(Parton propagation and) hadronization in nuclear matter

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Hampton U. & Jlab

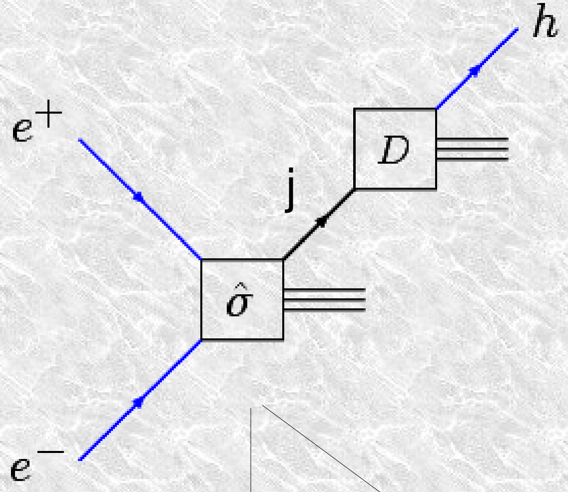
EIC workshop
Hampton U., 19-23 May 2008

Outline

- **Physics motivations**
- **Very short review of experimental data**
- **Formation times – theory review**
- **Making sense of HERMES / JLAB data**
  - Can we estimate the parton lifetime?
- **Perspectives at the EIC**
- **Homework assignments**

Physics motivations

Hadronization in elementary collisions



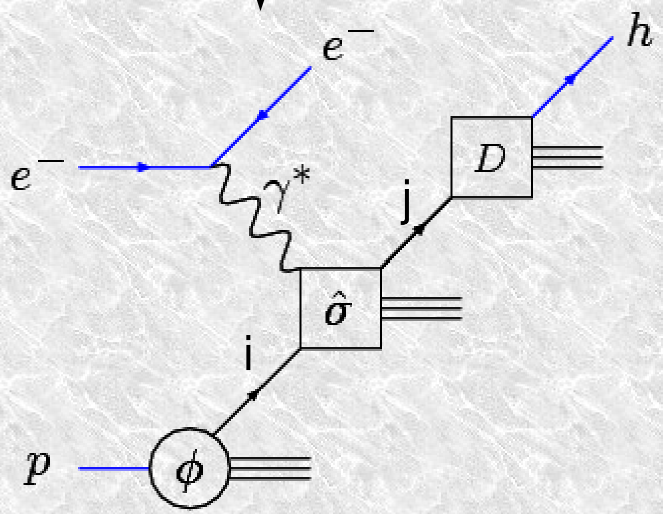
- **perturbative QCD factorization** of short and long distance physics

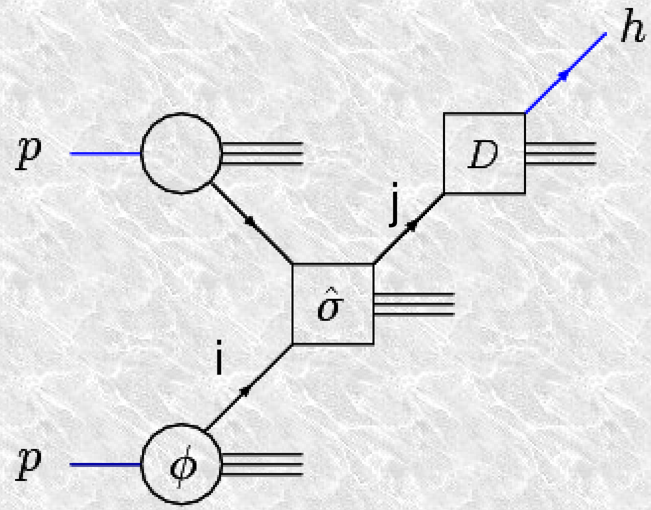
$$d\sigma_{\rm hadron} = \sum_{ij} \phi_i \otimes \hat{\sigma}^{ij}_{\rm parton} \otimes D_{j|h}$$

Parton Distribution Fns (from inclusive DIS)

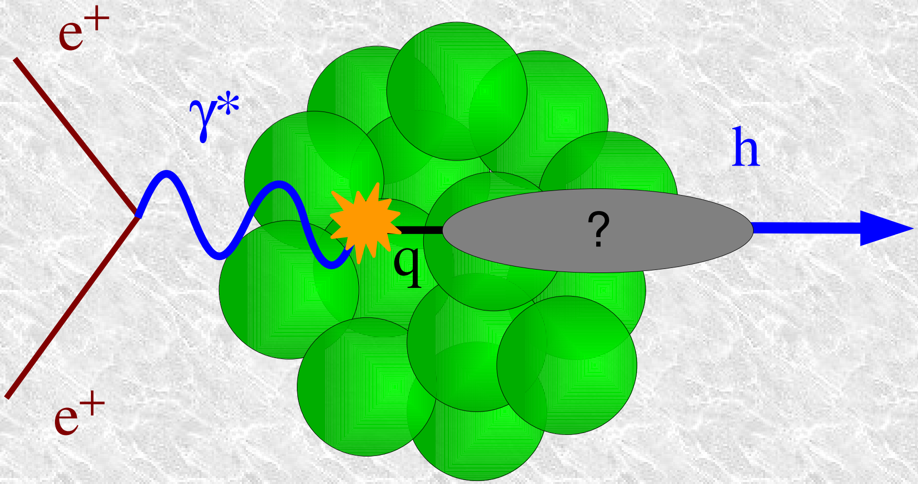
Fragmentation Fns (from $e^+ + e^- \to h + X$)

