Hadronization in cold QCD matter: data vs. phenomenology

Alberto Accardi
Hampton U. & Jlab

New ideas in hadronisation,
Durham, 15-17 April 2009

1868

Jefferson Lab

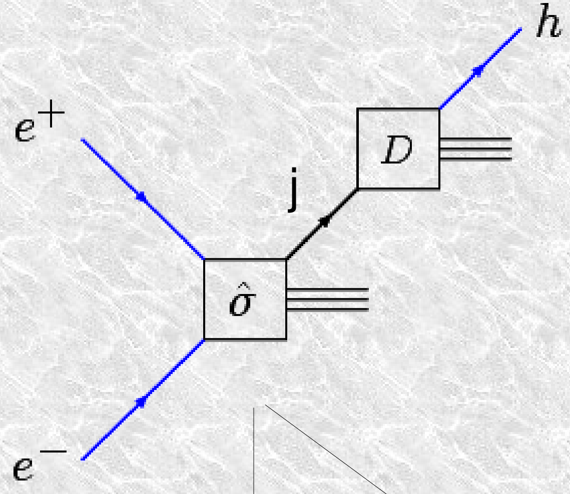
Outline

- **Physics motivations**
- **Very short review of DIS experimental data**
- **Formation times – theory review**
- **Making sense of HERMES / JLAB data**
  - Parton lifetime, dihadron correlations
- **From cold to hot QCD matter**
- **Perspectives at the Electron-Ion Collider (EIC)**
- **Conclusions**

Review: Accardi, Arleo, Brooks, d'Enterria, Muccifora
“Parton propagation and hadronization in QCD matter”
(soon to appear)

Physics motivations

Hadronization in elementary collisions



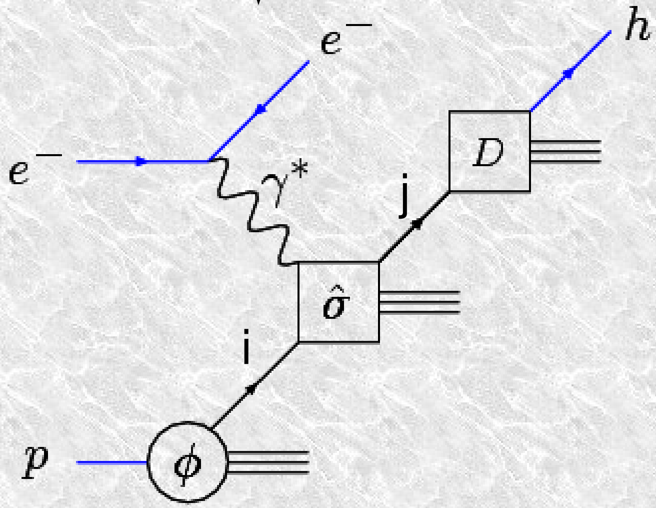
- **perturbative QCD factorization** of short and long distance physics

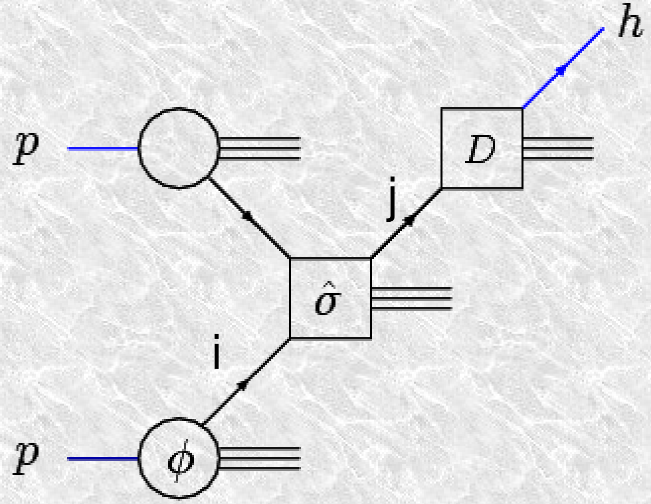
$$d\sigma_{\text{hadron}} = \sum_{ij} \phi_i \otimes \hat\sigma^{ij}_{\text{parton}} \otimes D_{j|h}$$

Parton Distribution Fns
(from inclusive DIS)

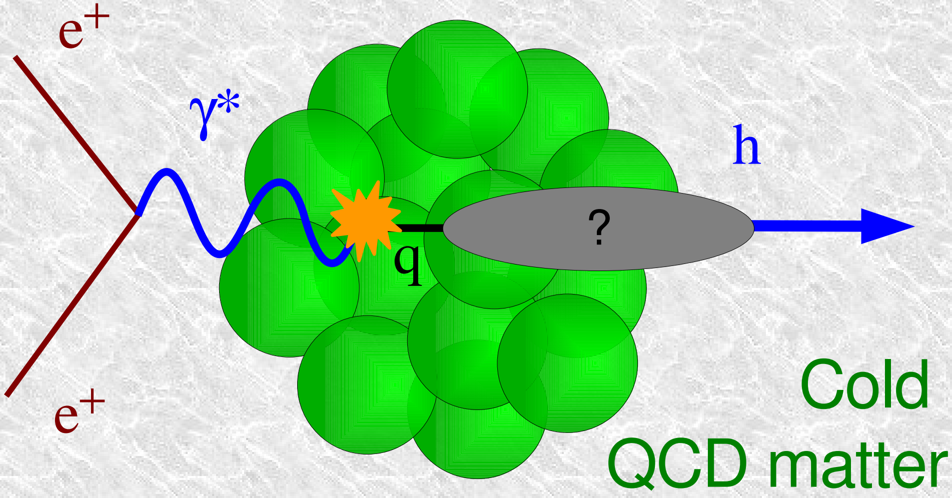
Fragmentation Fns
(from e^++e^- → h+X)

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

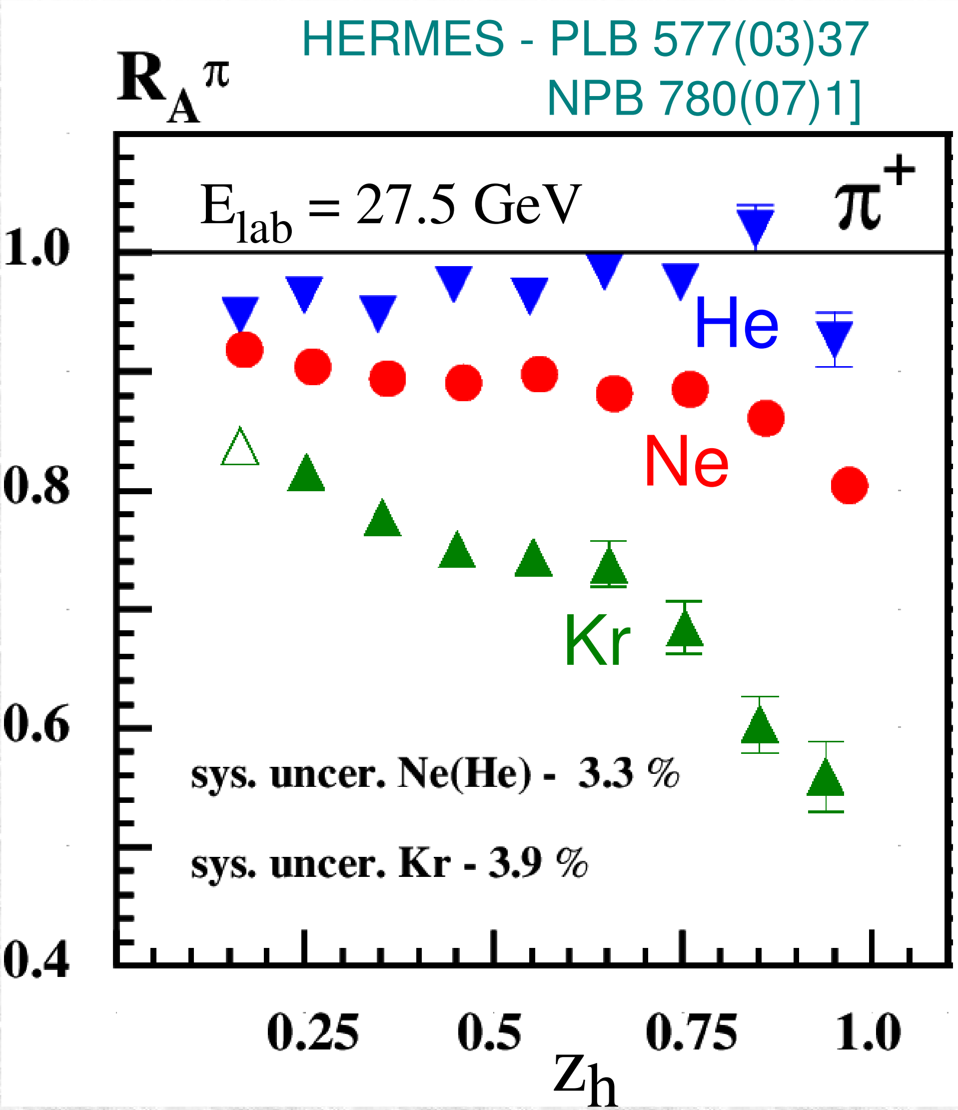




Nuclear collisions 1 - nDIS



$$R^h_M(z_h) = \frac{\frac{1}{N_A^{\rm DIS}} \frac{dN_A^h(z_h)}{dz_h}}{\frac{1}{N_D^{\rm DIS}} \frac{dN_D^h(z_h)}{dz_h}} \approx \frac{D_A(z)}{D_D(z)}$$

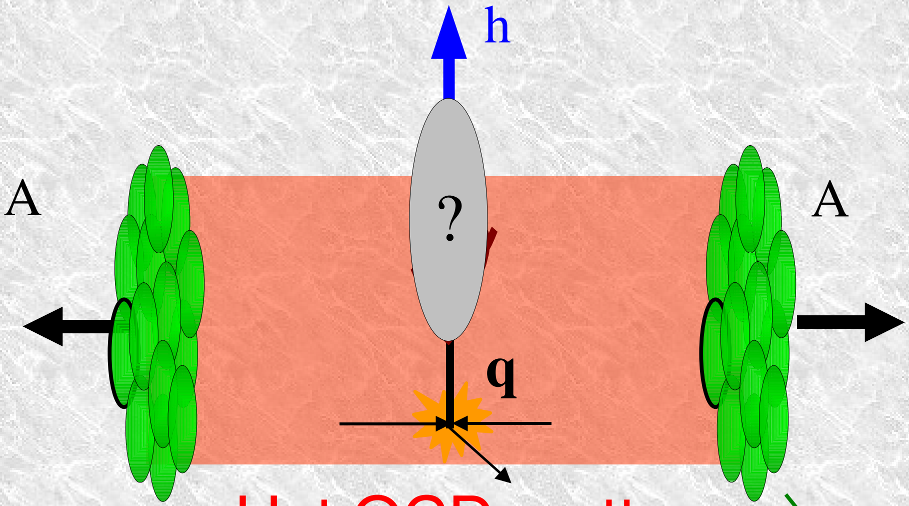


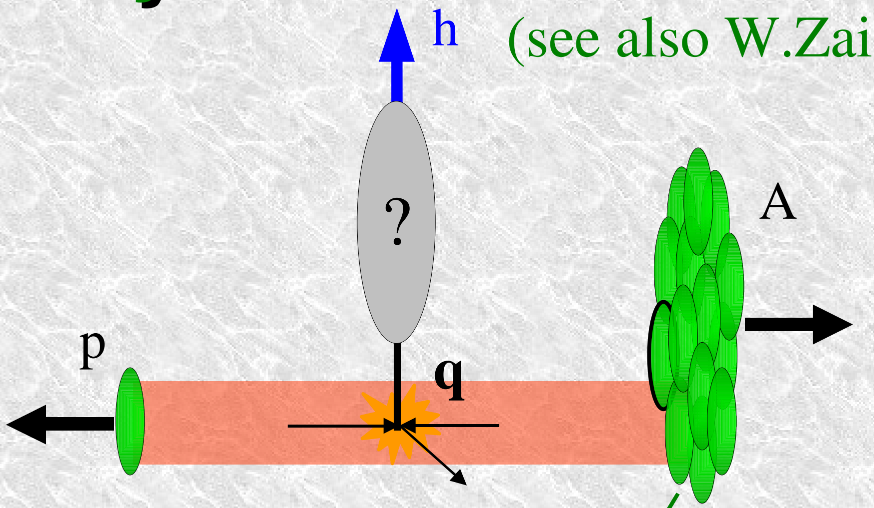
- Nuclear effects on PDF “cancel” in ratio
- Exposes modifications of hadronization

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

Nuclear collisions 2 – Heavy ion collisions

(see also W.Zaic)

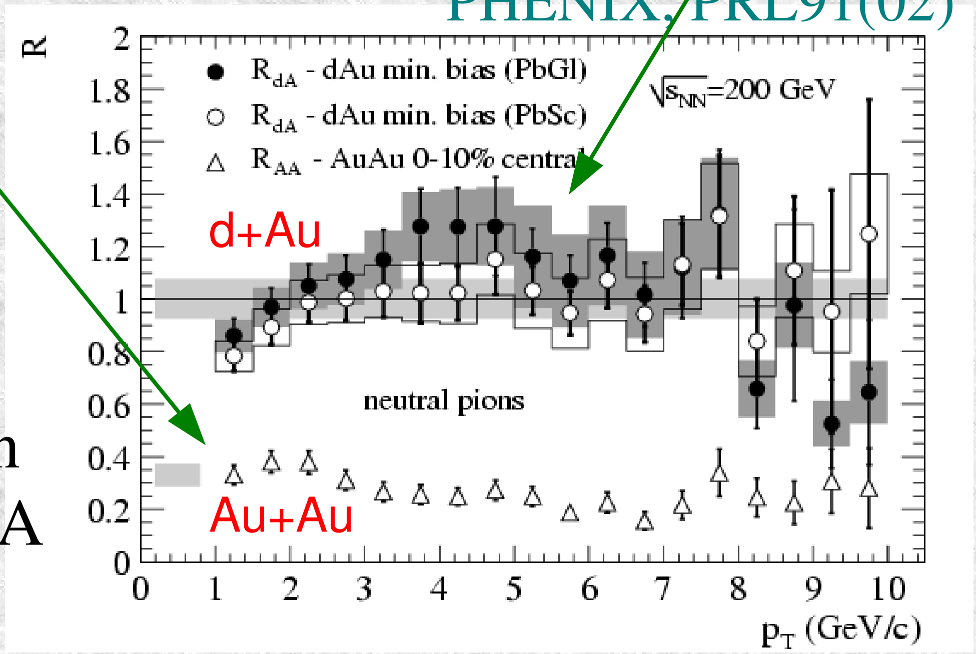




$$R^h_{AB}(p_T) = \frac{\left(dN^h/d^2p_T\right)_{A+B}}{T_{AB}(b)\,\left(d\sigma^h/d^2p_T\right)_{p+p}}$$

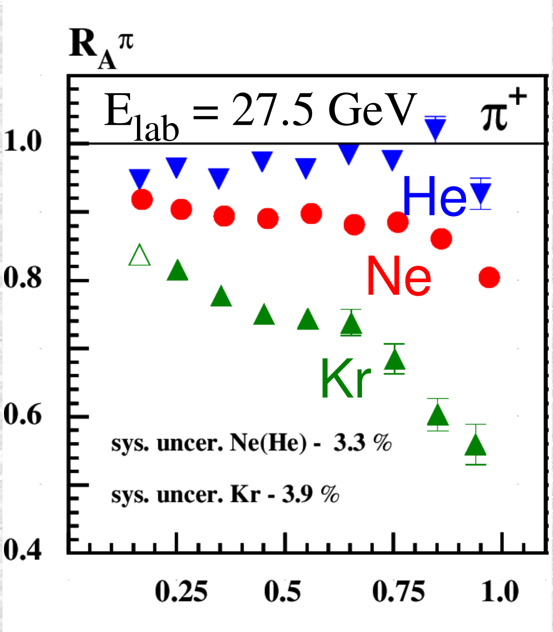
- Medium modifications of hadronization isolated by comparison of h+A and A+A

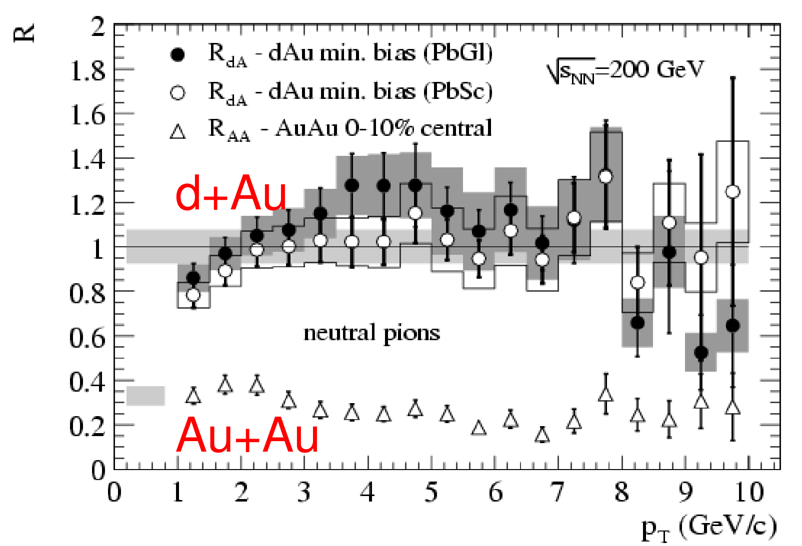
PHENIX, PRL91(02)



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

Breakdown of universality in nuclei

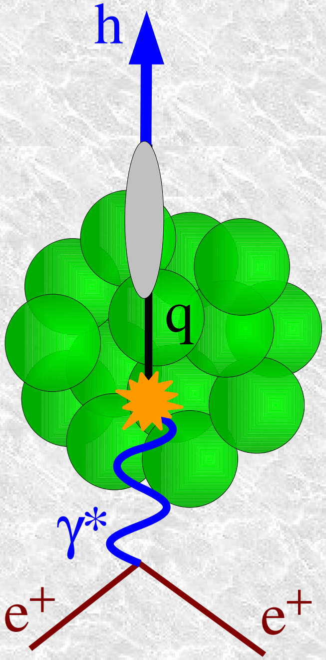


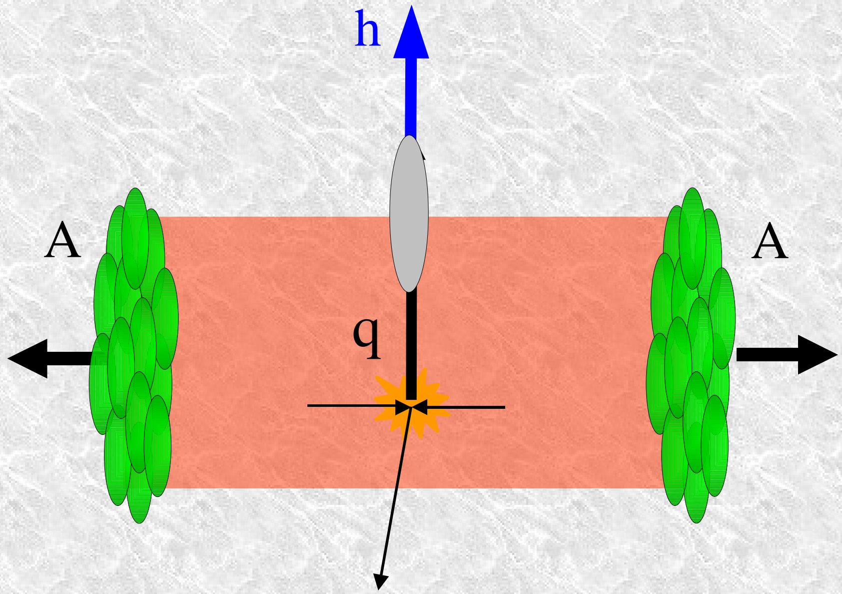


- Hadronization is no more process-independent
- Among possible causes:
  - struck quark interactions with the medium
  - (pre)hadron interactions with the medium
  - in-medium modifications of parton showers
  - other medium nuclear, e.g., partial deconfinement [Dias de Deus '87]
  - breakdown of factorization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

This talk

nDIS vs. A+A collisions





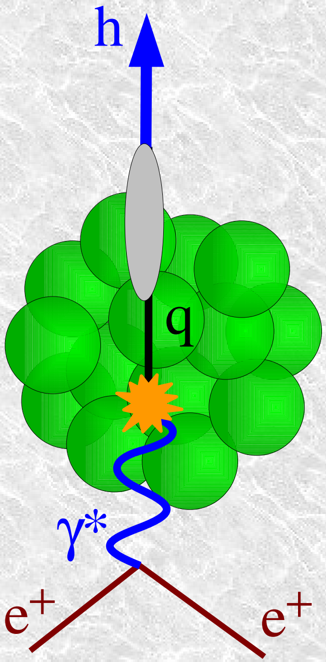
- nDIS is a clean environment for
  - **(1) space-time evolution of hadronization**
    - nucleons as femto-detectors
    - medium rather well known
  - **(2) Cold nuclear matter effects**
    - quark energy loss
    - nuclear modifications of FF
    - parton showers

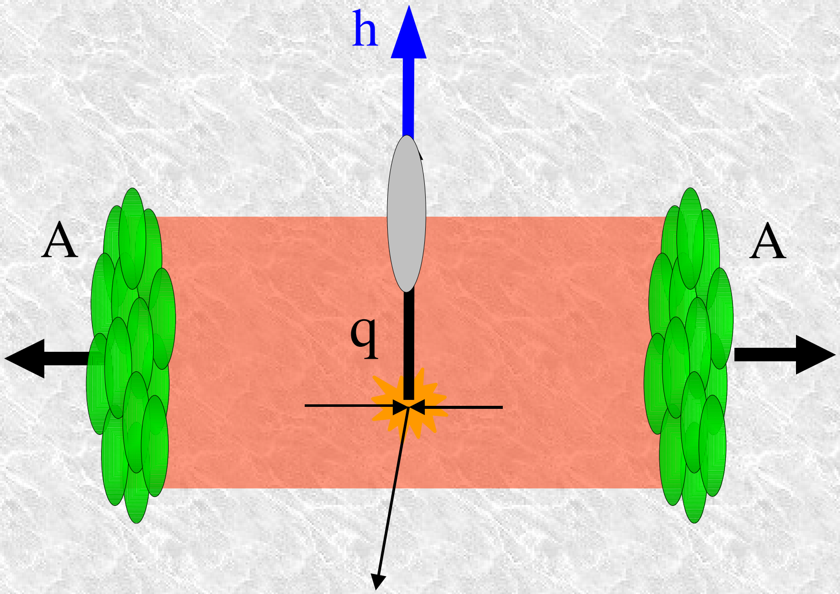
Jet-quenching in A+A

$\Downarrow$

properties of
hot nuclear matter

The fixed-target point of view





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

at HERMES/Jlab

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

$E_q = p_{Th} / z$

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

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

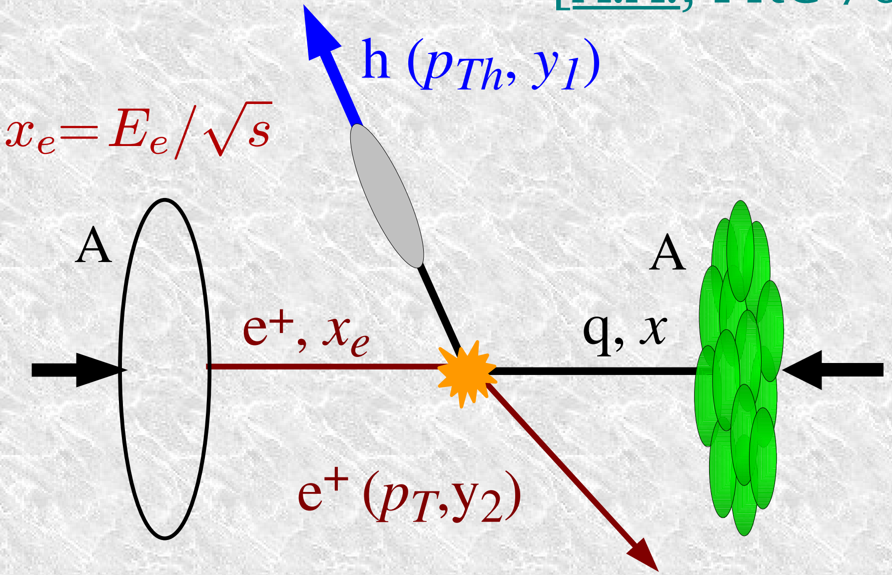
...but beware the virtuality: ≈ 2 GeV^2 vs. 5-70 GeV^2!!

