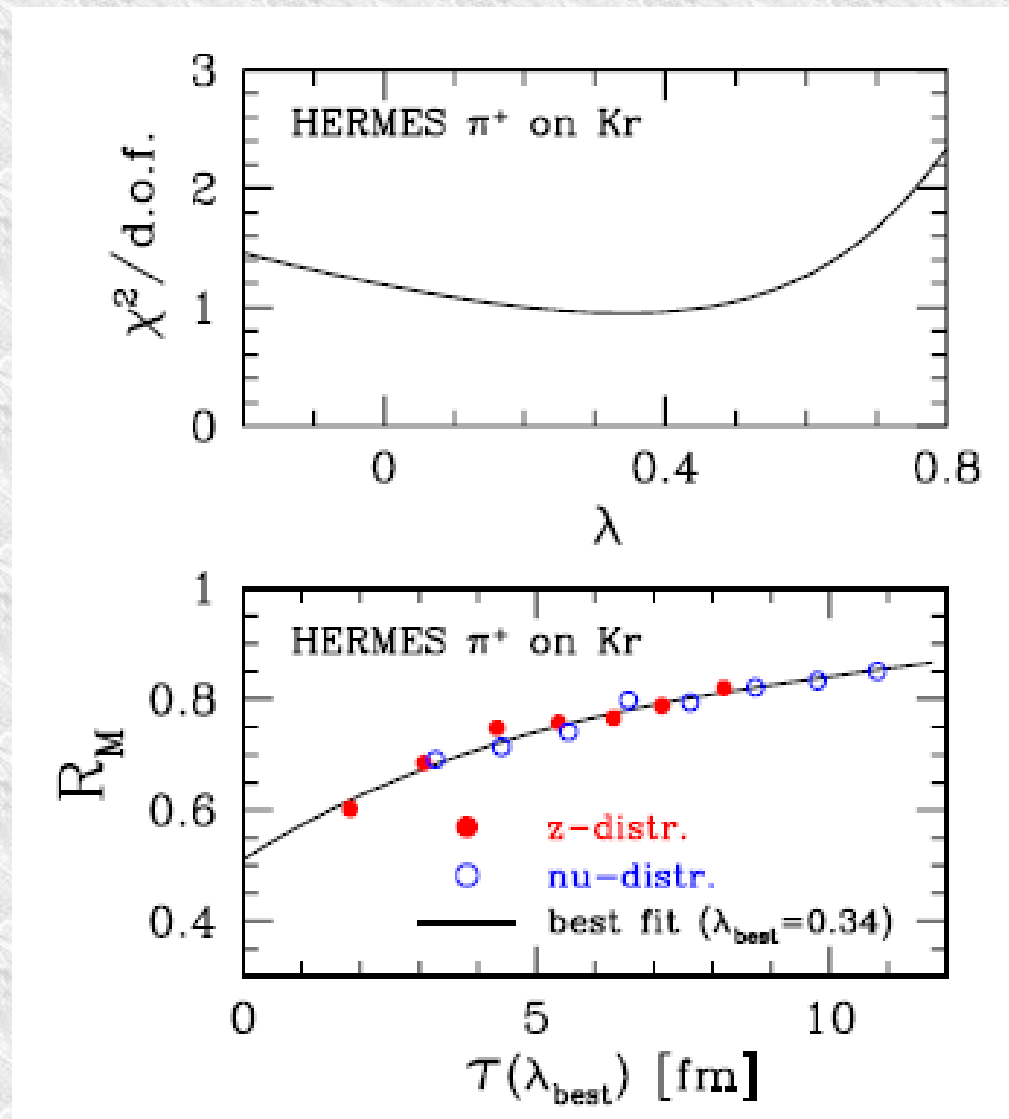
Results – E_{lab} = 12 GeV

- pions are still positive! confirms results at 27 GeV

- λ_{best}(h+) ~ 0 but λ_{best}(h-) > 0
  - proton anomaly hypothesis confirmed!

3) p$_T$ – broadening

high-z   low z

◆ **<p$_T$^{2}> 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.

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

◆ Can be cross-checked by the scaling analysis of R$_M$

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