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

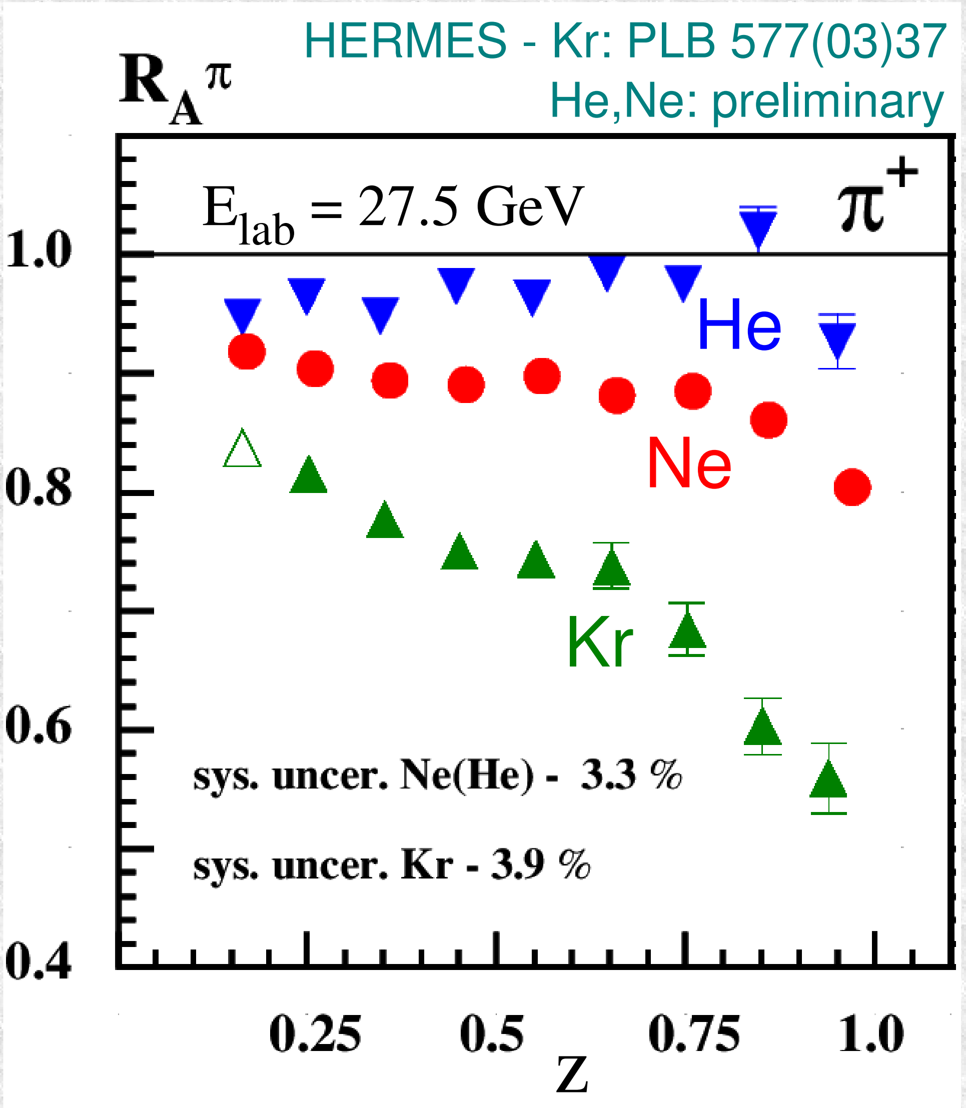




Nuclear collisions 1 - nDIS



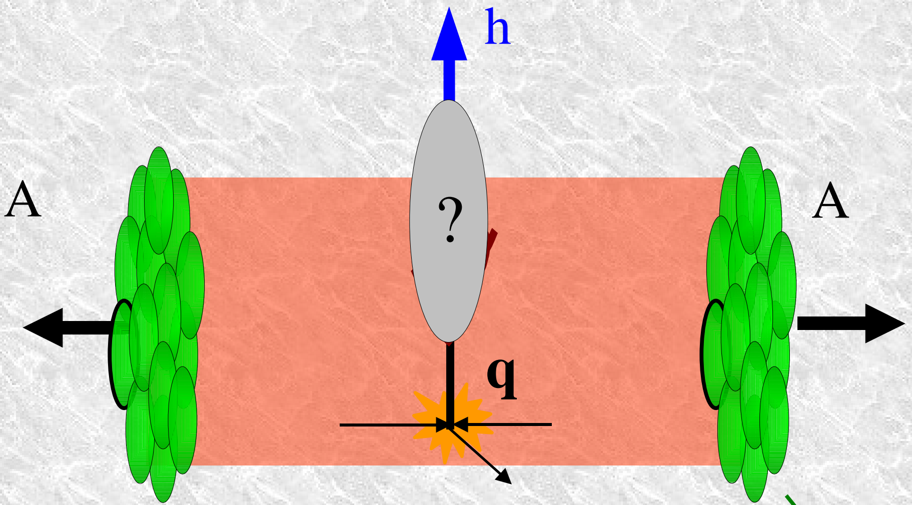
$$R_M^h(z) = \frac{\frac{1}{N_A^{DIS}} \frac{dN_A^h(z)}{dz}}{\frac{1}{N_D^{DIS}} \frac{dN_D^h(z)}{dz}}$$