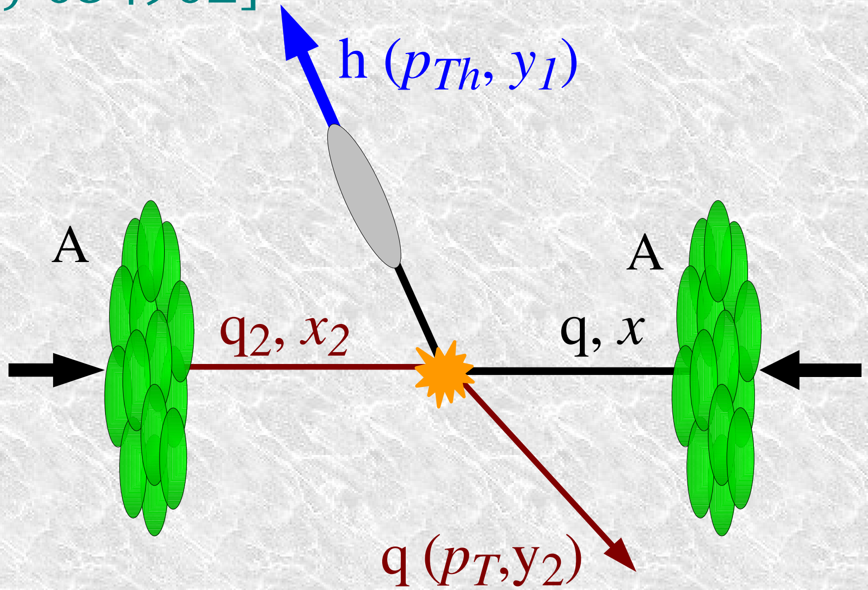
$Q^2 = -q^2$ is measured

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

The collider point of view

[A.A., PRC 76 (07) 034902]





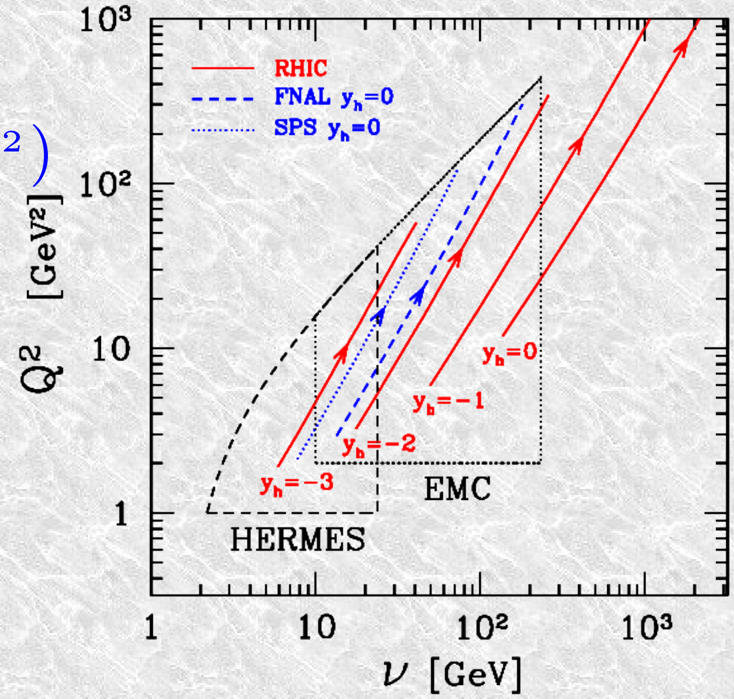
- In LO kinematics:

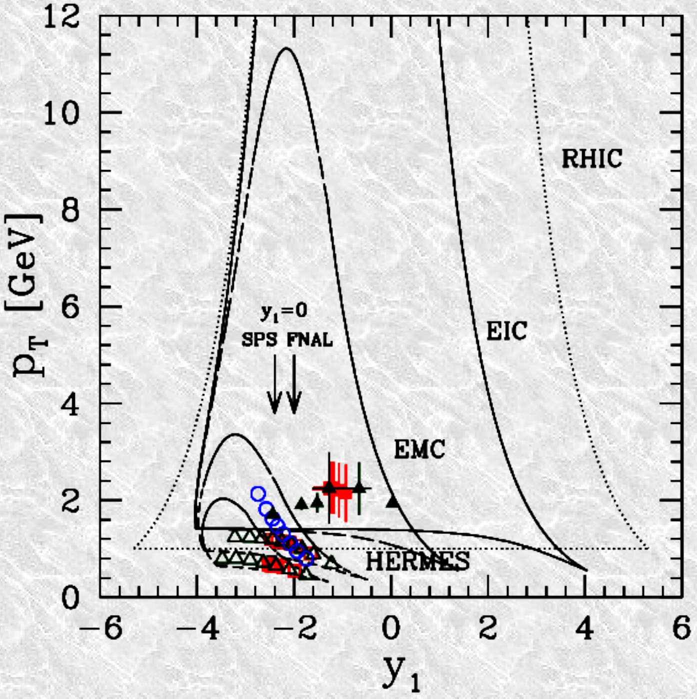
$$Q^2 = p_T^2(1+e^{y_1-y_2})$$

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

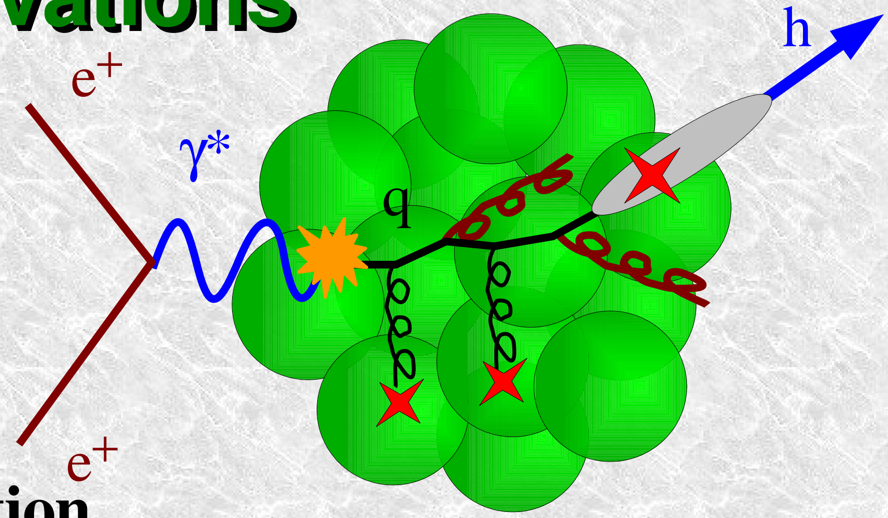
$$y = \frac{1}{1+e^{y_2-y_1}}$$

$$z_h = z$$





Physics 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? Space-time evolution of hadronization
  - color confinement dynamics
- **Parton propagation in perturbative QCD**
  - QCD energy loss: basic pQCD, only indirectly tested so far
  - DGLAP parton shower
- **Connection to other fields**
  - Calibration of jet-quenching in A+A ⇒ properties of QGP
  - Hadron attenuation corrections for ν-oscillation experiments
  - Tuning of parton showers in Monte-Carlo generators

Short review of e+A data

For the latest data see:

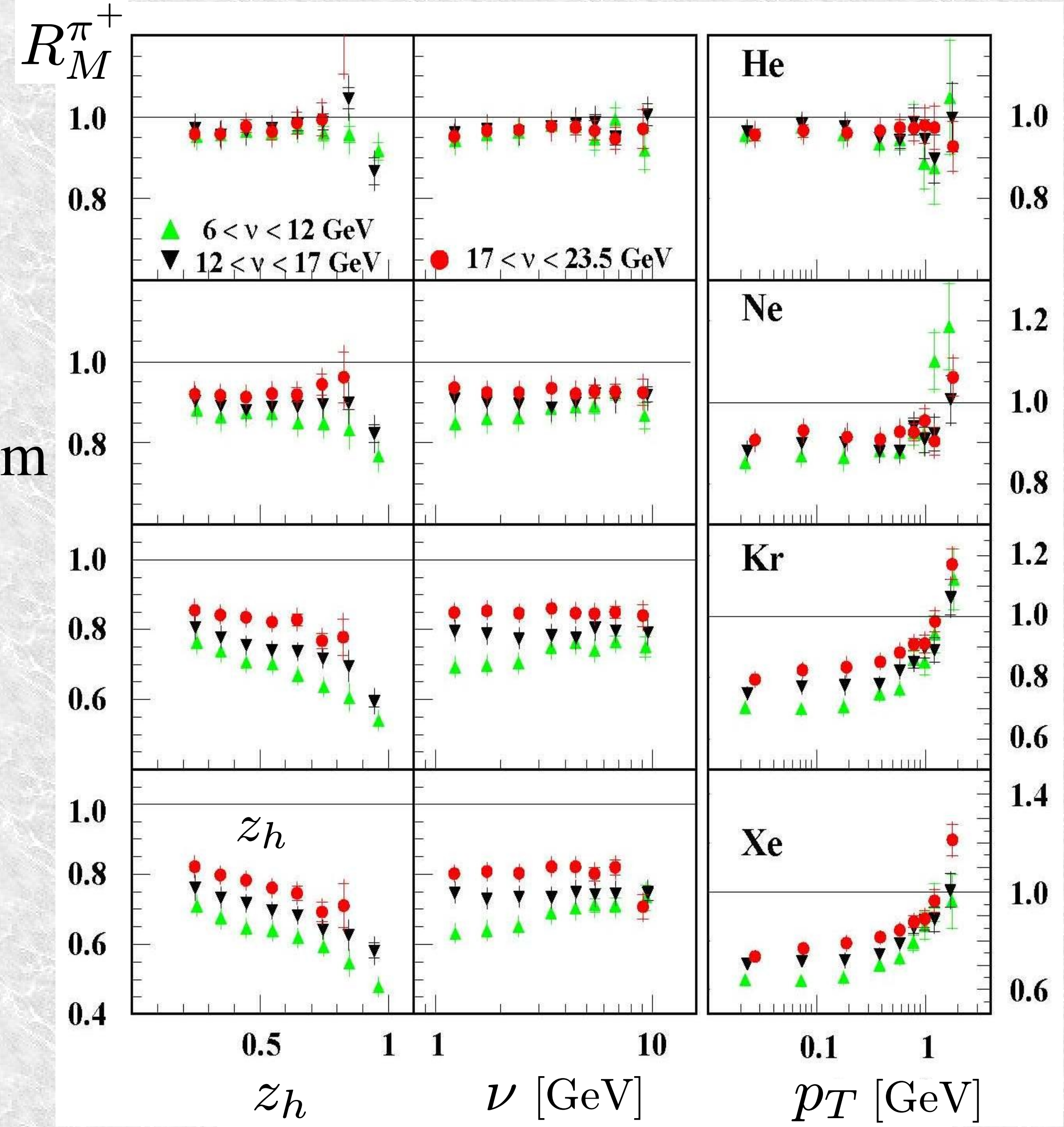
1) HERMES, NPB 780 (2007) 1

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

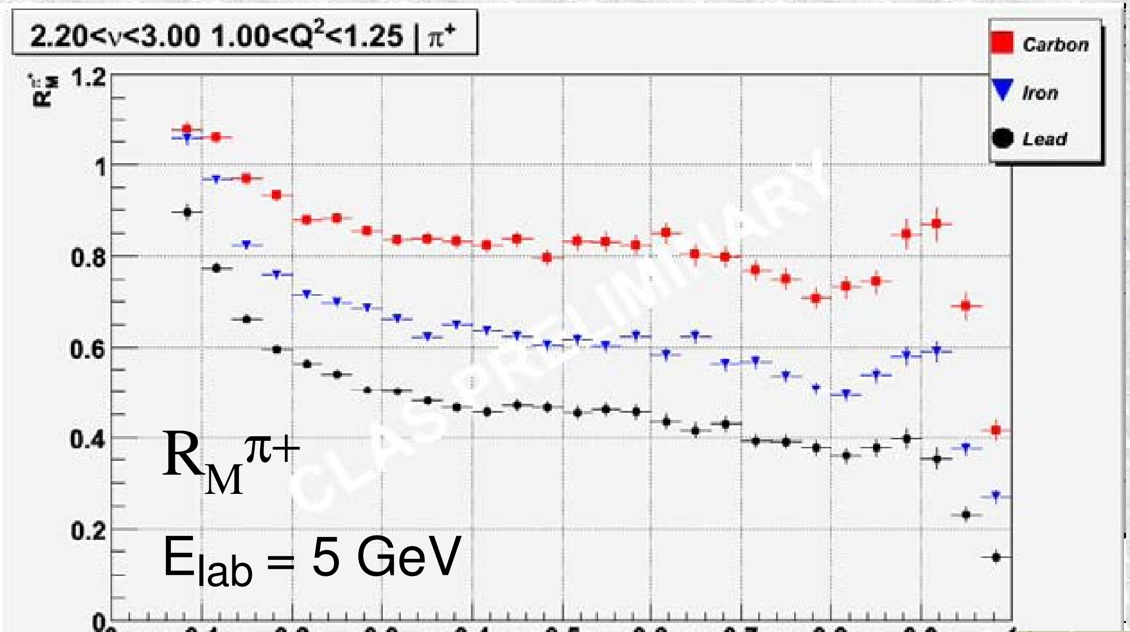
Measurements at HERMES @ HERA

- 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]



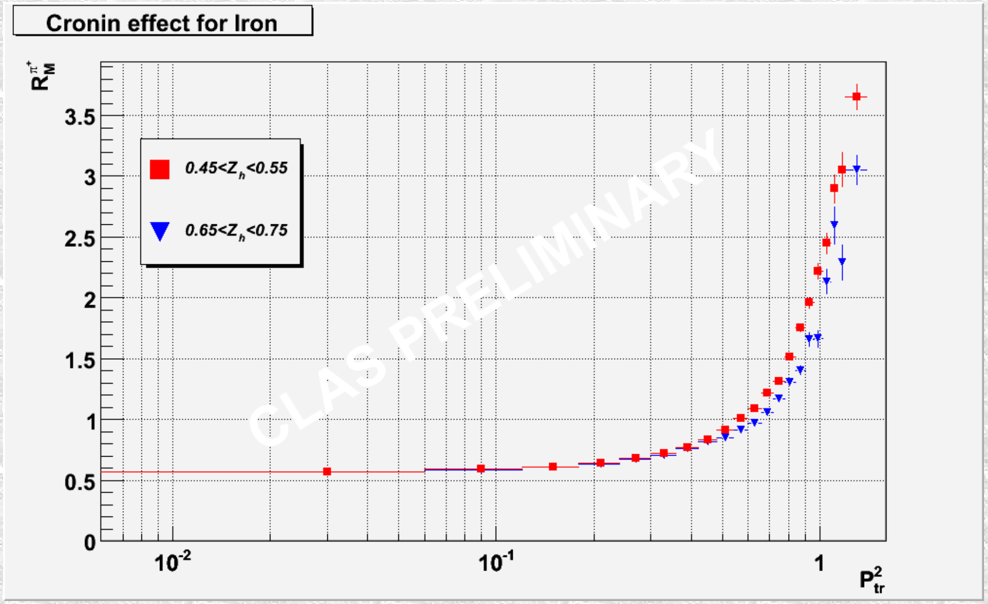
Preliminary results at CLAS @ Jefferson Lab

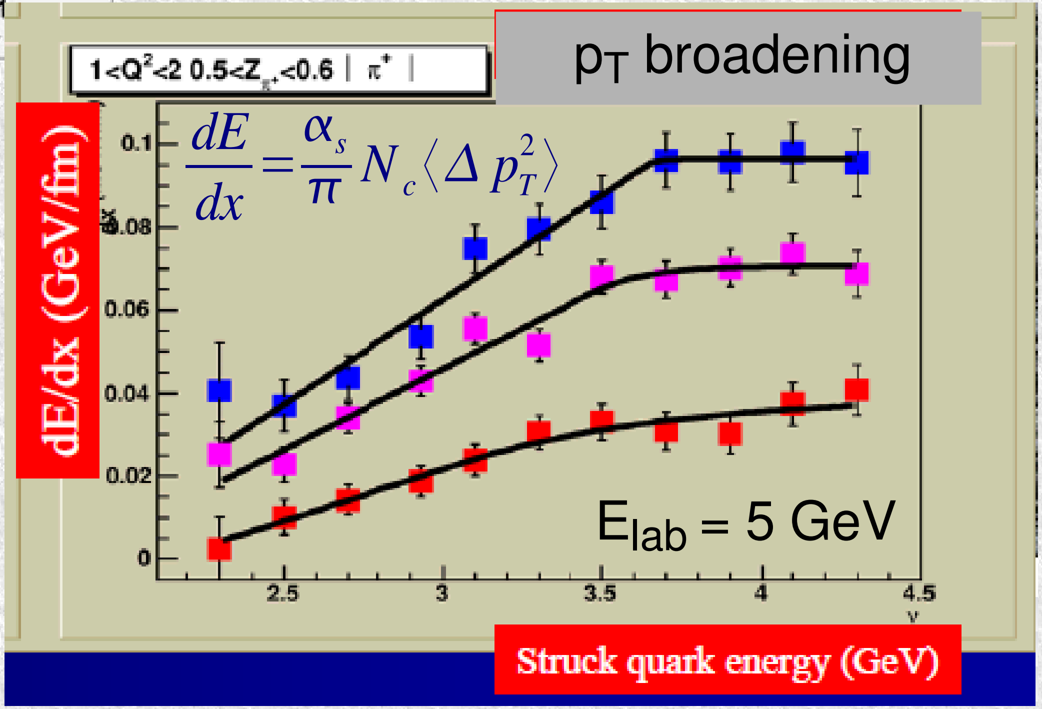


- 6 (12) GeV beam
- huge luminosity
  - multi-differential binning !!
  - γ+h correlations
  - and much more…