- 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



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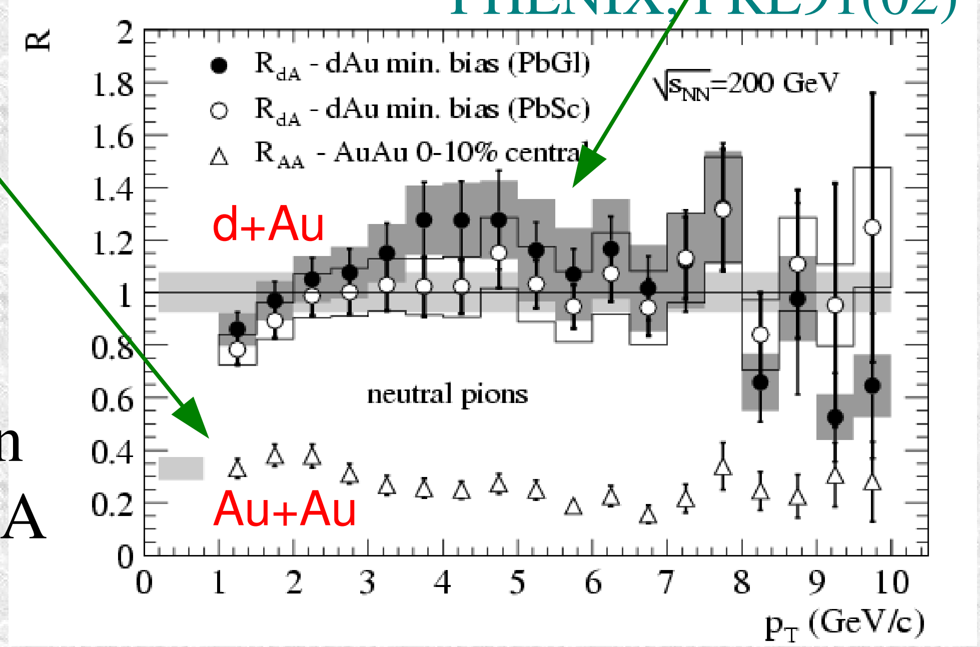
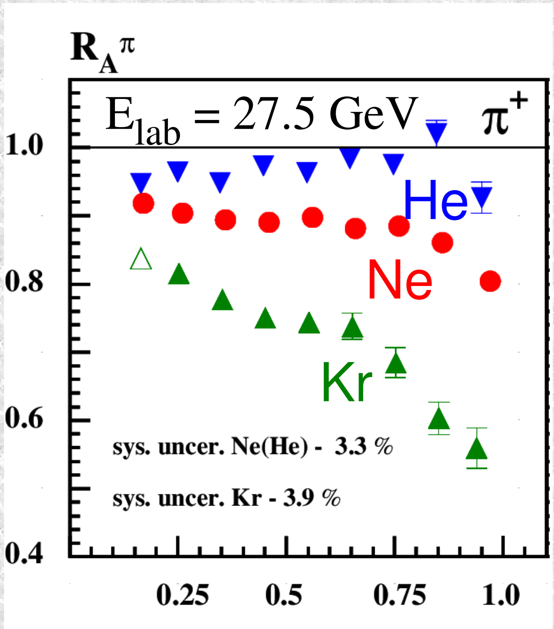


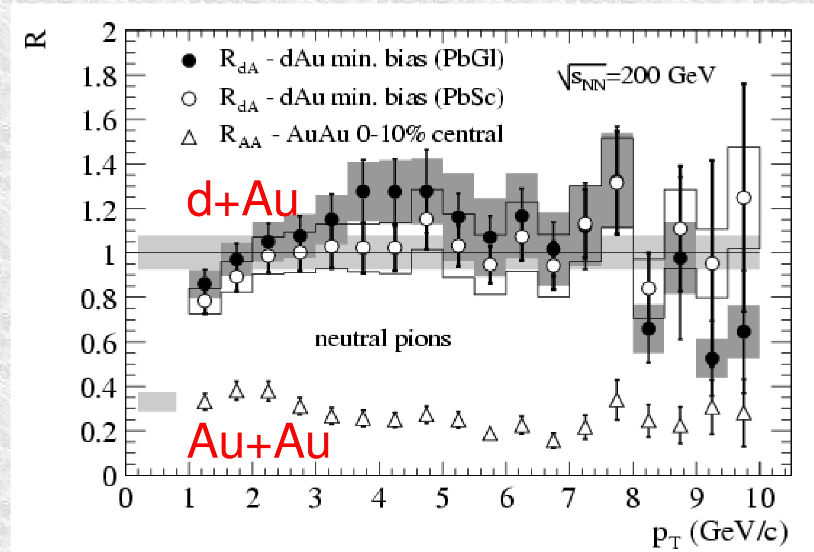
$$R_{AB} = \frac{(dN^h/d^2p_T)_{A+B}}{T_{BA}(b)\ (d\sigma^h/d^2p_T)_{p+p}}$$

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

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

Breakdown of universality in nuclei

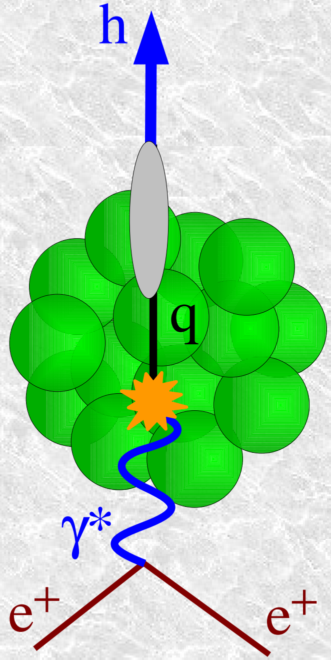


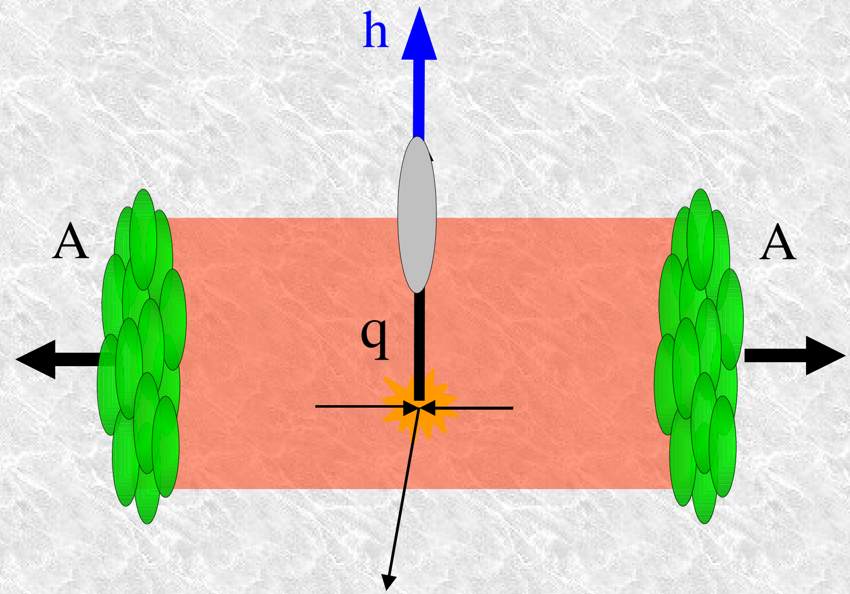


- Hadronization is no more process-independent
- Among possible causes:
  - struck quark interactions with the medium
  - (pre)hadron interactions with the medium
  - in-medium modifications of parton showers
  - other medium nuclear, e.g., partial deconfinement [Dias de Deus '87]
  - breakdown of factorization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

This talk

nDIS vs. A+A collisions





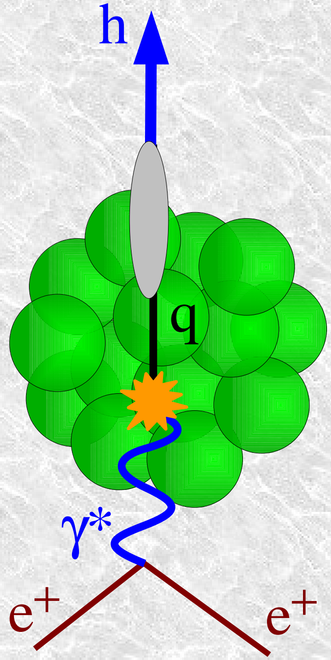
- nDIS is a clean environment for
  - (1) **space-time evolution of hadronization**
    - nucleons as femto-detectors
    - medium rather well known
  - (2) **Cold nuclear matter effects**
    - quark energy loss
    - nuclear modifications of FF