K.Hafidi, nucl-ex/0609005

Brooks, Hicks, talks at Trento Workshop



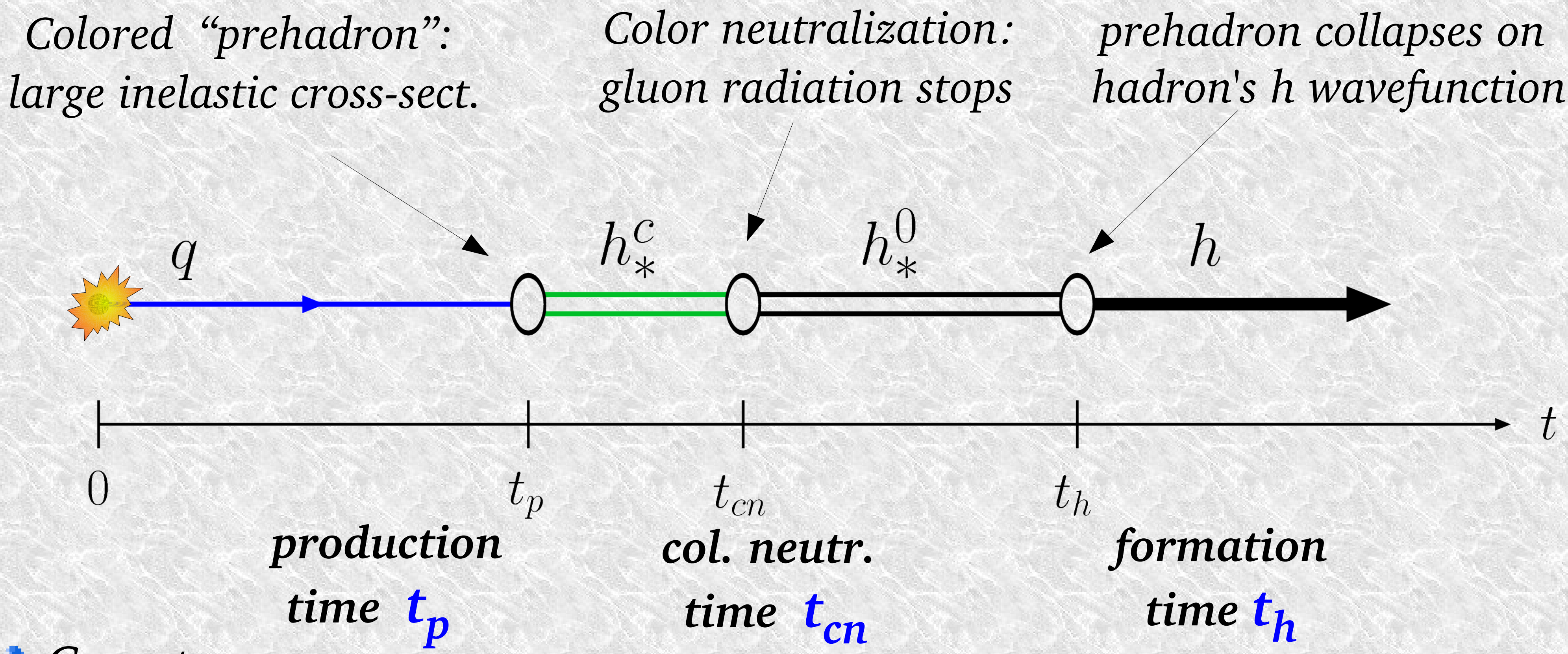


Hadron formation time:
a review of theory models

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

production time t_p

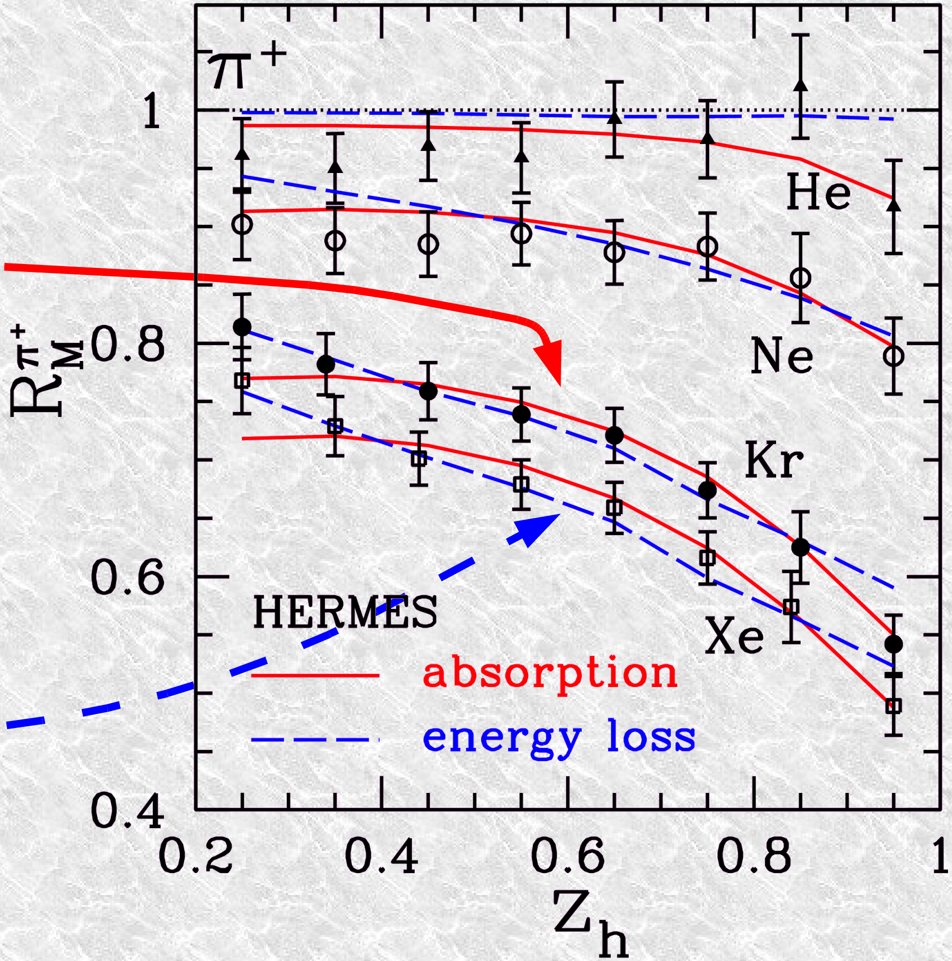
col. neutr. *time* t_{cn}

formation time t_h

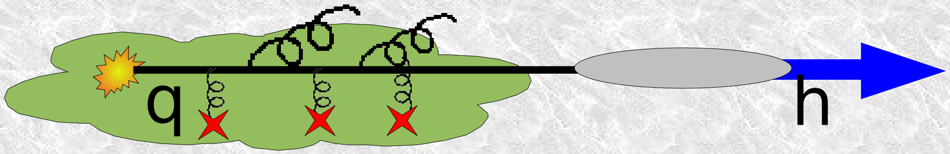
- *Caveats:*
  - It's tricky to define t_p , t_{cn} , t_h: working tools – simplify: $t_p = t_{cn}$
  - Leading-order pQCD mindset ($\gamma^* + q \rightarrow q$), but NLO may be large

Hadron attenuation in nDIS

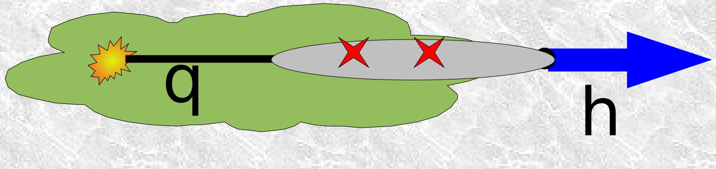
$$R_M^h(z) = \frac{\frac{1}{N_A^{\rm DIS}} \frac{dN_A^h(z)}{dz}}{\frac{1}{N_D^{\rm DIS}} \frac{dN_D^h(z)}{dz}}$$



- **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

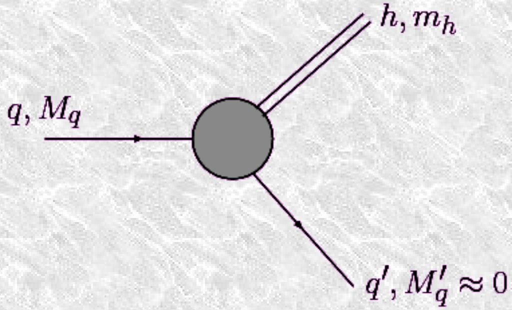


[A.A., et al., NPA 761(05)67]
[A.A., Acta.Phys.Hung. '06 & PRC '07]

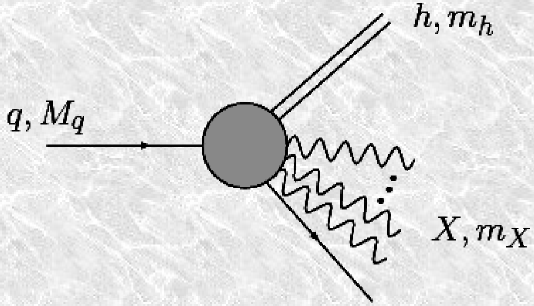
Formation time estimates 1 – pQCD estimate

- pQCD estimate [see Vitev, Adil '07]

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)	36 fm	11 fm	4 fm	1.2 fm	0.1 fm
RHIC (p_T^h ~ 7 GeV z~0.7)	26 fm	10 fm	4 fm	1.2 fm	0.1 fm

~ inside the medium !!

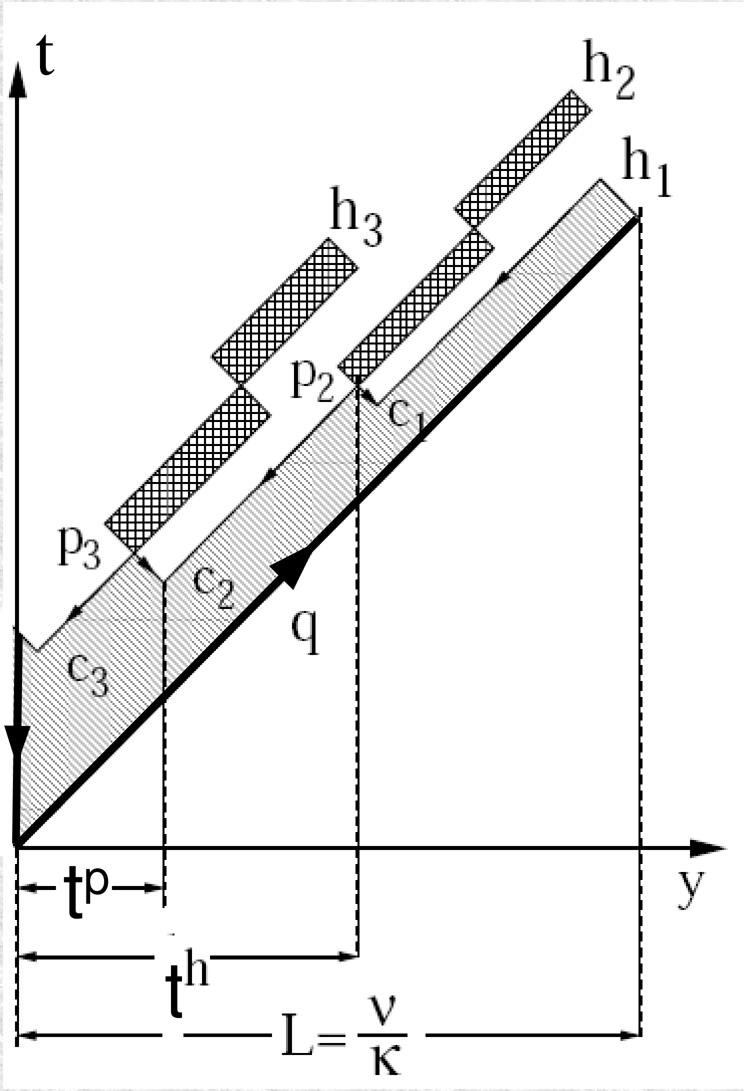
- Large π formation time, used in en. loss models to justify assumptions, but **neglect interactions of forming color field with the medium**

Formation time estimates 2 – Lund model

(see also T.Sjostrand)

- Prehadrons and hadrons [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
  - At large $z \to 1$
    $E_h \to \nu \Rightarrow$ string breaks early to leave all energy to the hadron: $\langle t_p \rangle \to 0$
  - At small $z \to 0$
    hadron created at high rank after many string breakings: $\langle t_p \rangle \to 0$



nucleus
remnant
X

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

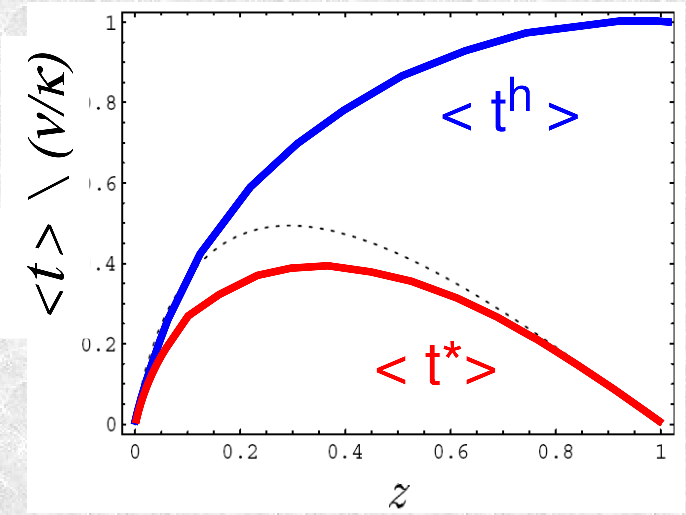
boost

string-tension
(non pert. scale)

energy conservation

Formation time estimates 2 – Lund model

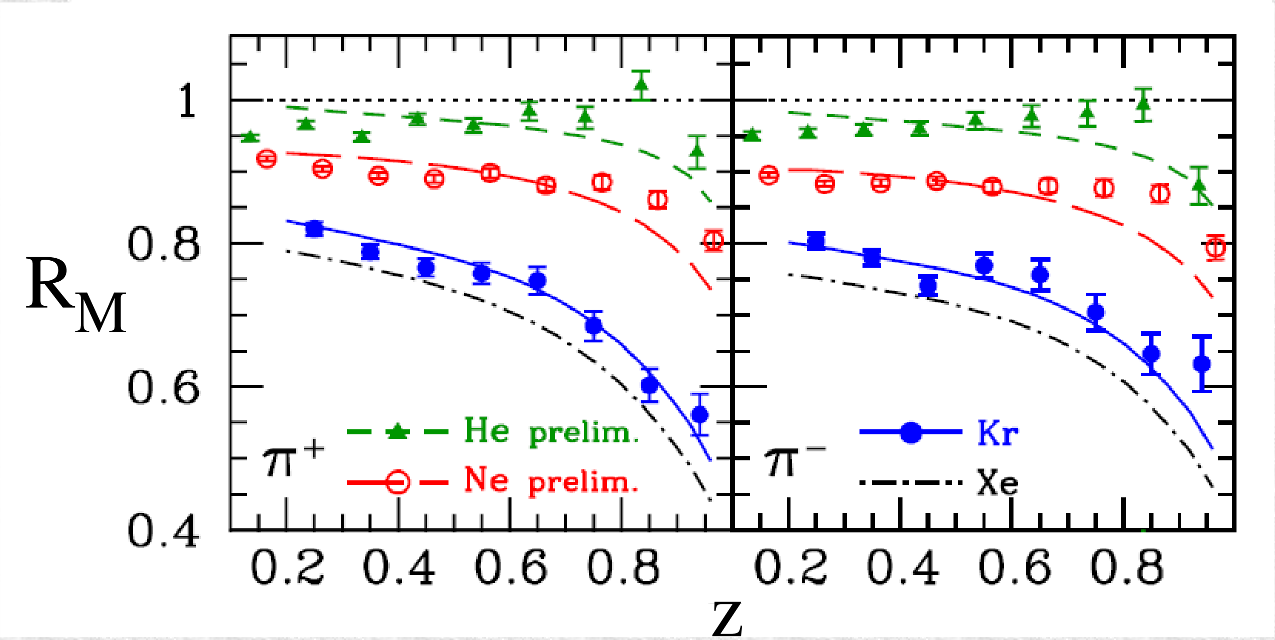
$$\begin{cases} \langle t_p \rangle = f(z_h)(1-z_h)\dfrac{z_h \nu}{\kappa} \\ \langle t_h \rangle = \langle t_p \rangle + \dfrac{z_h \nu}{\kappa} \end{cases}$$



- 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]

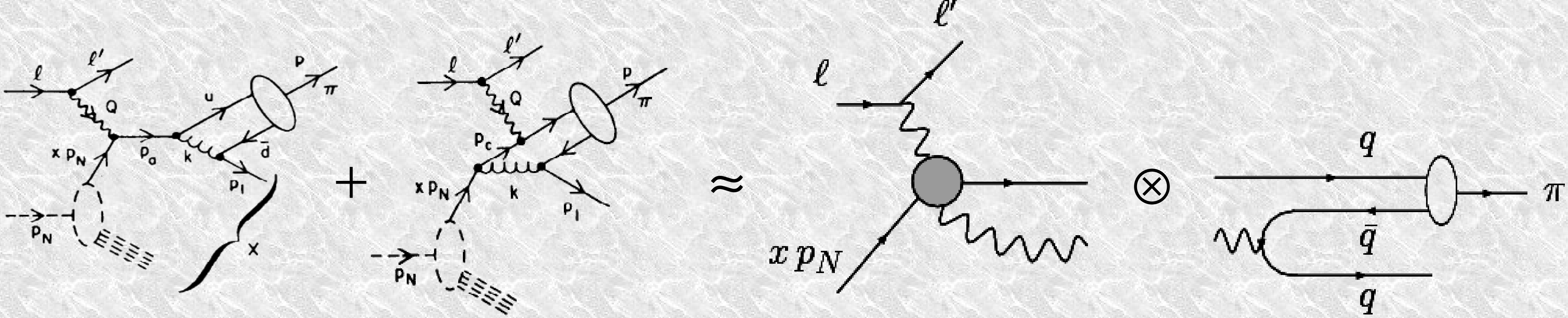


see also:
Falter, Gallmeister, nucl-th/0512104
for similar ideas in a transport model
Monte Carlo simulation

accardi@jlab.org

Formation time estimates 3 – Dipole model

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



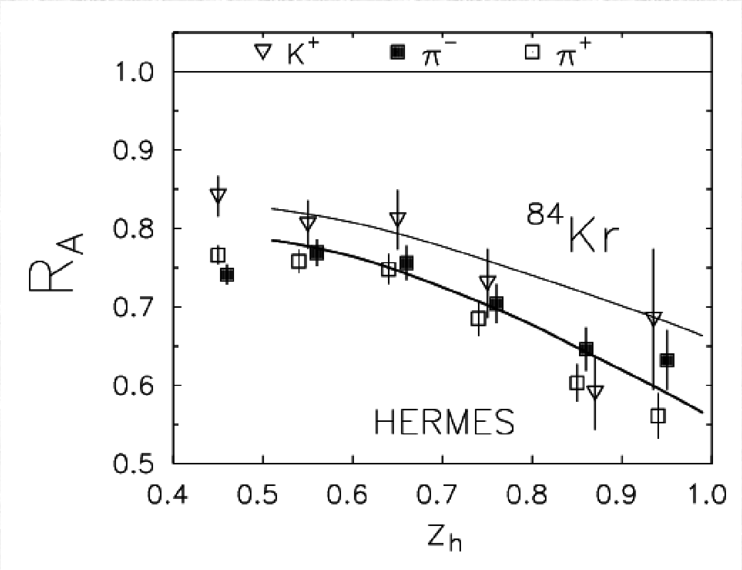
- Prehadron production time t_p
  = time at which gluon becomes decoherent with parent quark
- At large z → 1, $E_h \to \nu$ ⇒ quark must be short-lived
  (or radiates too much energy)

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

boost

energy
conservation

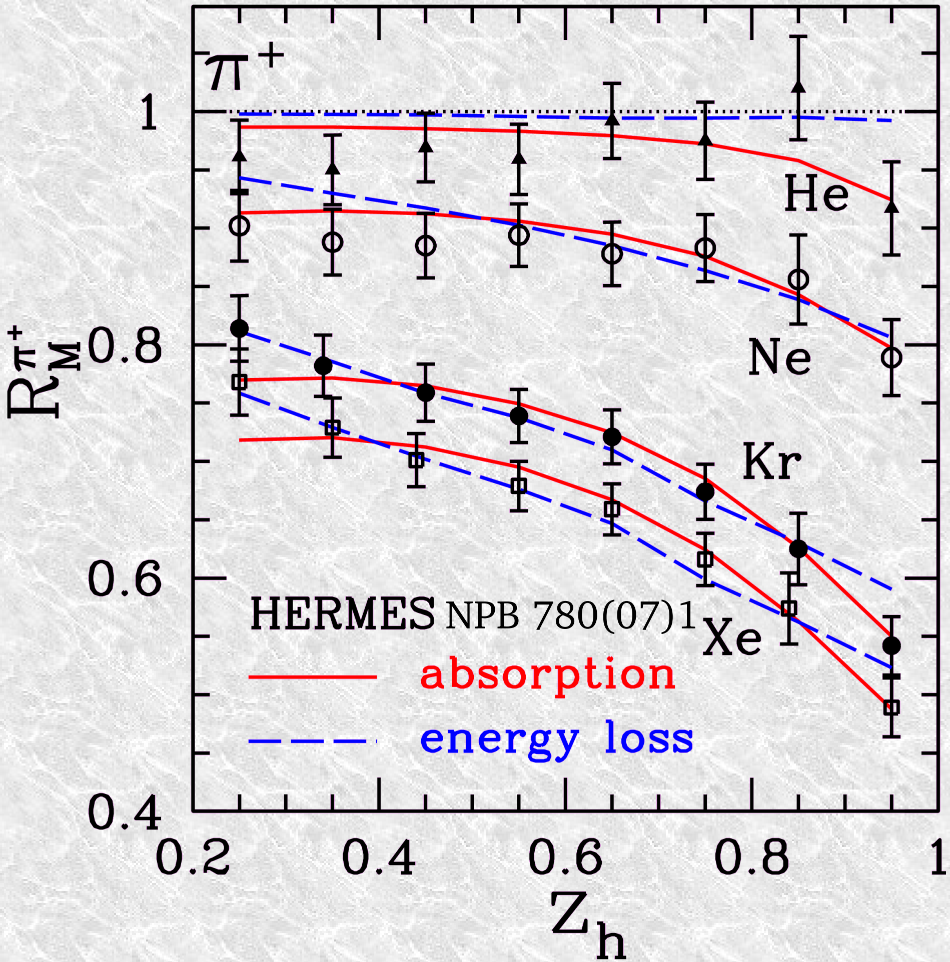
virtuality
(perturbative scale)



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

Can we measure the production time = quark lifetime?