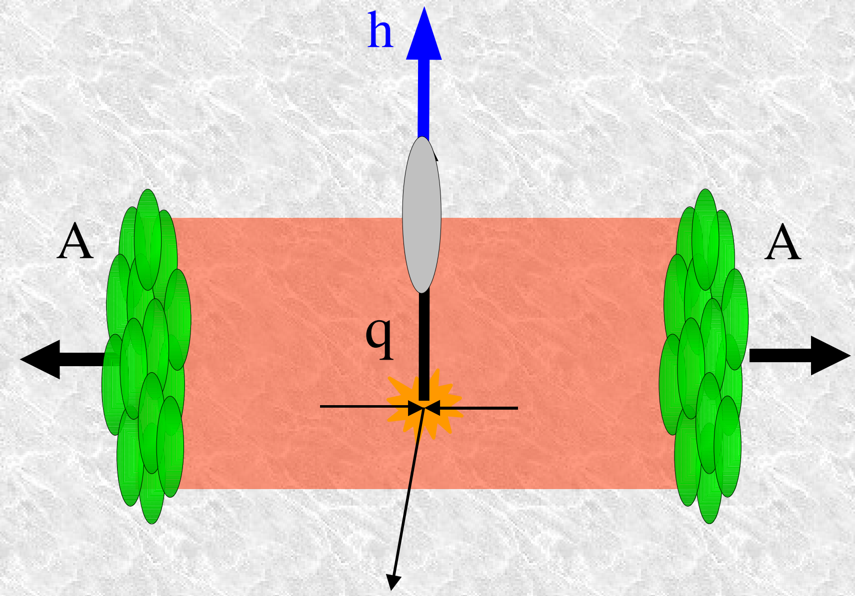
Jet-quenching in A+A

$\Downarrow$

properties of hot nuclear matter

The fixed-target point of view





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

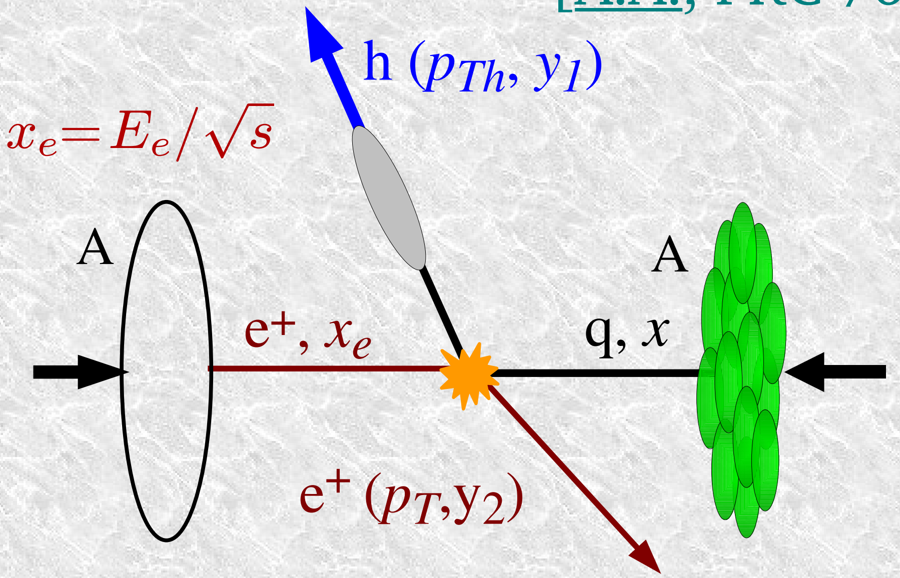
…but beware the virtuality: ≈ 2 GeV^2 vs. 5-70 GeV^2!!

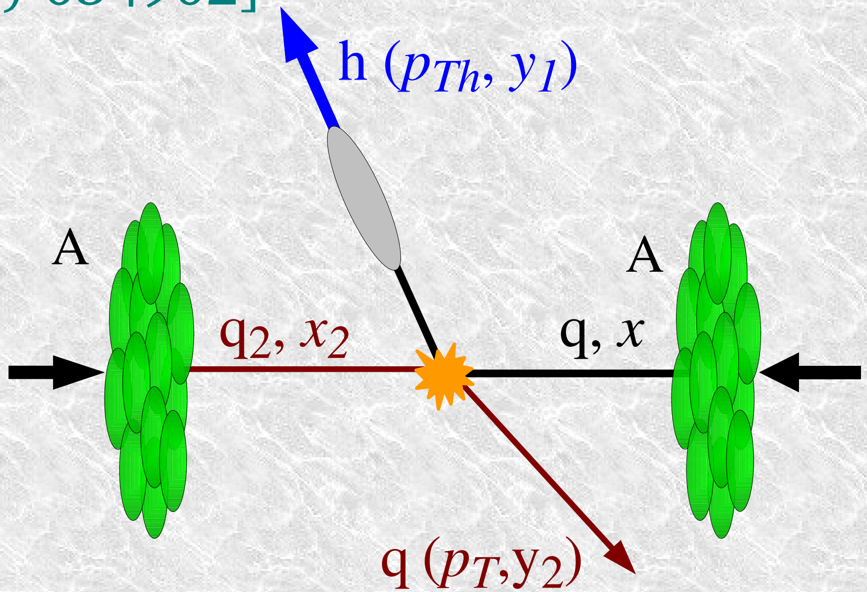
$Q^2 = - q^2$ is measured

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

The collider point of view

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





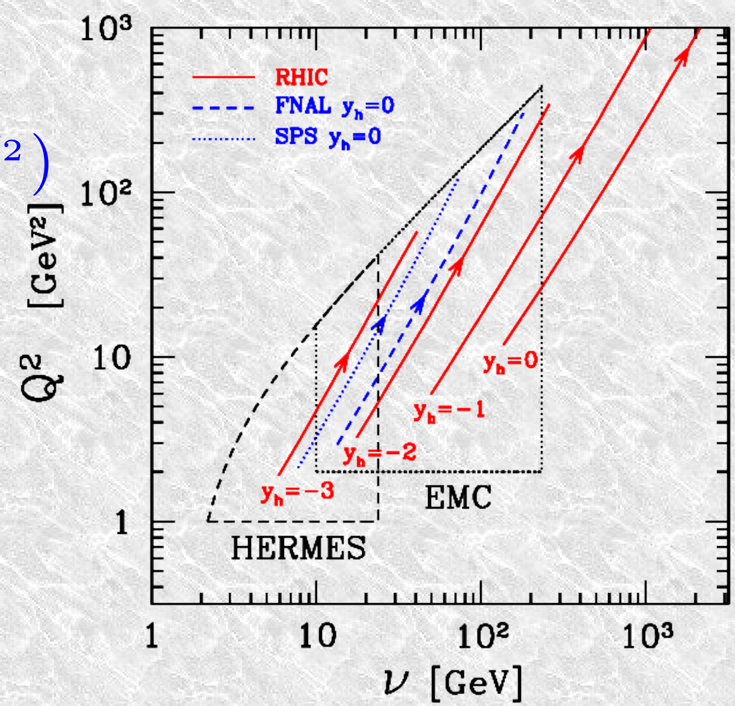
- In LO kinematics:

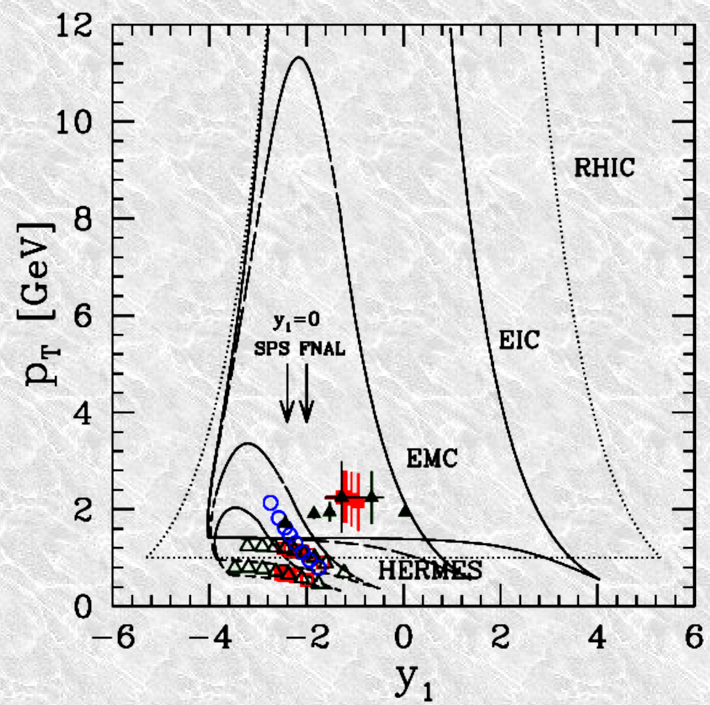
$$Q^2 = p_T^2(1+e^{y_1-y_2})$$

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

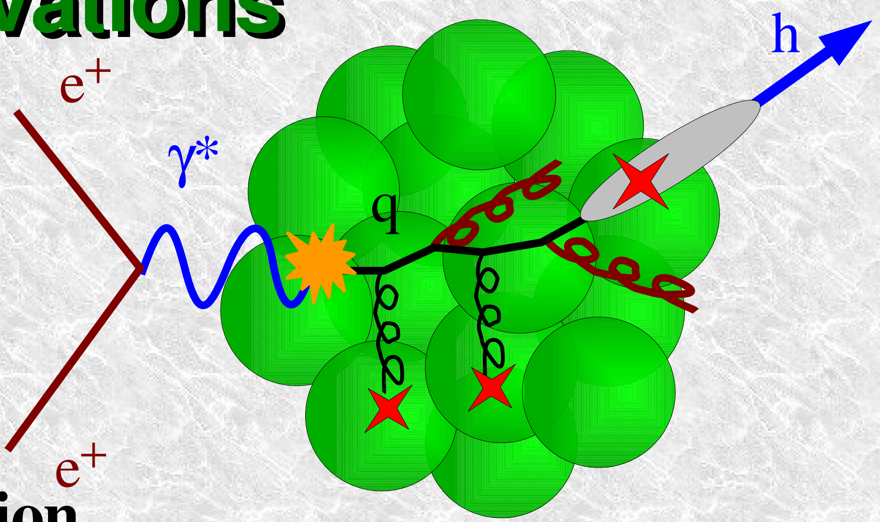
$$y = \frac{1}{1+e^{y_2-y_1}}$$

$$z_h = z$$





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
  - understanding of color confinement
- **Parton propagation in perturbative QCD**
  - QCD energy loss (LPM effect): basic pQCD, only indirectly tested
  - DGLAP parton shower
  - measurement of $\hat{q}_A \Longleftrightarrow Q_s(A)$