1) Hadron quenching vs. z_h



Red: absorption model
[A.A., et al., NPA 761(05)67]

Blue: energy loss model
with SW quenching weights
(see also K.Zapp)
[A.A., Acta.Phys.Hung. '06 & PRC '07]

Both describe the data:
no info on parton lifetime

- **Note:**
  - Medium geometry is crucial to describe the data
  - It is accounted for in the same way in both models
  - Both have the same $A^{2/3}$ dependence [A.A.,EPJC 2007]

accardi@jlab.org

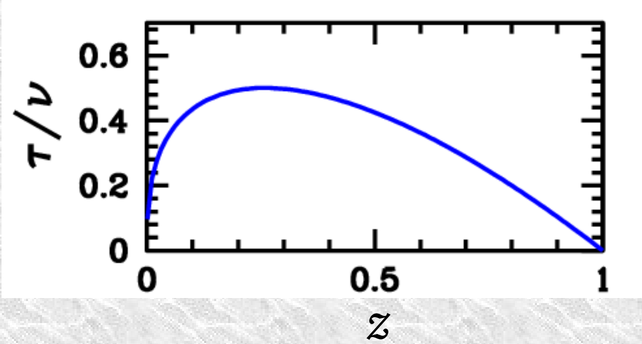
2) Scaling of R_M – basic idea

A.A., PLB B649 (07) 384

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

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

- "Scaling exponent" λ can distinguish absorption and energy-loss
  - **Short quark lifetime, absorption**: $\lambda > 0$

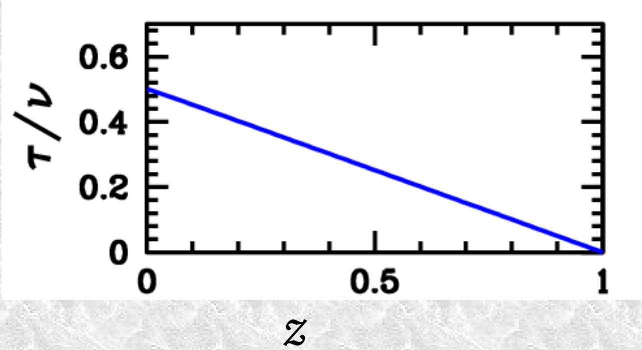


$$\langle t_p \rangle = f(z_h)(1 - z_h)\frac{z_h \nu}{\kappa} \approx \tau(z_h, \nu)$$

energy conservation

Lorentz boost

  - **Long quark lifetime, energy loss:** $\lambda \lesssim 0$

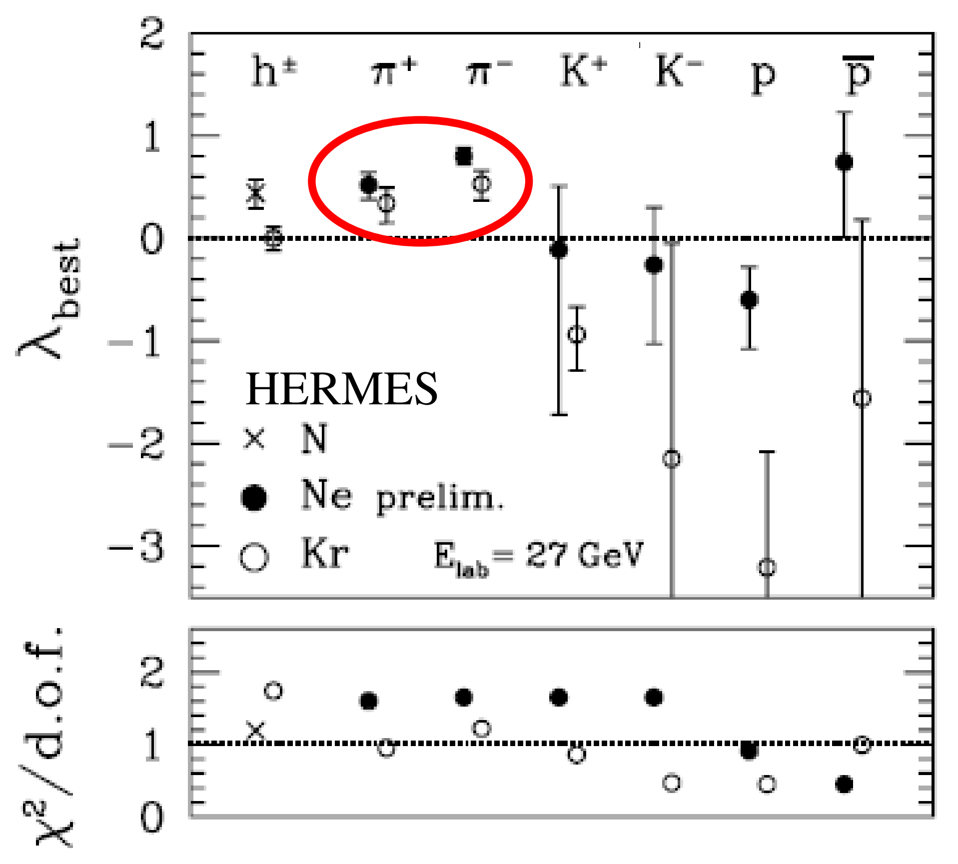


radiated energy: $\varepsilon < (1 - z_h)\,\nu$

energy conservation

2) Scaling of R_M – χ^2 fits

A.A., PLB B649 (07) 384



- Formation-time scaling for pions!

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

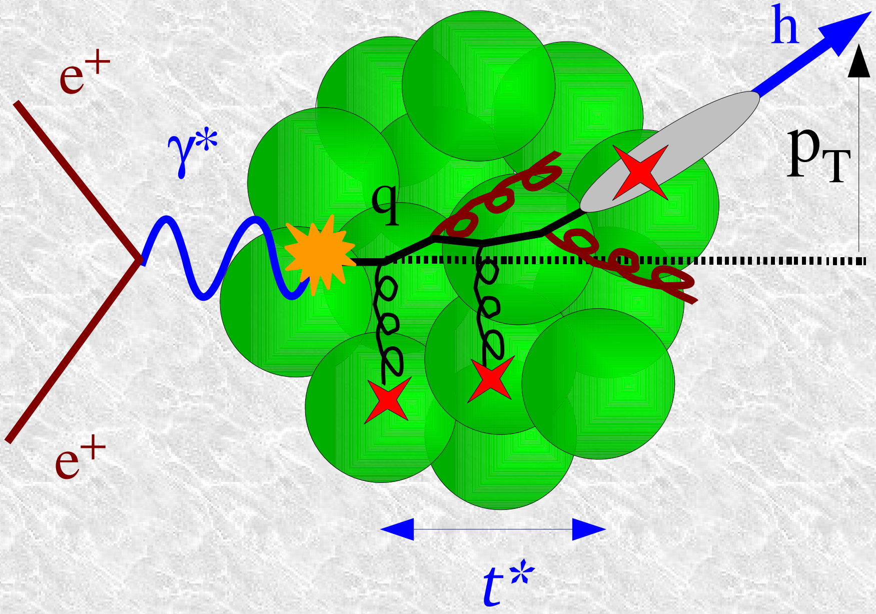
Hadronization starts inside the nucleus!

How much inside?

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

- Let's assume no energy loss for a moment:
  - In prehadron stage, no broadening: elastic scattering very small
  - Incoherent partonic scattering: $\Delta\langle p_T^2\rangle$ linear in quark in-medium path

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



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

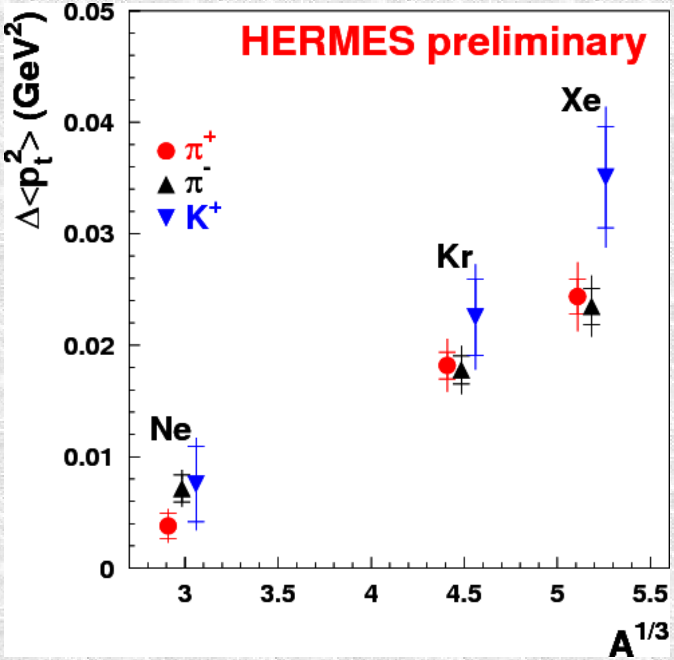
- It should:
  1) rise with $A^{1/3}$ until $\langle t_p\rangle \sim R_A$, then level off
  2) decrease as $z_h \to 1$
  3) rise with ν, then level off
  4) possibly, decrease with Q^2 (if $\langle t_p\rangle \propto \nu/Q^2$)

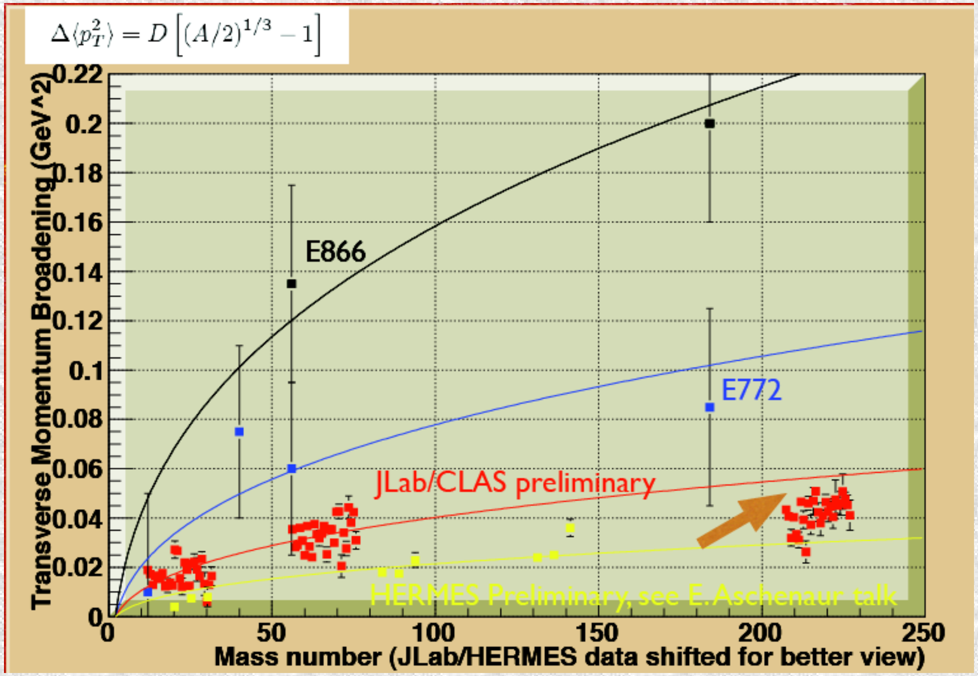
3) p_T – broadening [A.A., nucl-th/0808.0656]

- Let's assume no energy loss for a moment:

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

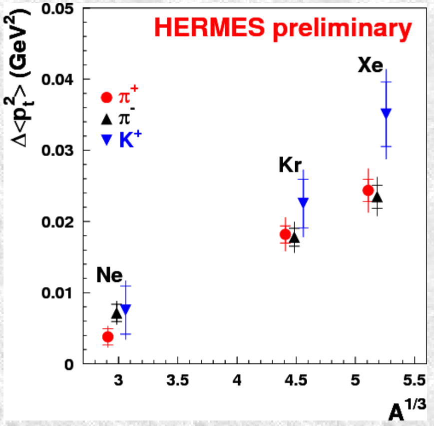
- It should:
  1) rise with $A^{1/3}$, then level off ☺





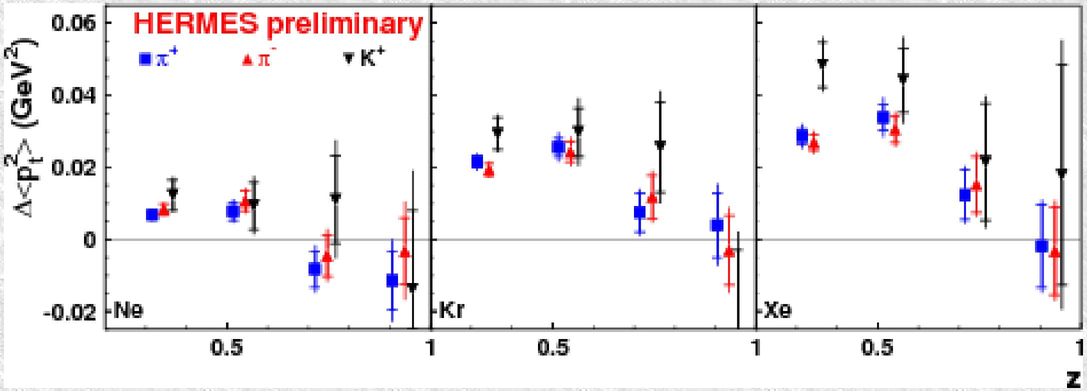
JLAB preliminary, Will Brooks, Trento workshop

3) p_T – broadening [A.A., nucl-th/0808.0



- Let's assume no energy loss for a moment:

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

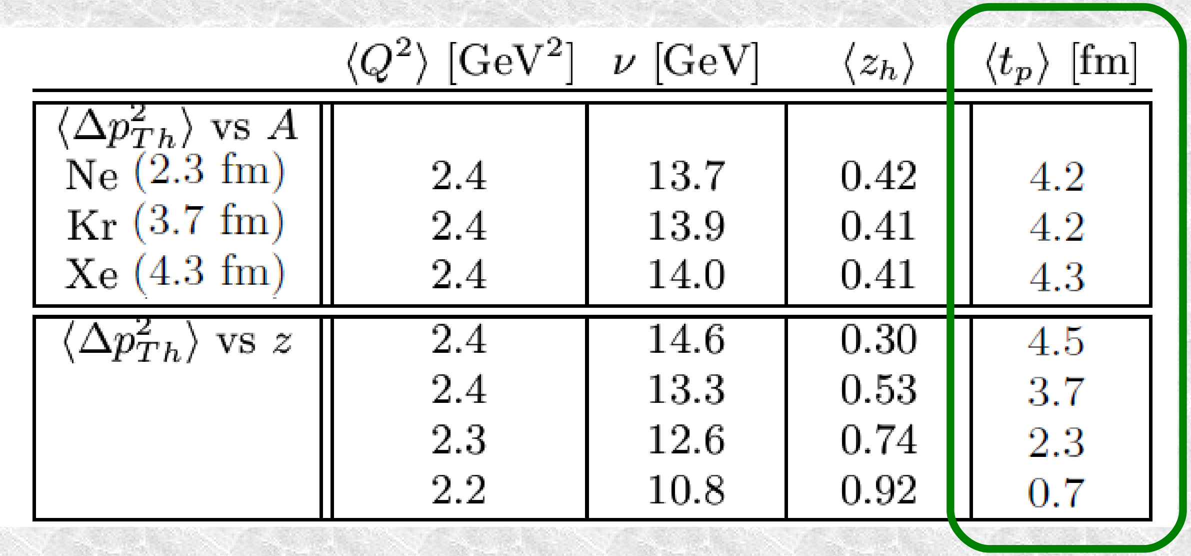


- It should:
  1) rise with $A^{1/3}$, then level off ☺
  2) decrease as $z_h \to 1$ ☺

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

➔ $C \approx 0.8$ GeV/fm

prehadrons formed
on short time scales!



	$\langle Q^2\rangle$ [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

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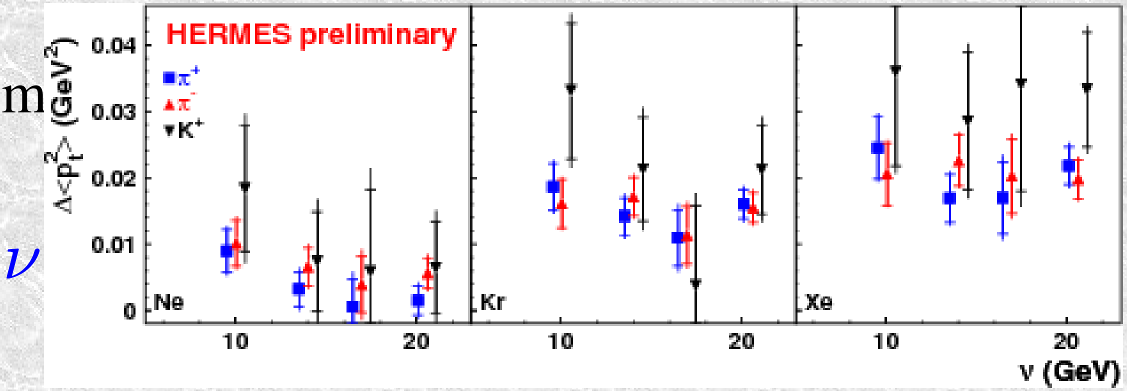
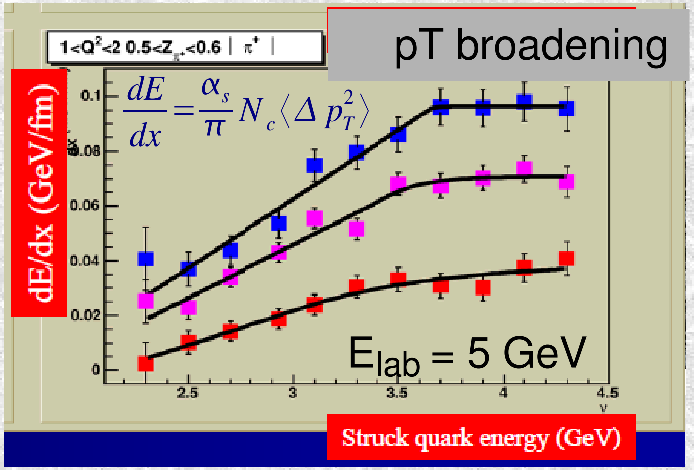
3) p_T – broadening [A.A., nucl-th/0808.0656]

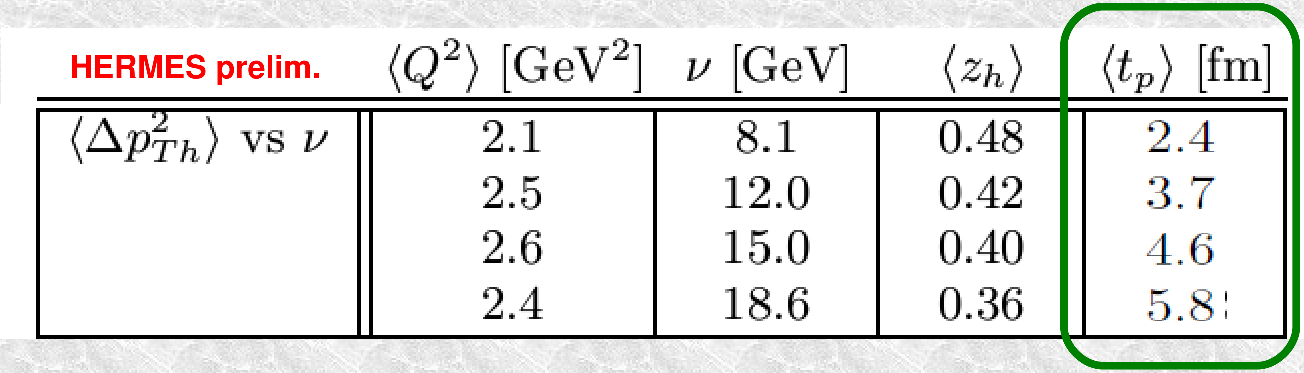
- Let's assume no energy loss for a mom



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

- 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 ? ?