see Wang's talk

- **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

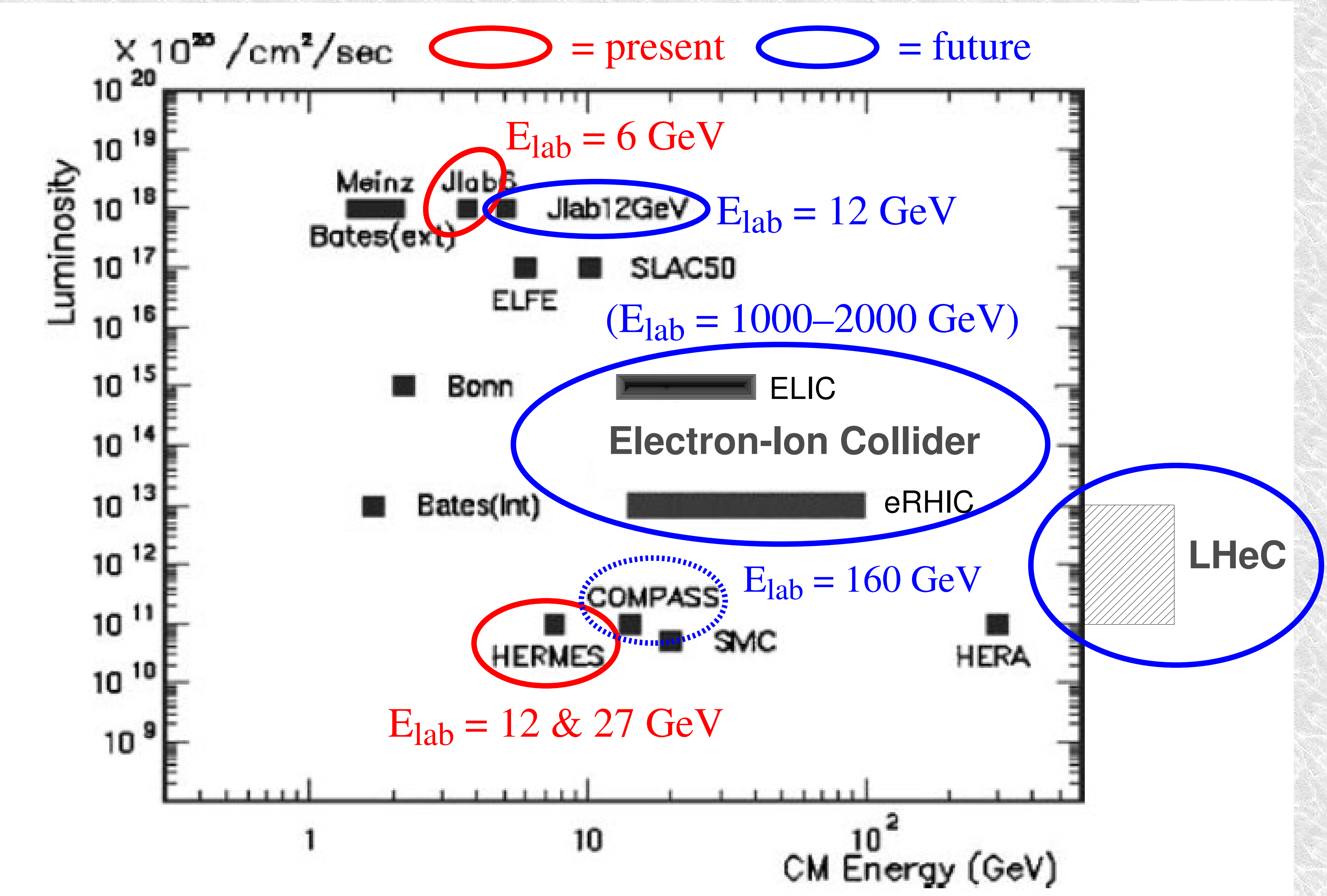
Short review of e+A data

For the latest data see:

1) HERMES, NPB 780 (2007) 1

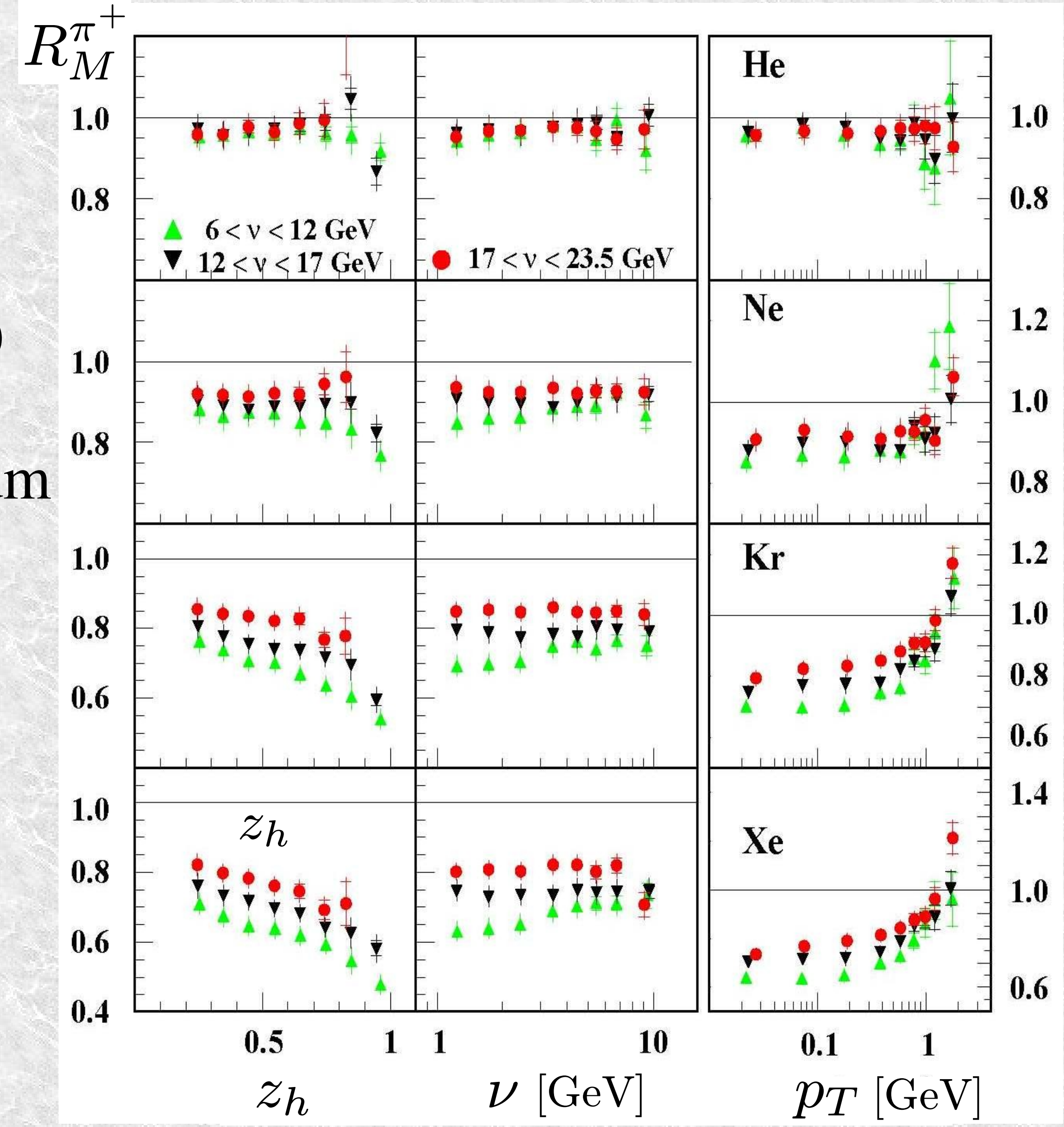
2) Trento Fragmentation Workshop, Feb 2008
http://arleo.web.cern.ch/arleo/ff_vacuum_medium_ect08/