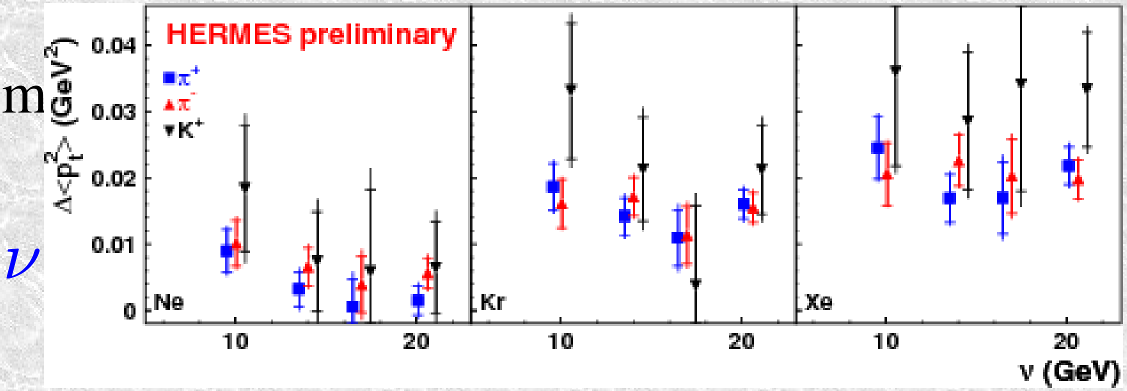


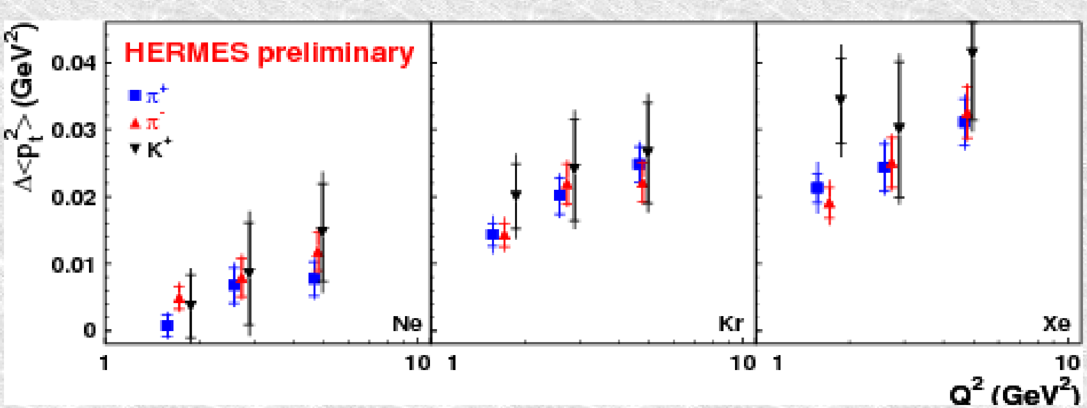
HERMES prelim.	$\langle Q^2\rangle$ [GeV^2]	ν [GeV]	$\langle z_h\rangle$	$\langle t_p\rangle$ [fm]
$\langle\Delta p_{Th}^2\rangle$ vs ν	2.1	8.1	0.48	2.4
	2.5	12.0	0.42	3.7
	2.6	15.0	0.40	4.6
	2.4	18.6	0.36	5.8

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

- 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 ? ?
  4) possibly, decrease with Q^2 (if $p_T^2 \propto 1/Q^2$)

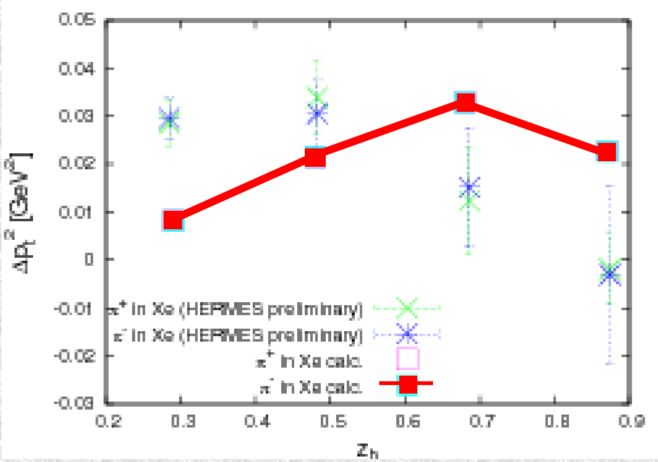
at strong variance with dipole model

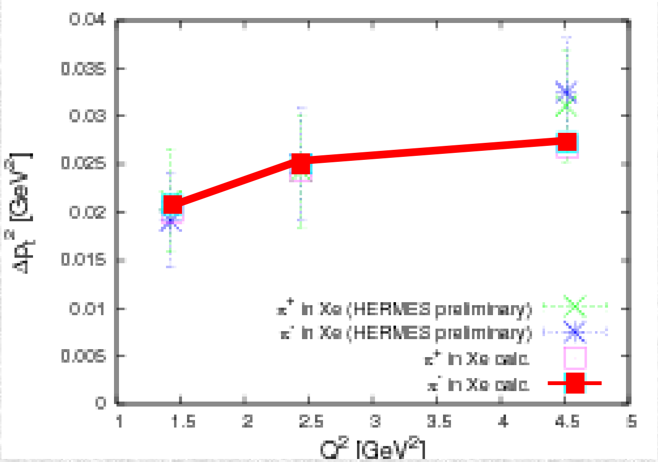
- **Signals of partonic dynamics beyond production time & multi-scattering**

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]

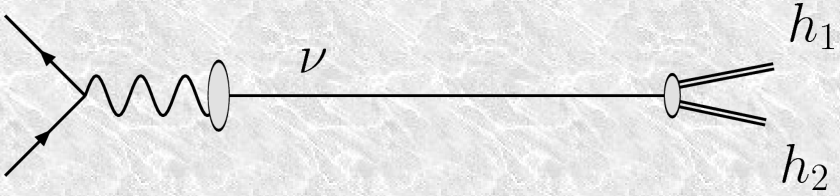




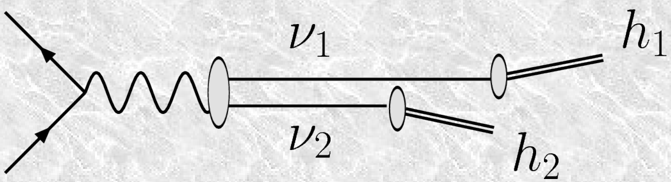
$$(\Delta p_\perp^2)_h(Q^2) = (\Delta p_\perp^2)_h(\bar{Q}^2) + z_h^2\,\nu\,\rho_0\,\langle\sigma q_\perp^2\rangle\left(\frac{1}{\bar{Q}^2} - \frac{1}{Q^2}\right)$$

[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

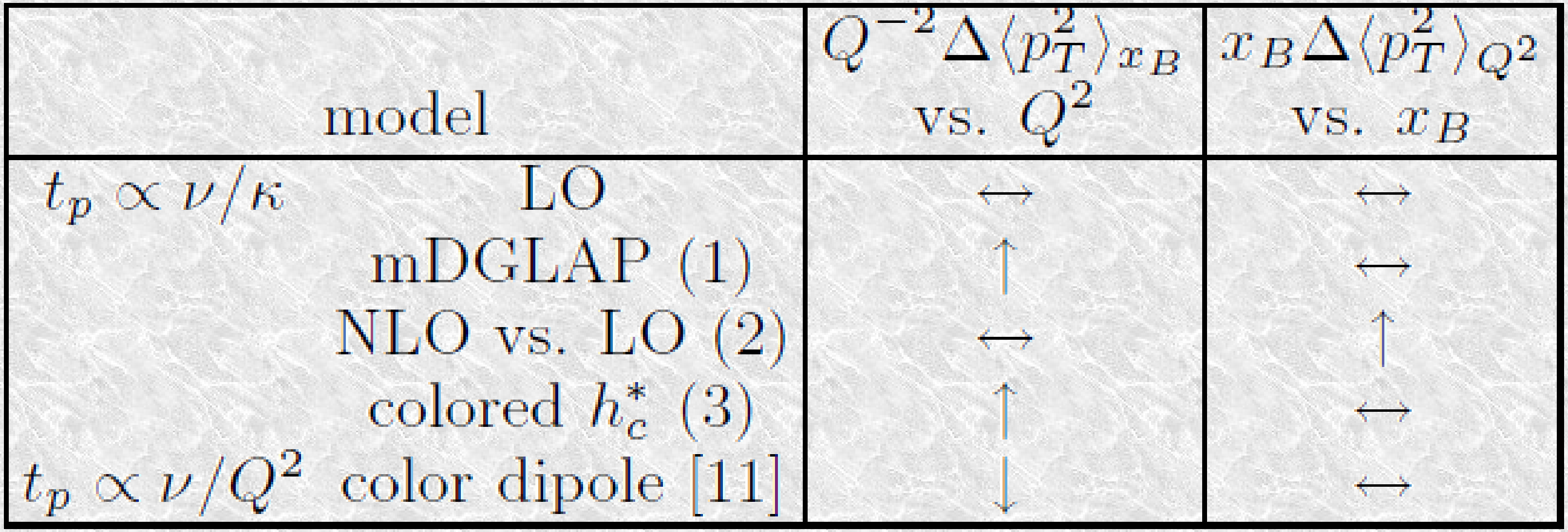
[A.A., nucl-th/0808.0656]

- 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]	$\downarrow$	$\leftrightarrow$

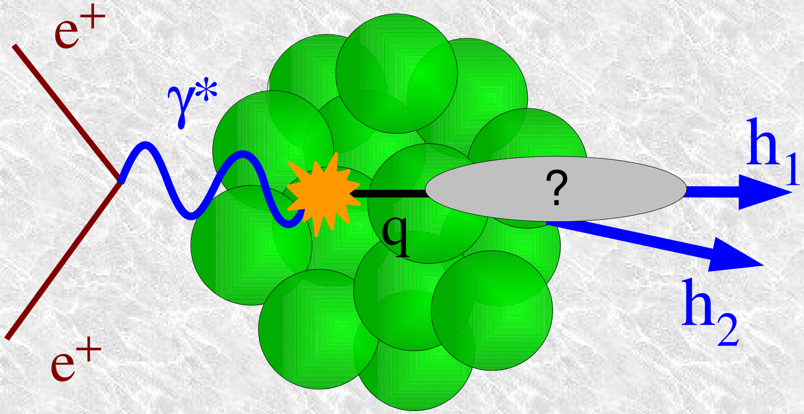
accardi@jlab.org

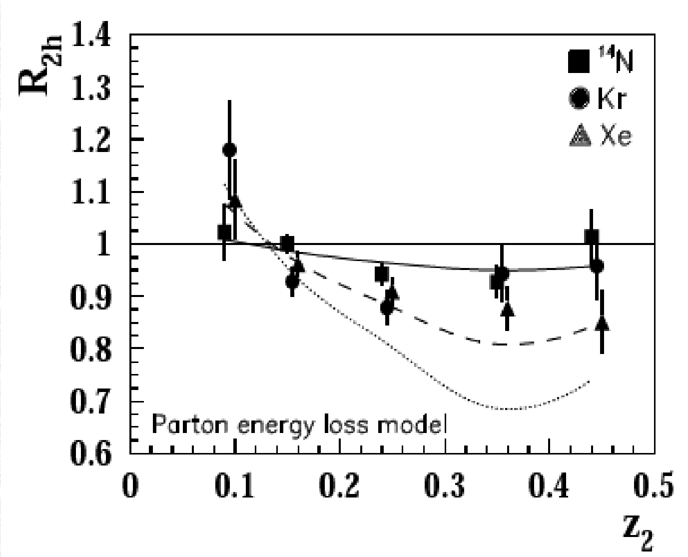
Two-particle correlations at HERMES

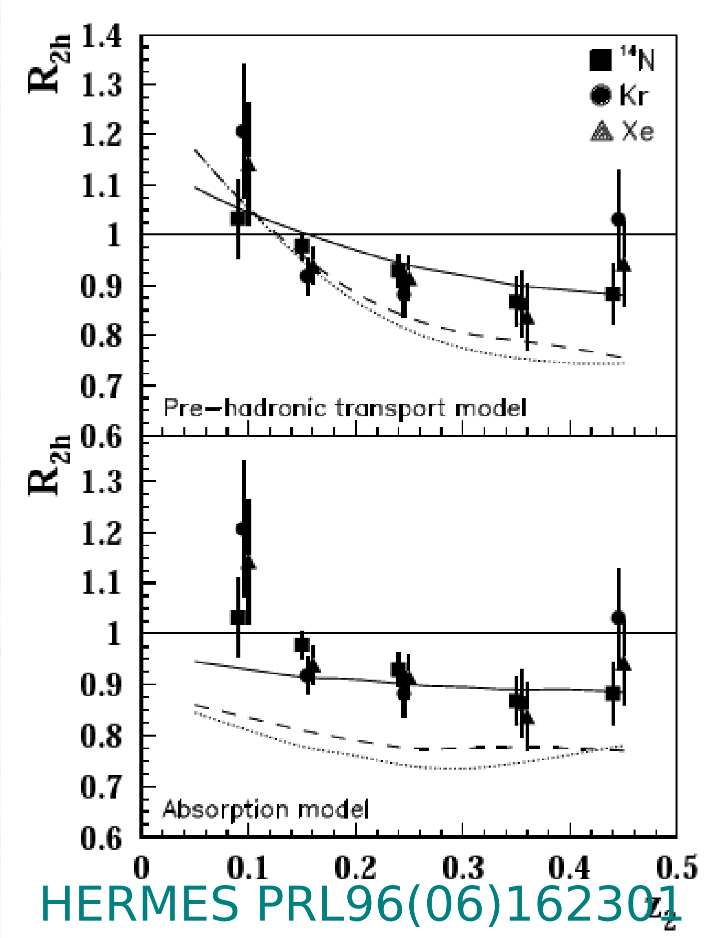
- **Double hadron attenuation** R_2
- in A+A = “same-side correlations”, (akin to jet yield on top of ridge)

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

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



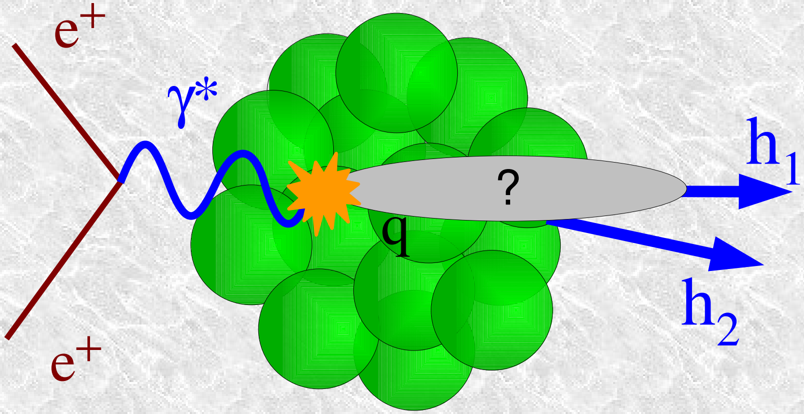




HERMES PRL96(06)162301

Two-particle correlations at HERMES

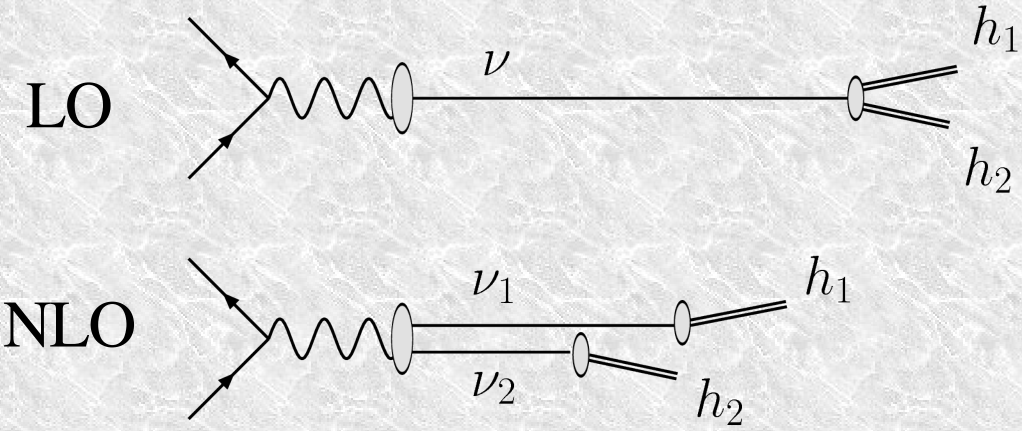
- Small A-depence: surface bias?



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

$$z_2 \leq z_1 \ ; \ \ z_1 \geq 0.5$$

- E.g., NLO hard scattering



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

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

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

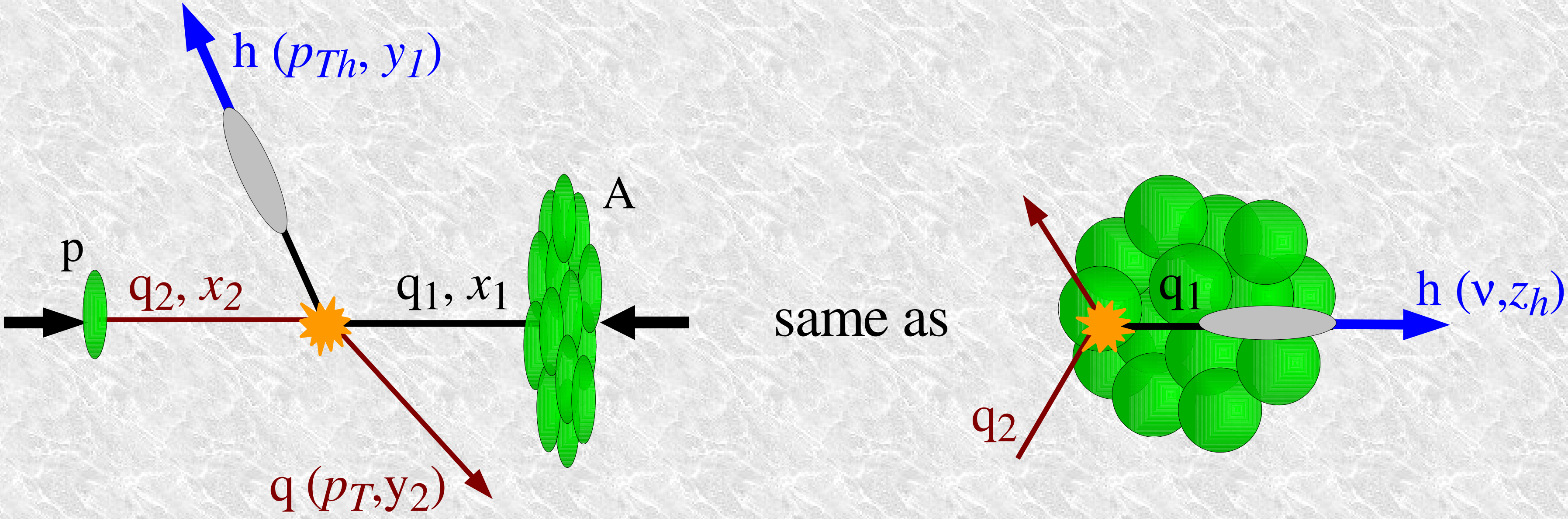
From nDIS to Heavy-Ions

Cold quenching in p+A collisions

A.A., PRC76 (07) 034902

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

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



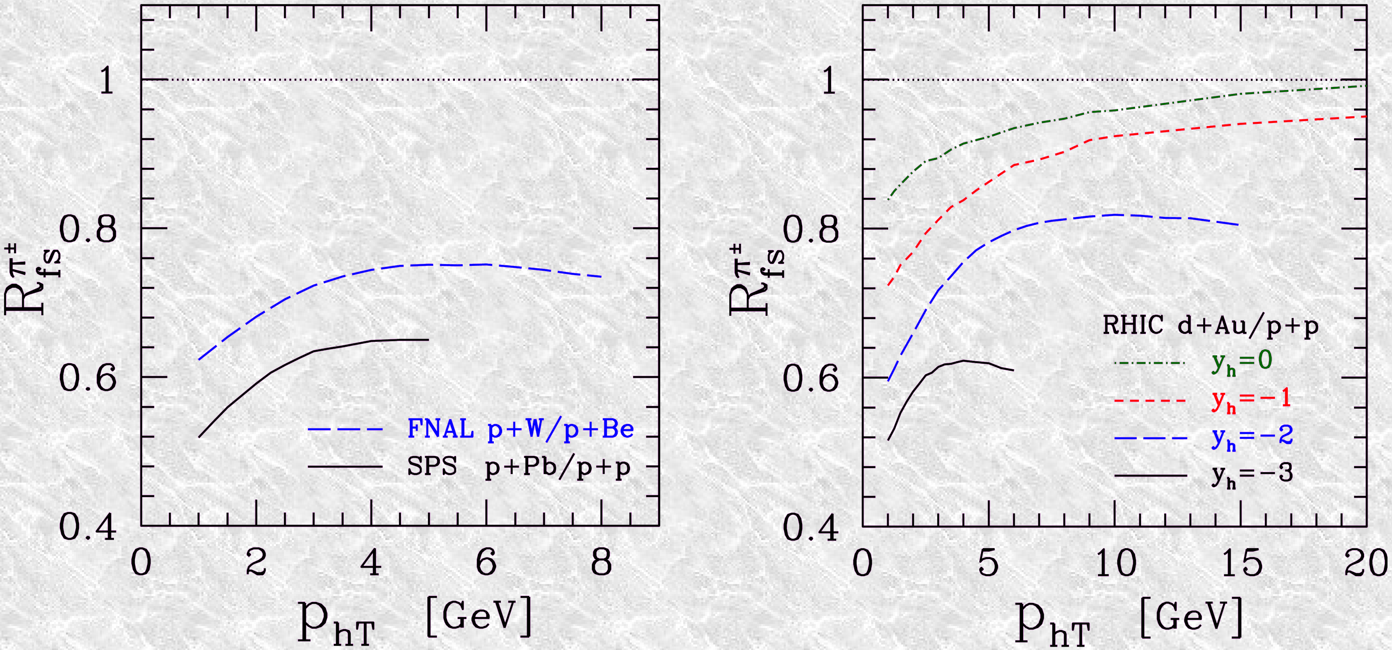
- If parton is slow enough (small ν) the hadron will be quenched in the cold nucleus by the same mechanism that quenches it in nDIS.

Cold quenching in p+A collisions

A.A., PRC76 (07) 034902

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

  in any hadron quenching model validated by HERMES R_M data
  - e.g., energy loss with SW quenching weights [AA, ...]

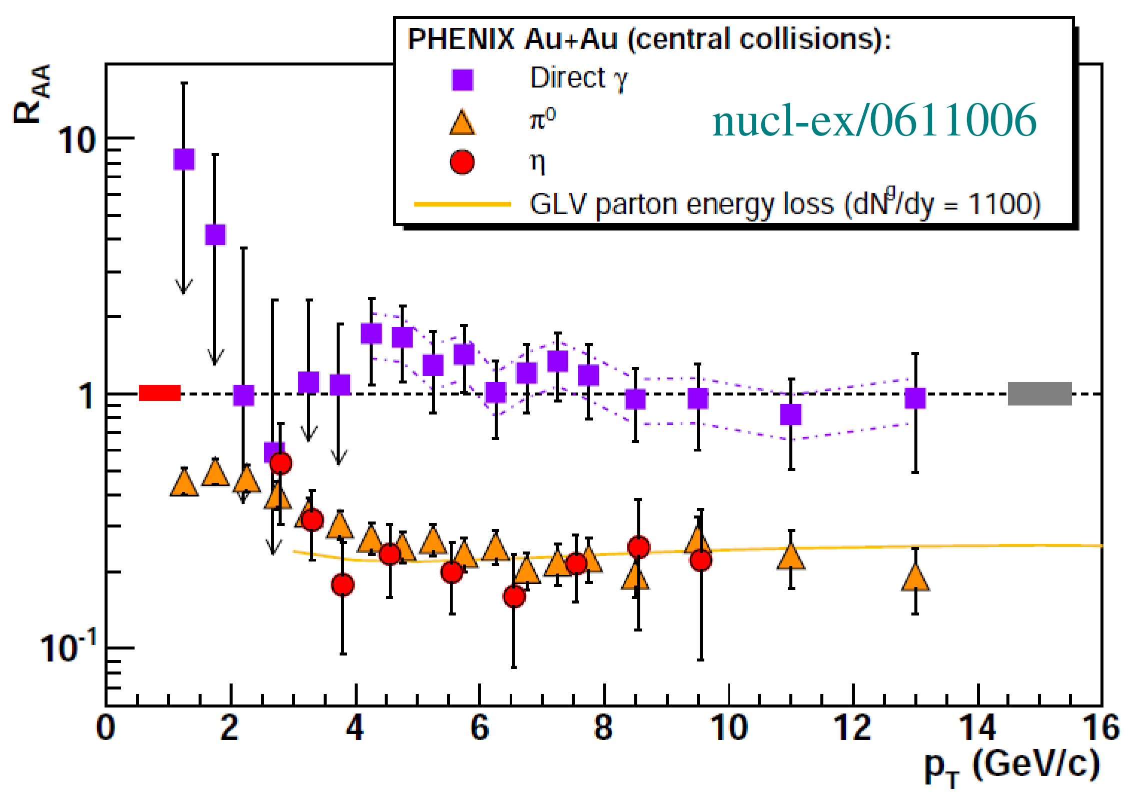


- For **A+A at $\eta = 0$**, suppression comes from both nuclei ⇒ ~ squared:

Cold quenching in target nuclei not negligible in A+A at SPS: easily competes with quenching from hot medium

Parton lifetime in hot QCD matter – 1

- 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



nucl-ex/0611006

- Is it so also in nDIS? [η is heavier ⇒ hadronizes earlier, larger x-sec]
  - measurement possible at CLAS (low Q^2), EIC (high Q^2)

accardi@jlab.org

Parton lifetime in hot QCD matter – 2

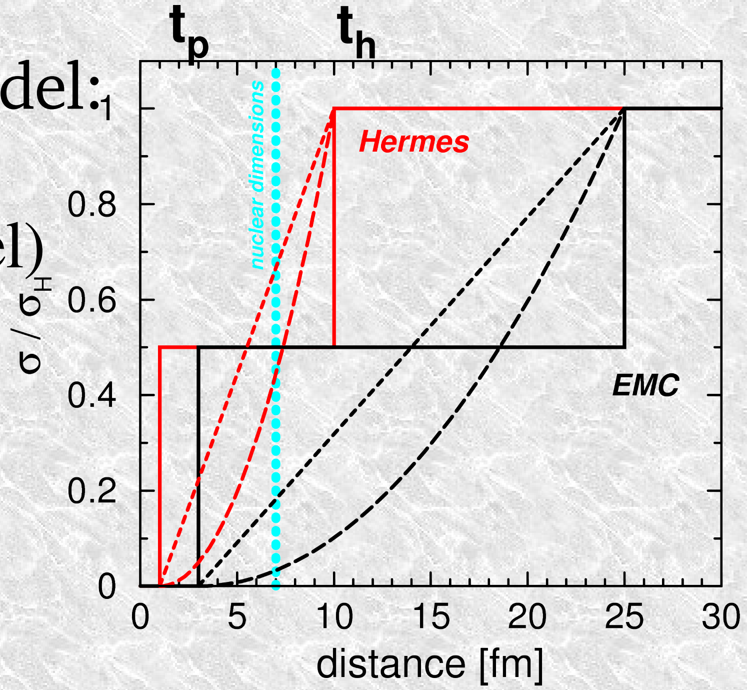
- Take the GiBUU Monte-Carlo absorption model:
  [Falter et al. PRC '04, Gallmeister, Mosel NPA '08]

  Formation times: t_p from PITHYA (Lund model)

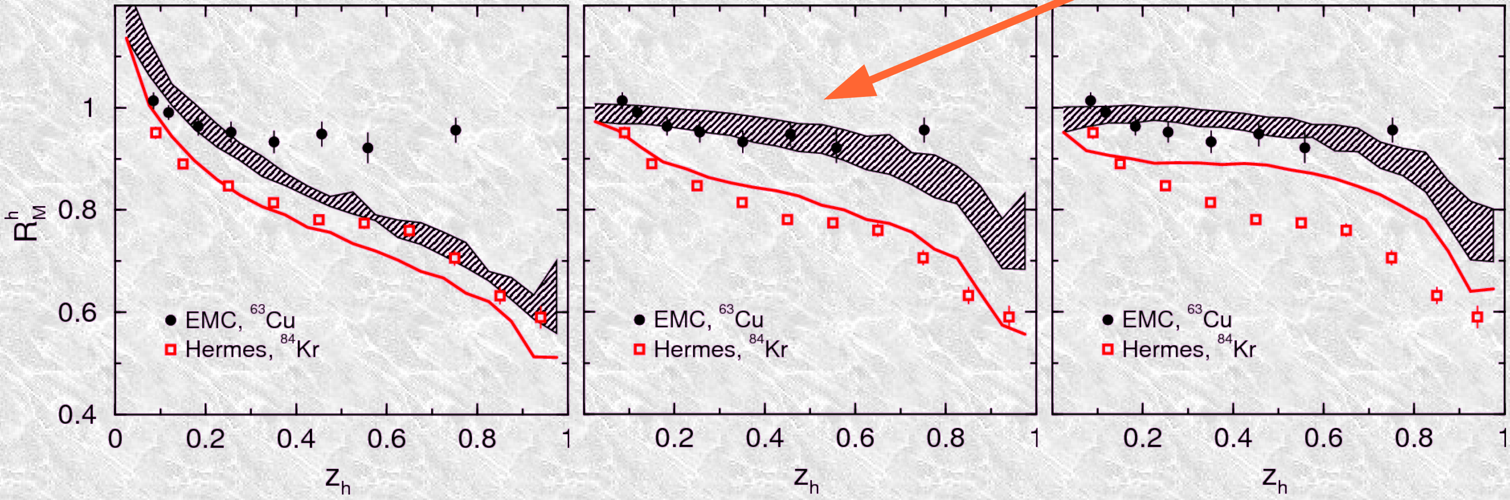
  Cross sections: leading h: $\sigma_* = f(t)\,\sigma_h$

  subleading h: $\sigma_* = 0$

$$f(t) \propto \begin{cases} \text{const.} & \\ t & \text{(linear, or quantum diffusion)} \\ t^2 & \text{(color transparency)} \end{cases}$$

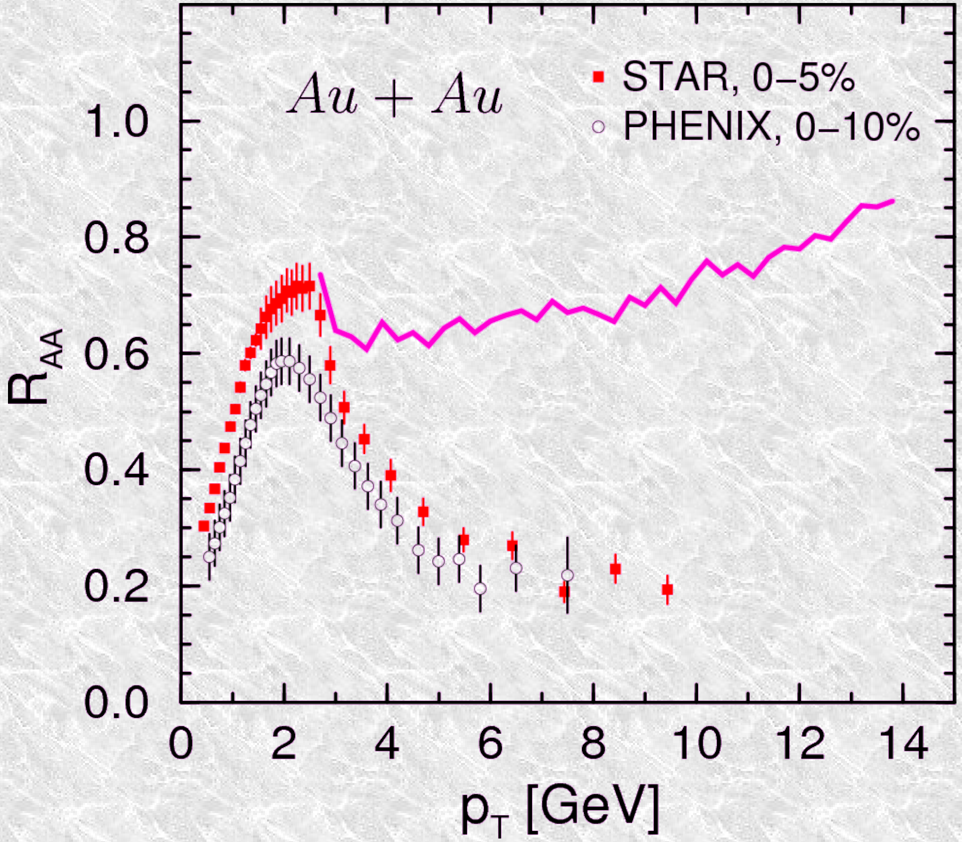


- Consistency of HERMES + EMC data selects linear $f(t) \sim t$
  [Gallmeister, Mosel NPA'08]



Parton lifetime in hot QCD matter – 2

- Apply it to Au+Au collisions at RHIC:
  [Cassing, Gallmeister,Greiner NPA '04; Cassing, Gallmeister NPA '05]



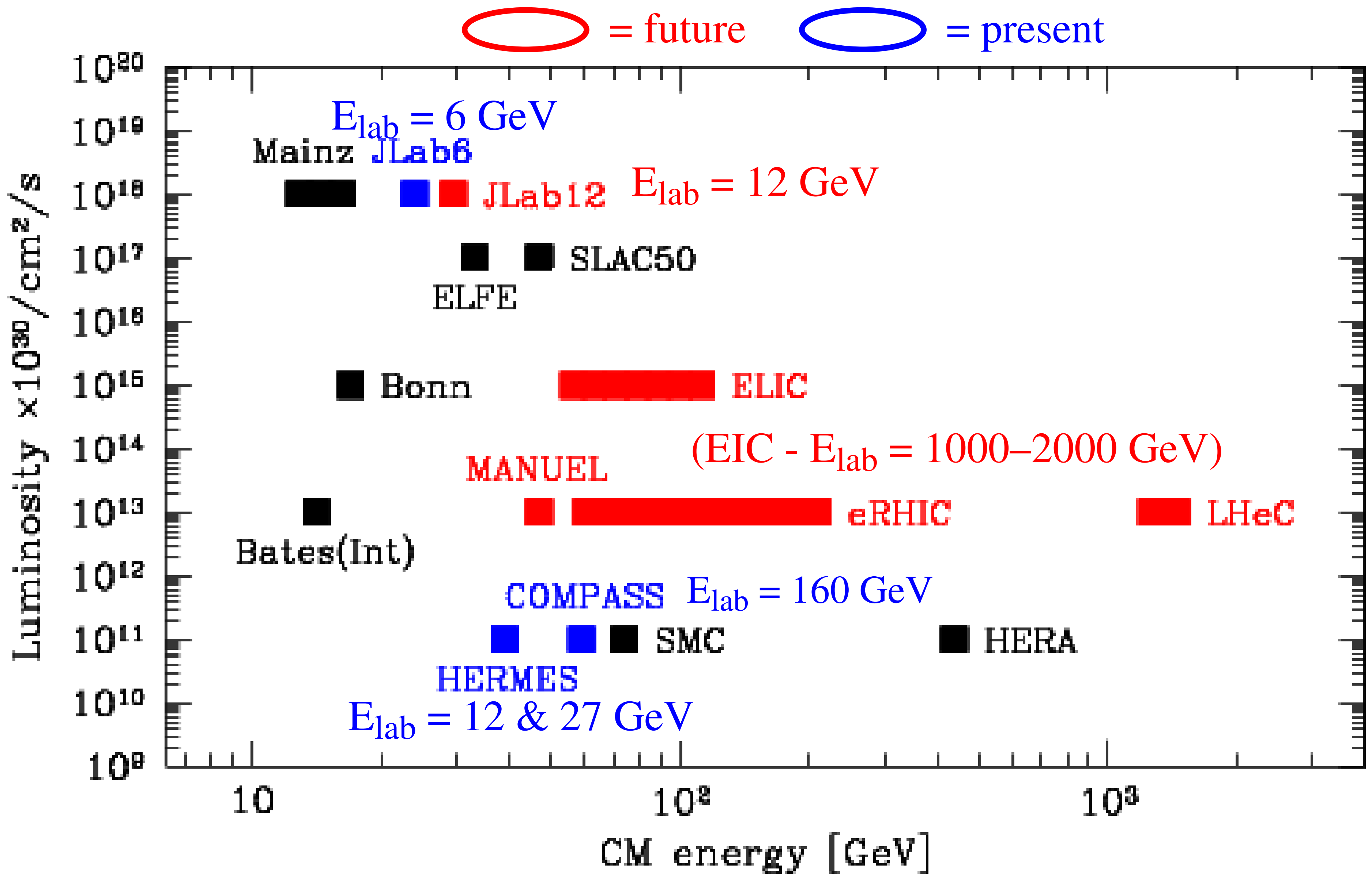
Way too little suppression:
long lived partons in QGP?

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

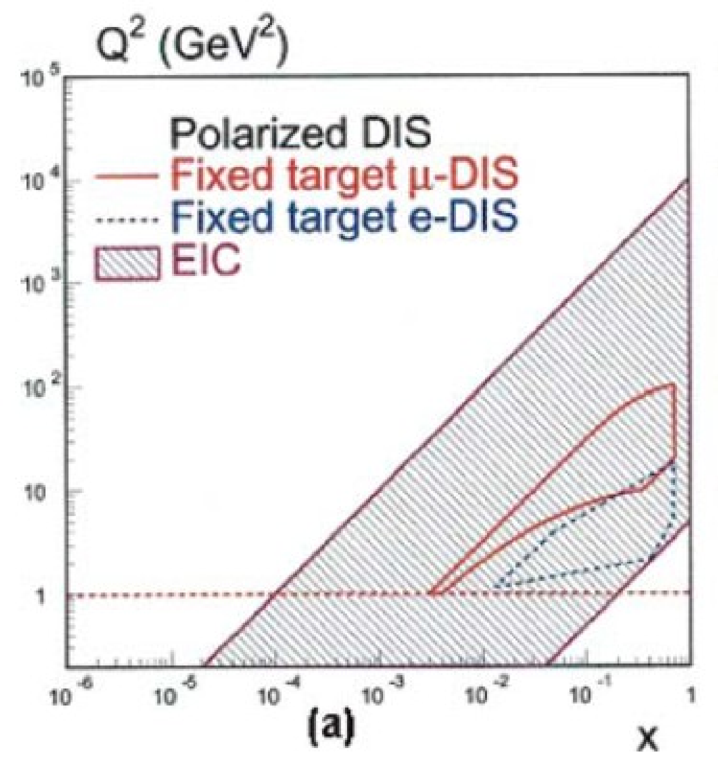
accardi@jlab.org

Perspectives at the EIC

Present and future e+A facilities

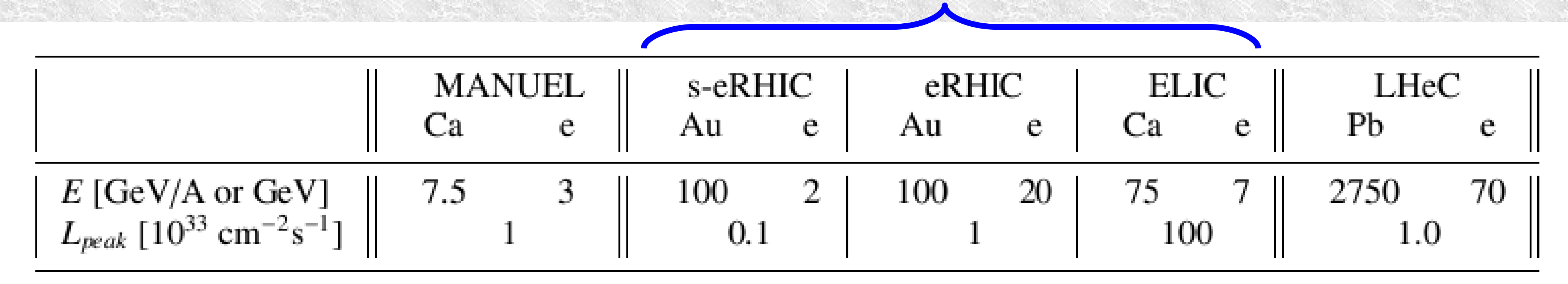


The EIC



- high luminosity ≥ 100 × HERMES
- small x, large ν, large Q^2 reach
- It will test /extend HERMES/JLAB
  - cross-check results
  - multi-differential observables
  - 2-particle correlation (h-h, γ-h, ...)
  - many more channels
- It is unique: tests of parton dynamics

EIC



	MANUEL Ca	 e	s-eRHIC Au	 e	eRHIC Au	 e	ELIC Ca	 e	LHeC 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
  - effects due to parton propagation can be experimentally isolated

- 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:
  - E.g., interplay of radiative and collisional parton energy loss (big deal for heavy quarks at RHIC, LHC)
  - J/psi "normal" absorption in clean environment

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

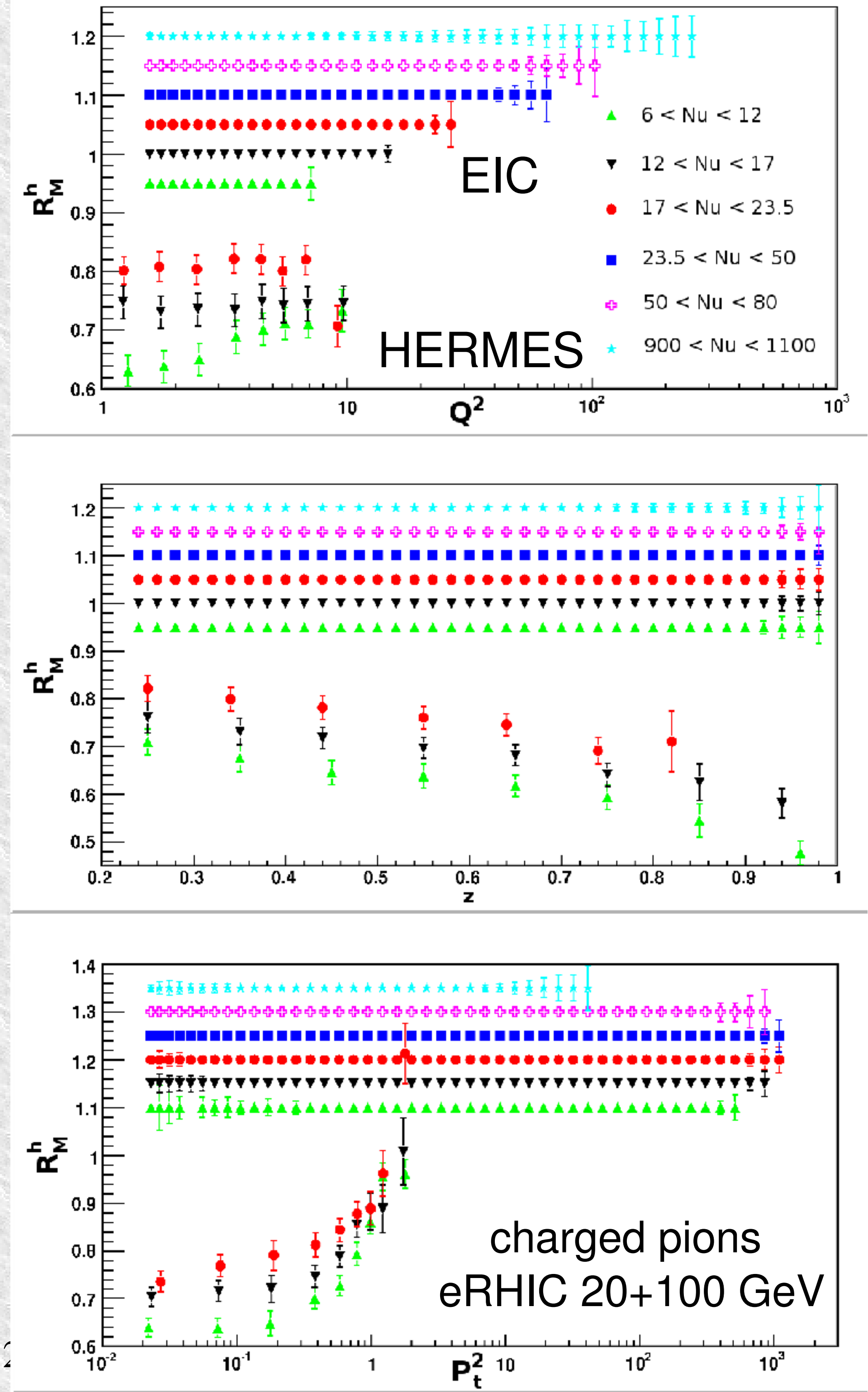
EIC vs. HERMES

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

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

- Simulation with PYTHIA 6.4.19
  - no nuclear effect yet
  - 10 weeks of beam at eRHIC
- High statistics:
  - from 2D to 5D distributions
- Large reach in p_T and Q^2 (x_B)
- Large range in ν
  - small ν – hadronization inside A
  - large ν – precision tests of QCD parton en. loss, DGLAP evolution, parton showers

(Simulations courtesy of R.Dupré)



Conclusions

- Quark lifetime:
  - rather short in cold matter seems, O(R_A)
  - but long in hot matter at RHIC – a QGP signal ???
- In nDIS, pT-broadening is next theoretical challenge
  - test of space-time evolution of hadronization
  - best place to test: pQCD energy loss, DGLAP, MC parton showers
- 2-hadron correlations little studied
  - role of NLO hard scatterings
  - hadron-photon correlations interesting
- At the EIC:
  - cross-check / improve HERMES, CLAS
  - many new channels (jets, heavy flavors, ...)
  - long parton lifetimes: precision study of pQCD en.loss, DGLAP
  - opportunities for theoretical developments

need Monte-Carlo(s)
for cold QCD matter!!

The end

Backup slides

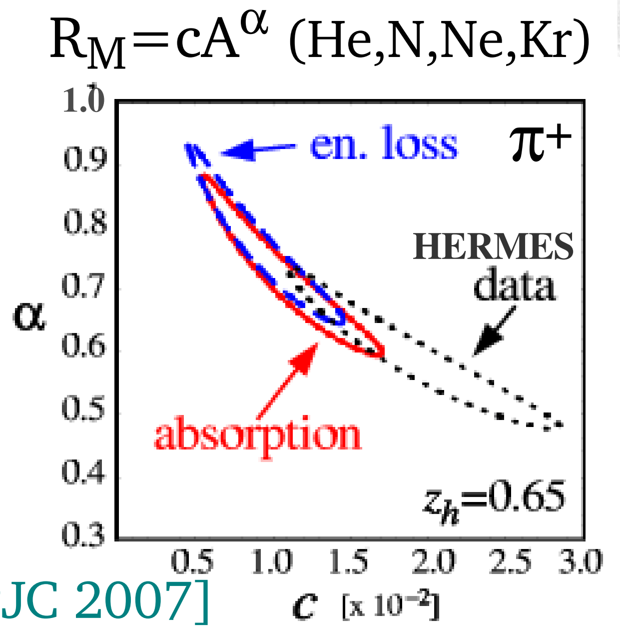
1) The “$A^{2/3}$ power law”

- 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: $1\text{-}R_M \sim$ ~~$< \text{no. of nucleons seen} > \sim L \sim$~~ $A^{1/3}$

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)



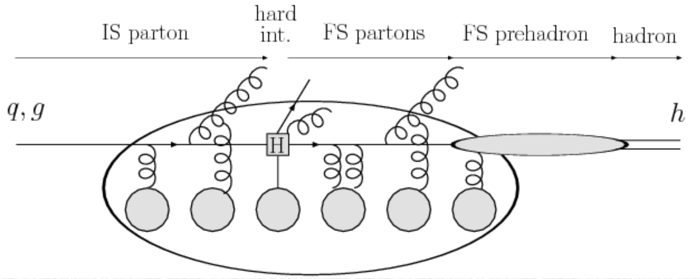
[A.A.,EPJC 2007]

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

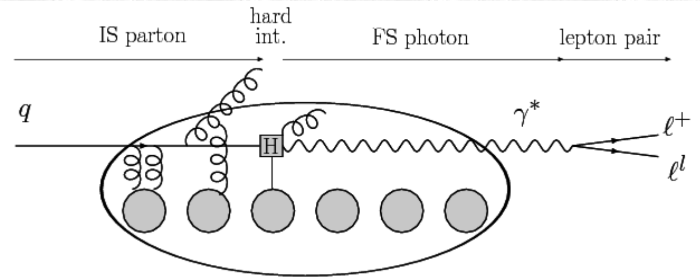
Initial state parton energy loss in p+A / A+A

- Initial & final state cold energy loss in p+A / A+A :

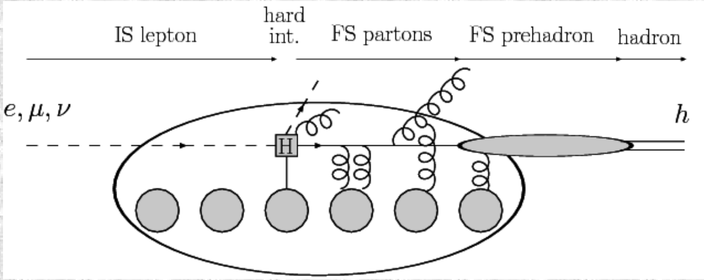
p+A
(A+A)



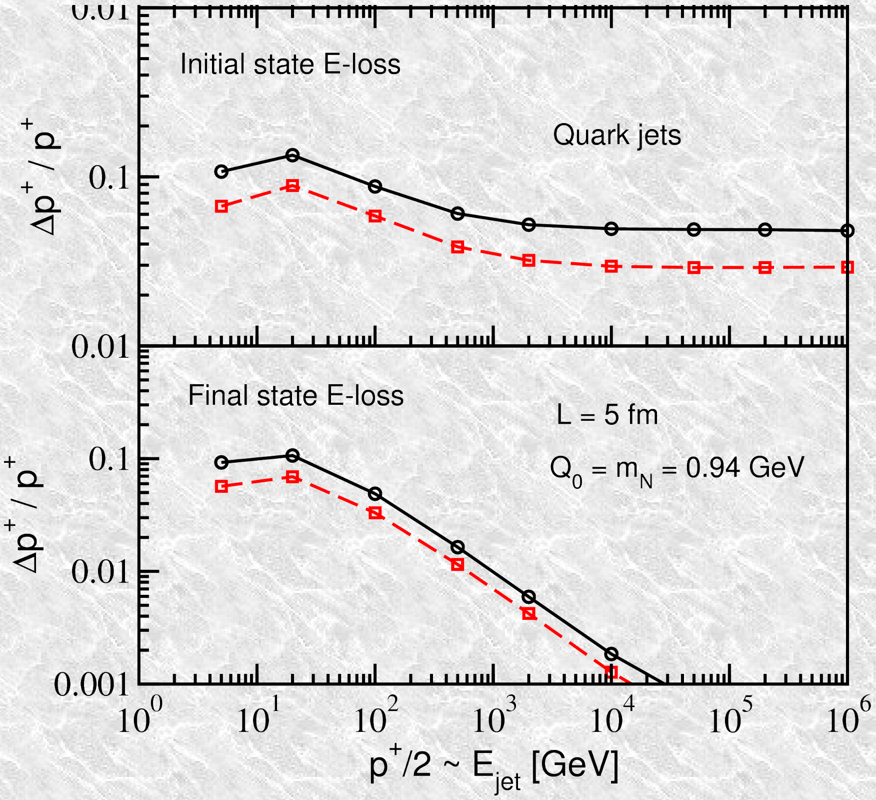
DY



nDIS



Vitev PRC'07

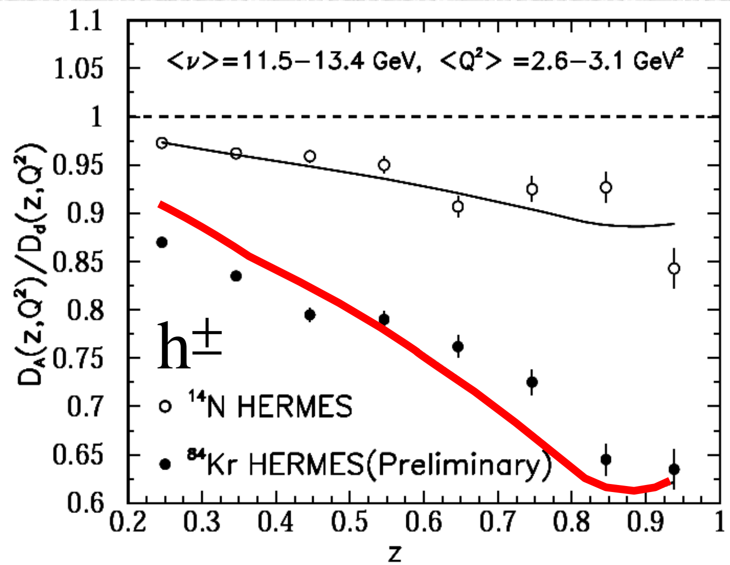


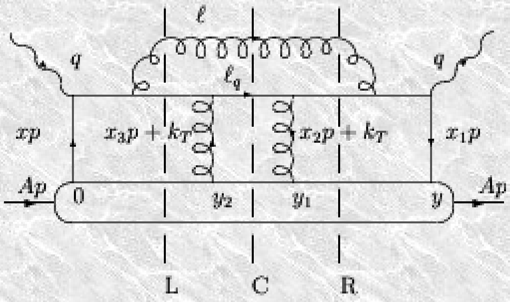
- Initial state energy loss can be large [Vitev PRC'07]
  - test models against DY data (but beware nuclear effects in target w.f.)

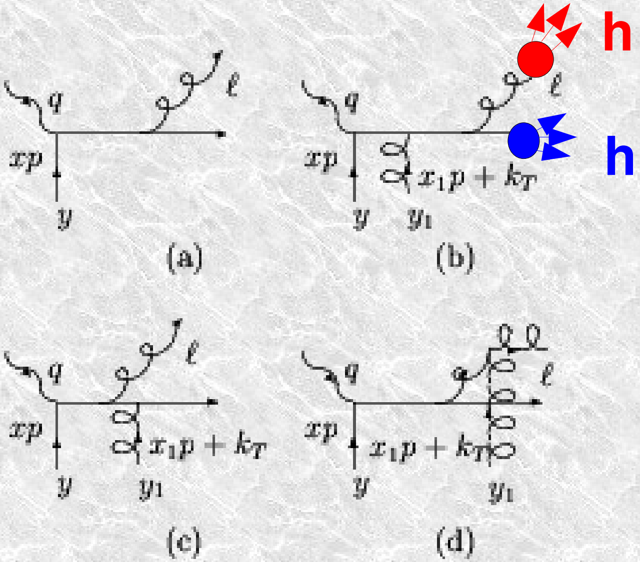
Needs unified energy loss formalism for DY, nDIS, h+A

Formation time estimates 1 – energy loss models

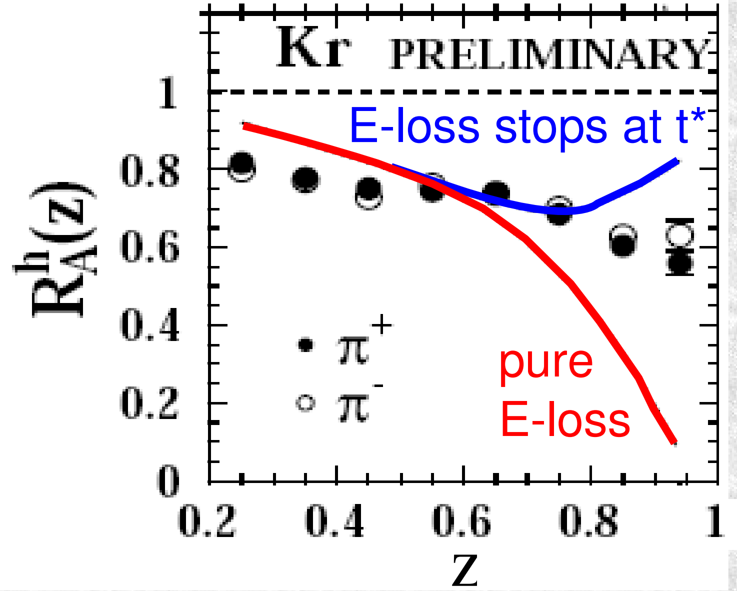
- Twist-4 modified Fragmentation Fns. [Wang&Guo '00, Wang & Wang '02]

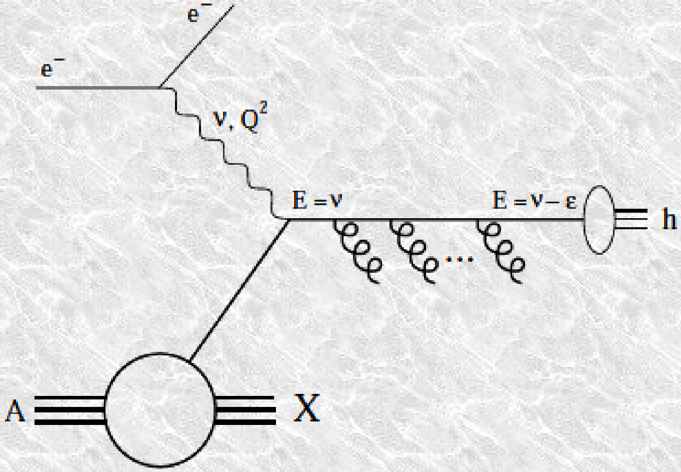






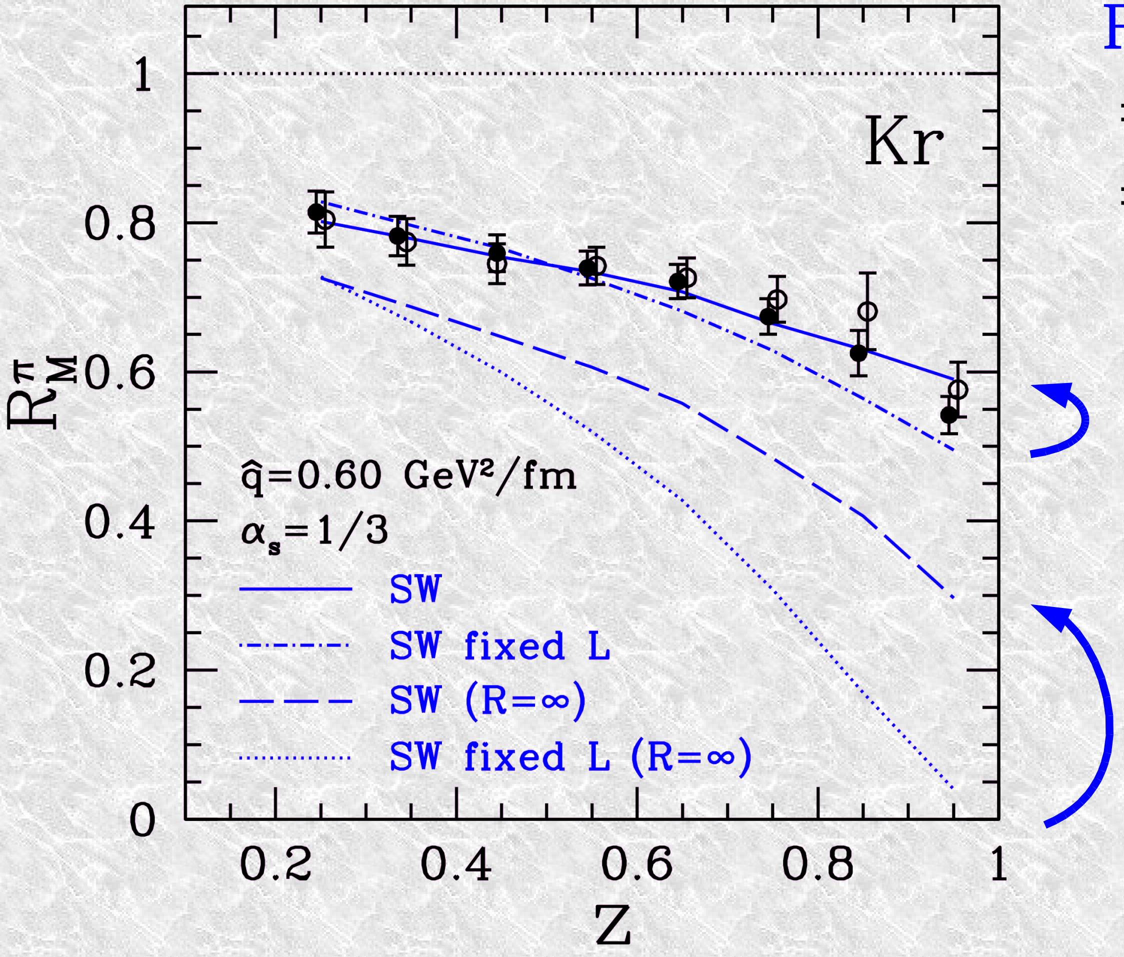
- Quark energy loss *à la* BDMPS [Arleo '02]





Effect of medium geometry approximations

- Example: energy loss model with SW quenching weights



Fixed vs. variable path length:

$\Rightarrow$ change in slope

$\Rightarrow$ variable p.l. describes data, fixed L too steep

Thick vs. finite size medium:

$\Rightarrow$ changes $\hat{q}$

$\Rightarrow$ thick: $\hat{q} \approx 0.2\ \text{GeV}^2/\text{fm}$

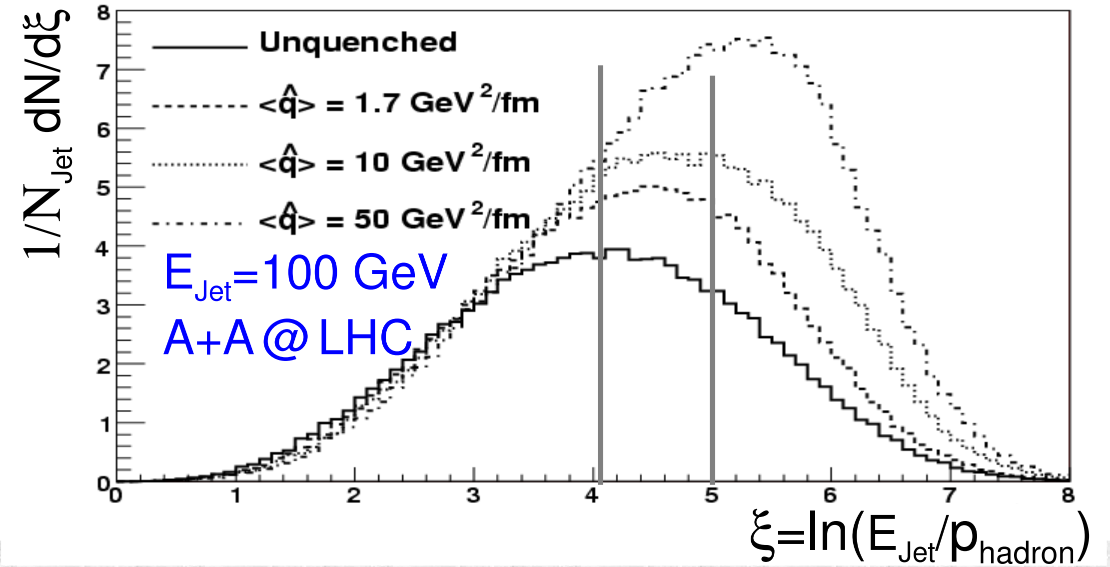
$\Rightarrow$ f.s.: $\hat{q} \approx 0.6\ \text{GeV}^2/\text{fm}$

- **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]

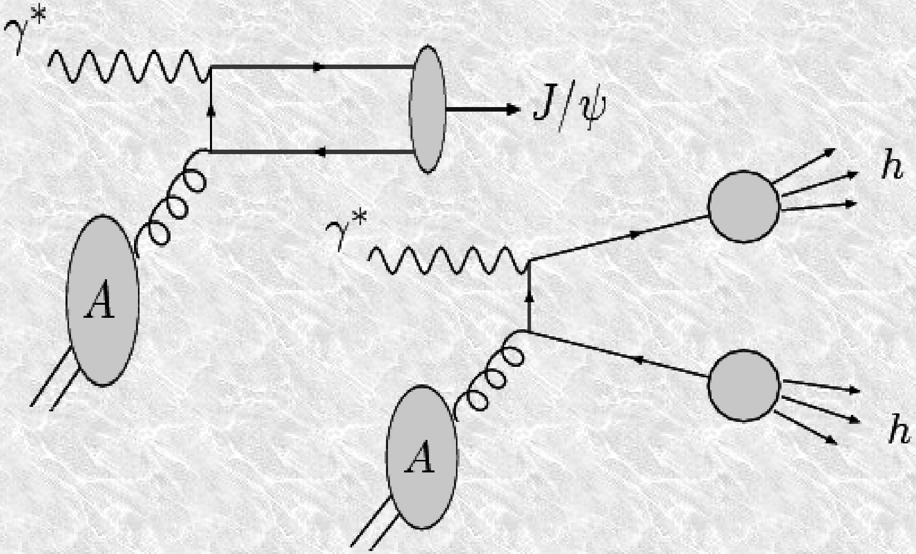


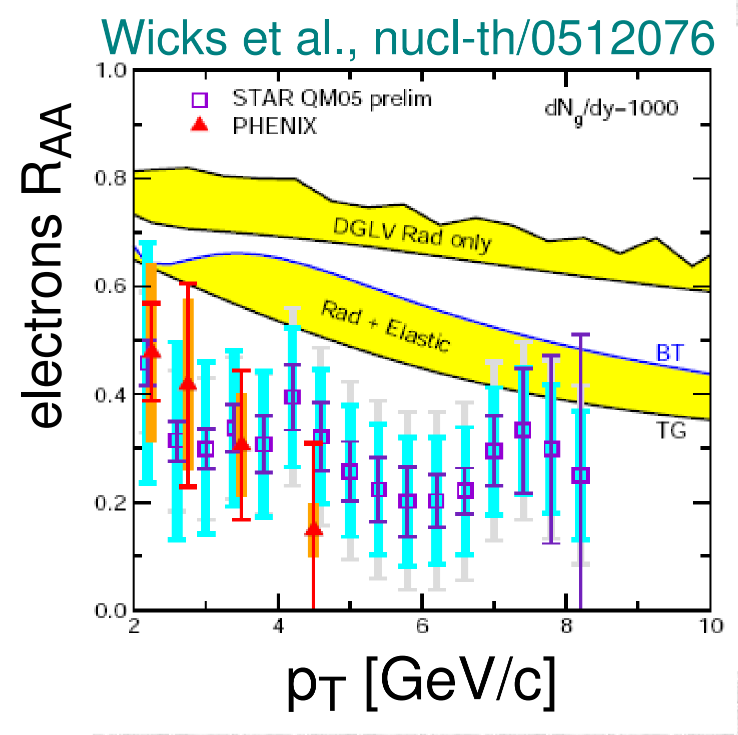
  - light-quark jets vs. heavy-quark jets vs. gluon jets
  - dijets, γ-jet correlations, …

accardi@jlab.org

The EIC – small x

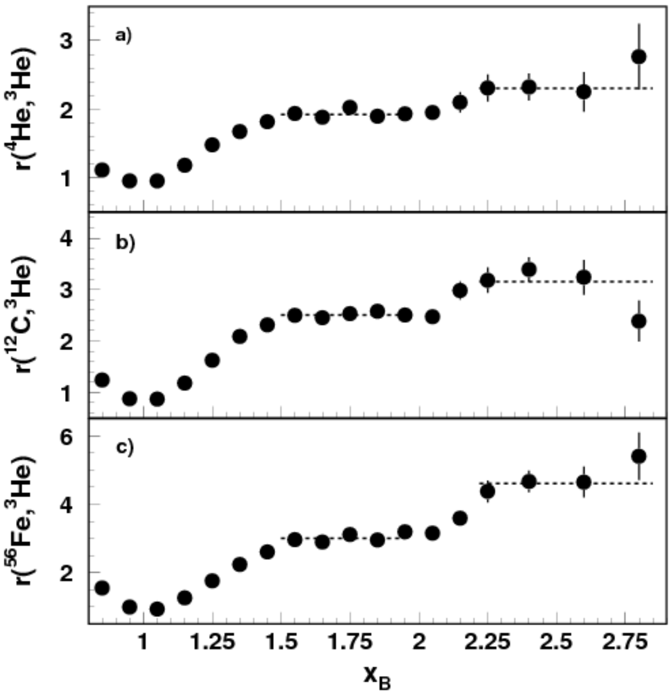
- Increased production of heavy flavors
- heavy quarks ⇒ D, B mesons
  - "heavy quark puzzle" at RHIC
- J/ψ "normal suppression"
  - J/ψ, ψ', χ suppression pattern
  - theoretically and experimentally cleaner in e+A
- back-to-back partons
  - "away-side" correlations: hadron-hadron, γ-hadron




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
    - …

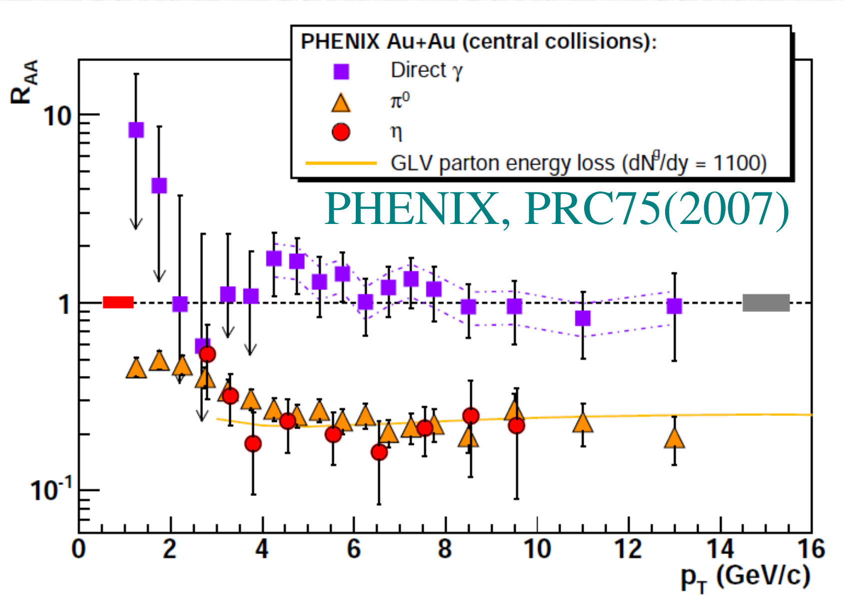


CLAS, PRL96(2006)

Quasi-elastic regime

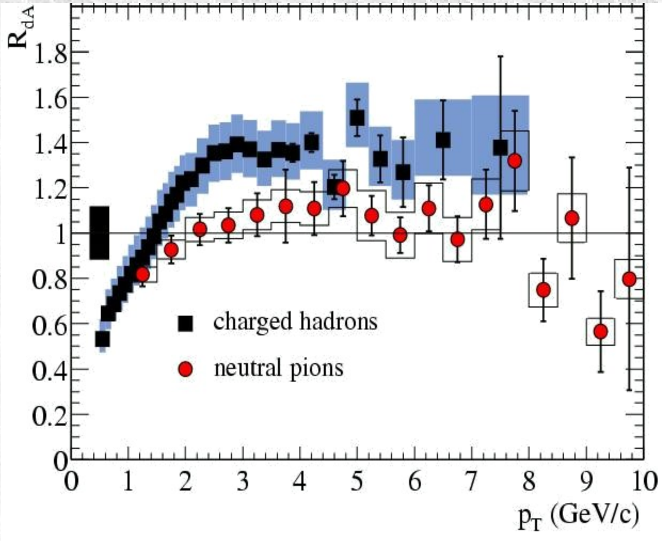
The EIC – large W^2

- Heavy mesons from fragmentation, large rate
  - η vs. π attenuation (no difference at RHIC)
    - low-ν $\Rightarrow$ η is heavier, hadronizes earlier
    - high-ν $\Rightarrow$ same valence, same partonic effects?
    - role of Q^2 (at RHIC, $Q^2 \sim$ 10-50 GeV^2)
  - extend to strange / charm sector



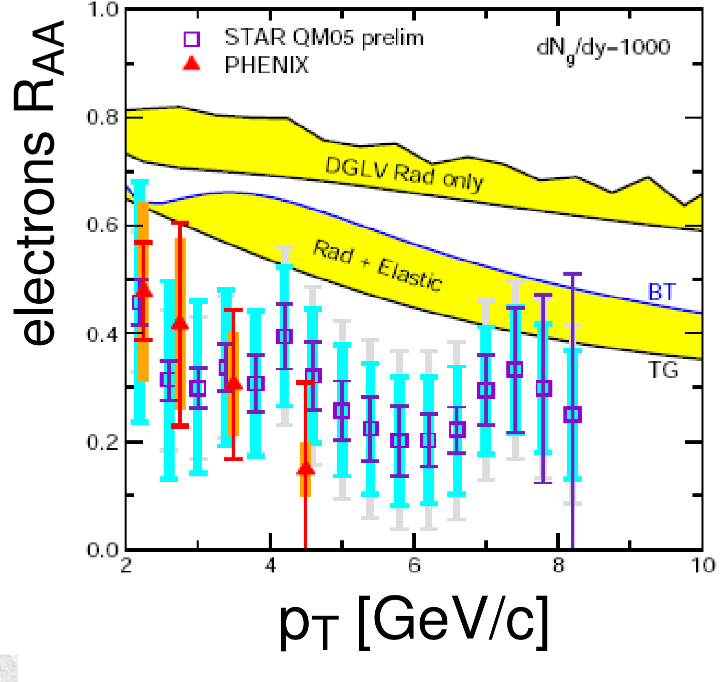
PHENIX, PRC75(2007)

- 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, ...



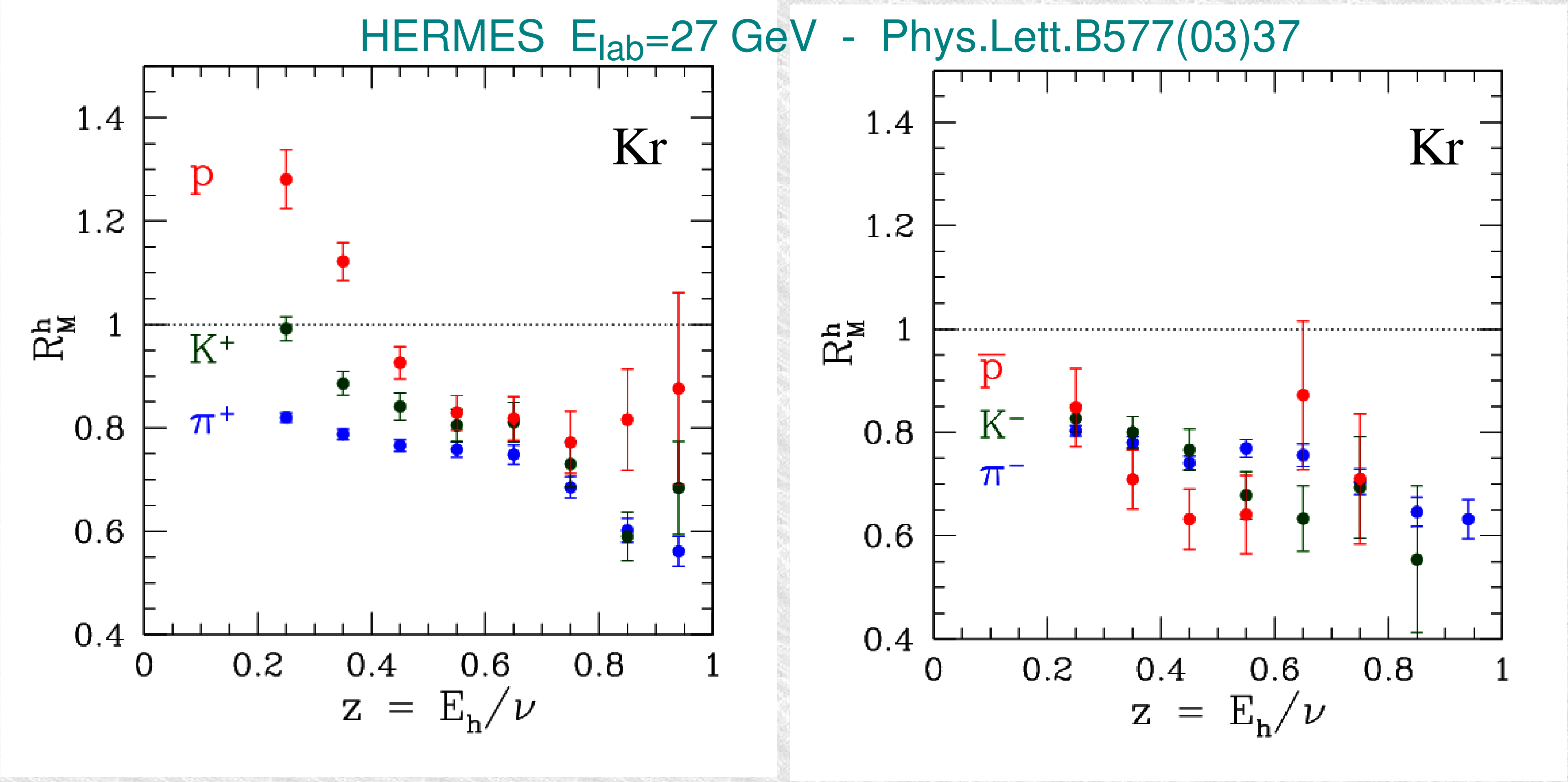
The EIC – large W^2

- 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
- Needs an Electron-Ion Collider!



Wicks et al., nucl-th/0512076

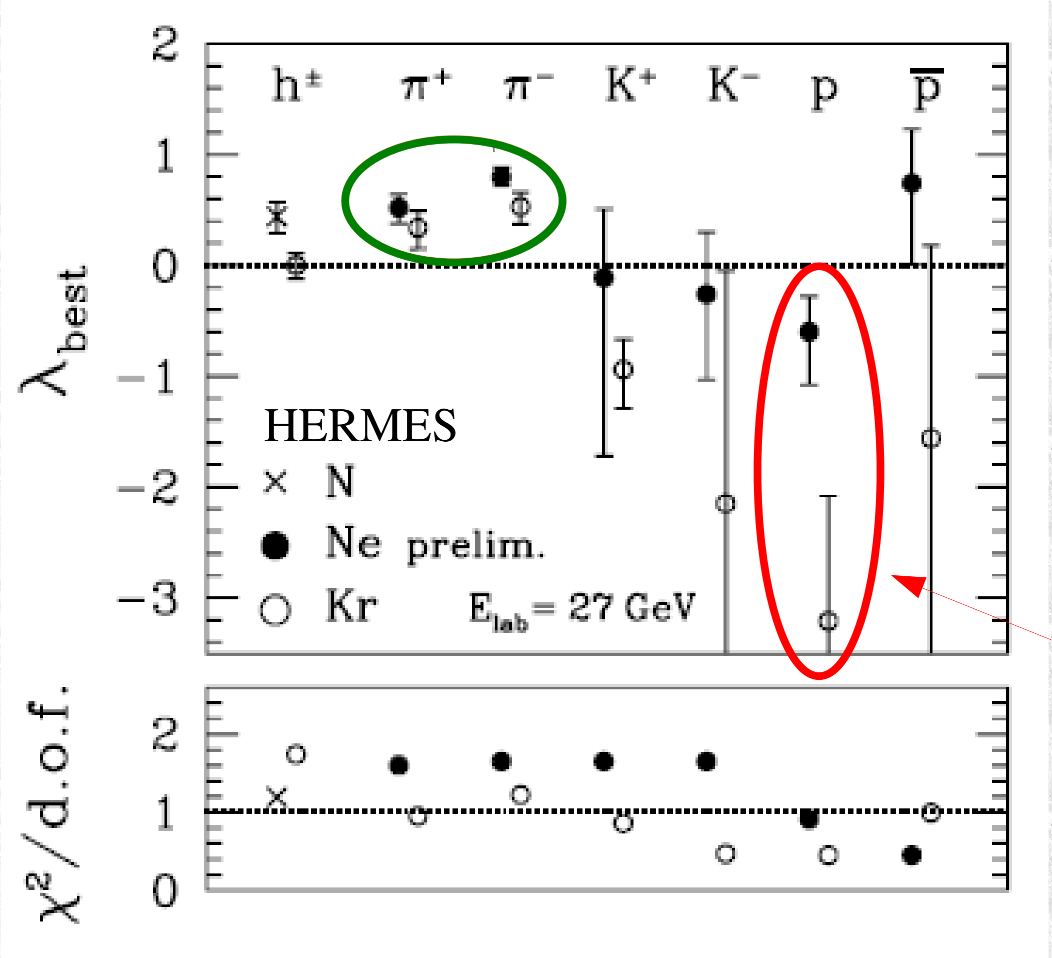
Measurements at HERMES

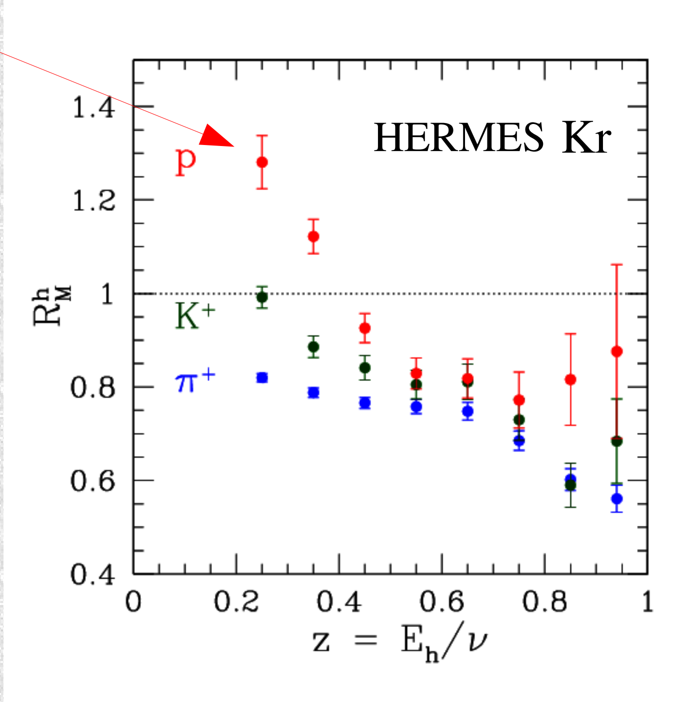


HERMES E_{lab}=27 GeV - Phys.Lett.B577(03)37

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

Results – E_{lab} = 27 GeV

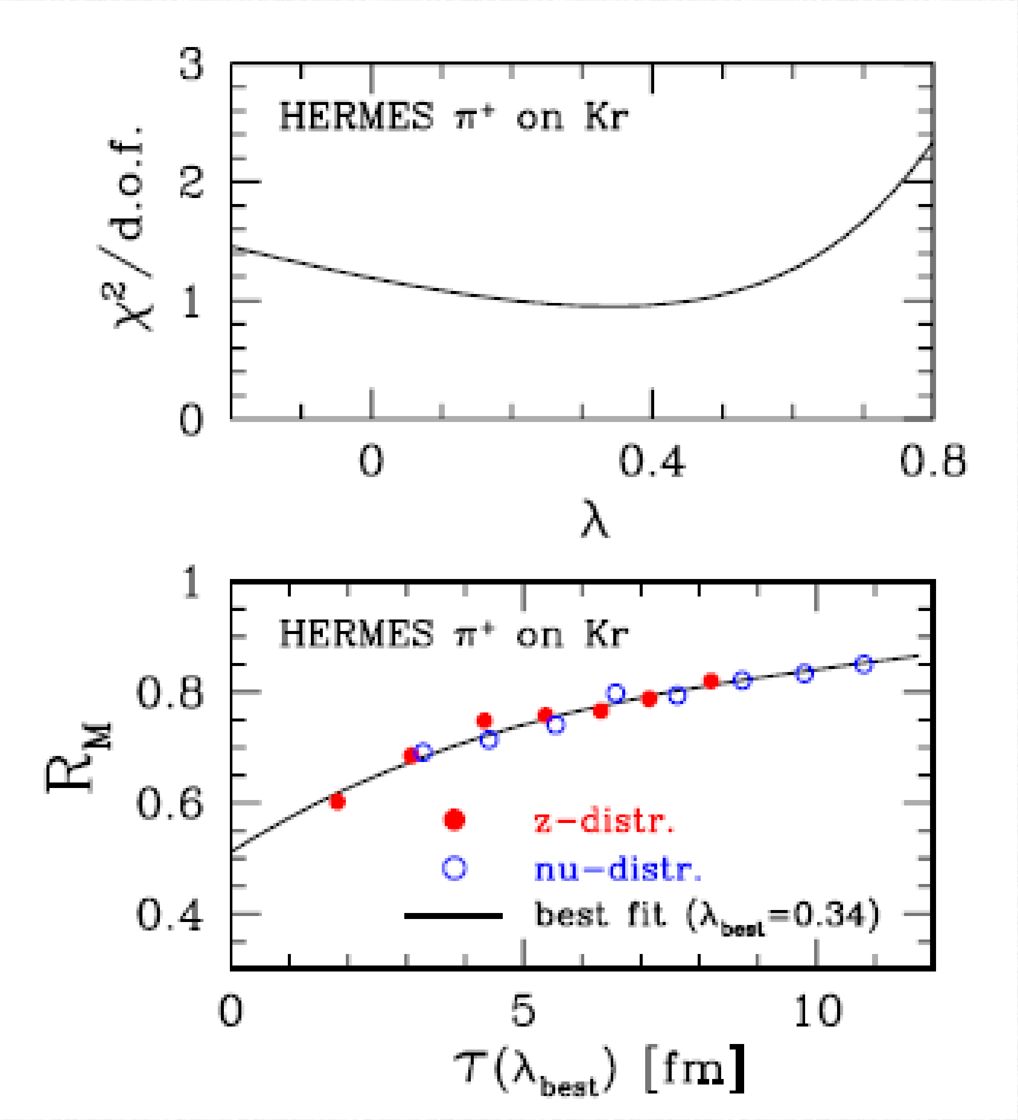




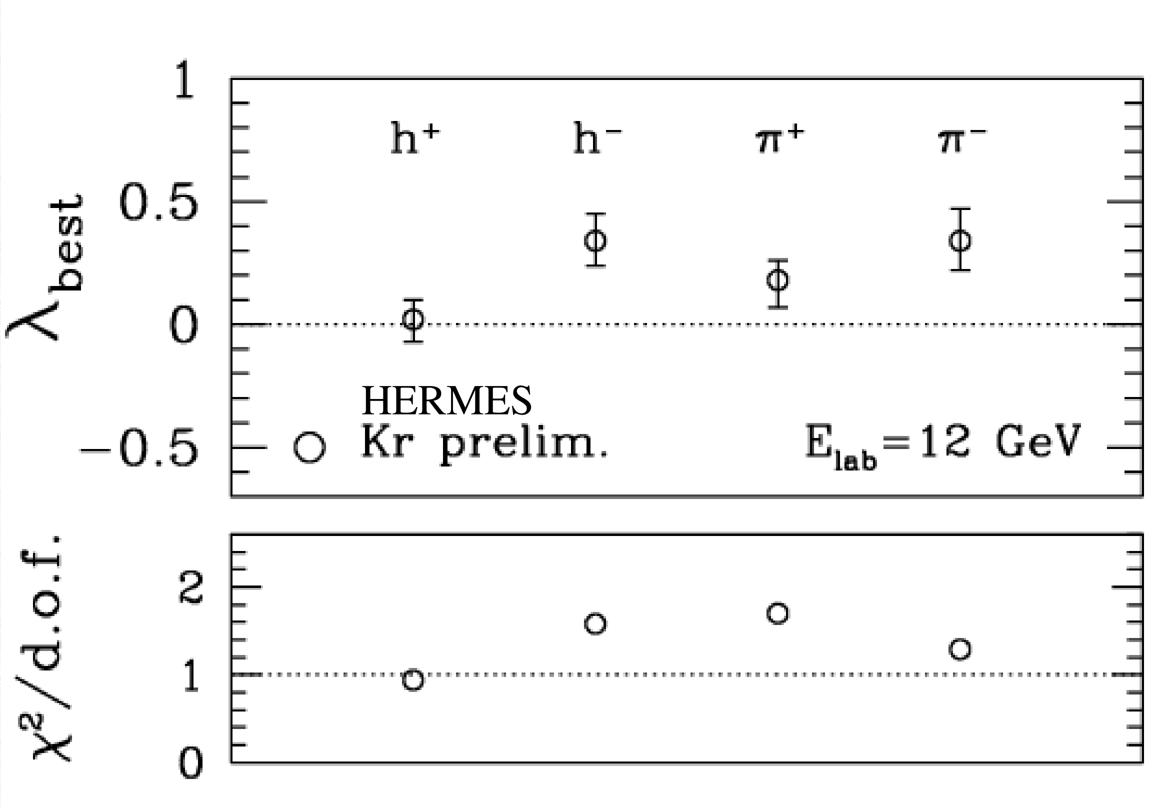
- $\lambda(\pi)>0$: **Formation-time scaling for pions!**
- Why $\lambda_{best}(h^\pm) \sim 0$ on Kr?
  - proton anomaly!

2) Scaling analysis - example

A.A., PLB B649 (07) 384

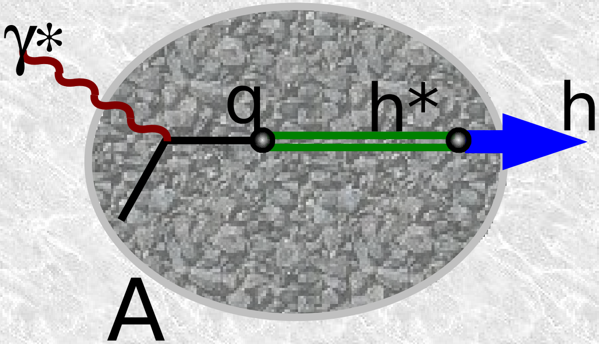


Results – E_{lab} = 12 GeV

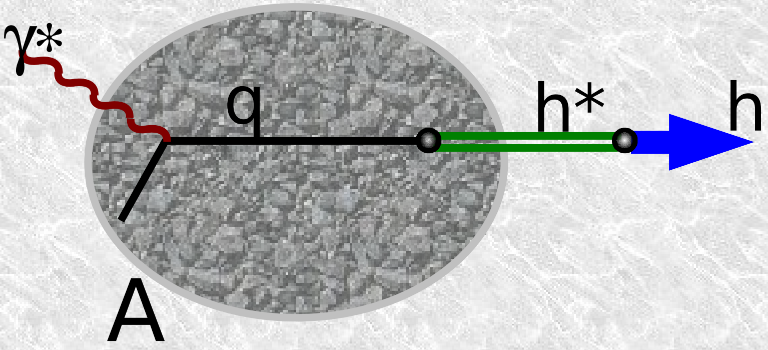


- pions are still positive! confirms results at 27 GeV
- $\lambda_{best}(h^+) \sim 0$ but $\lambda_{best}(h^-) > 0$
    - proton anomaly hypothesis confirmed!

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

- **“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