Present and future e+A facilities



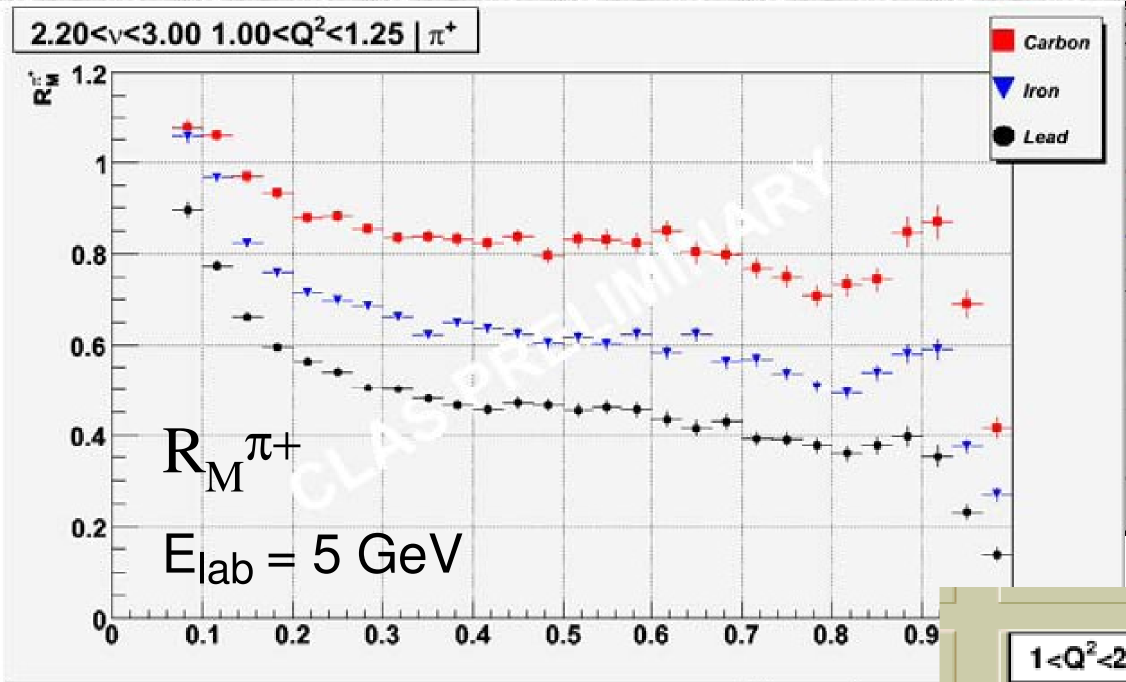
Measurements at HERMES

- 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
- 2-dimensional binning (!)



[HERMES, NPB 780 (2007) 1]

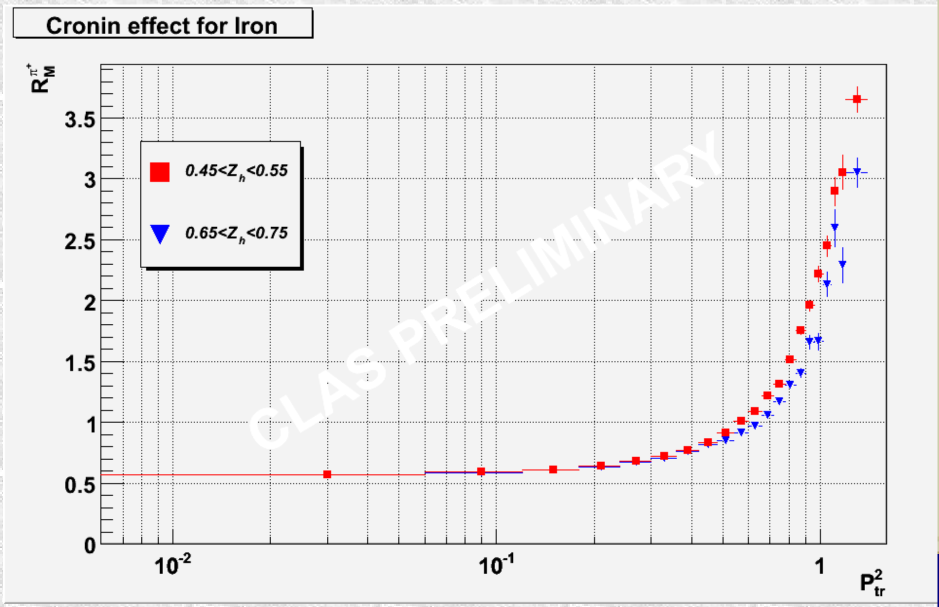
Preliminary results at CLAS

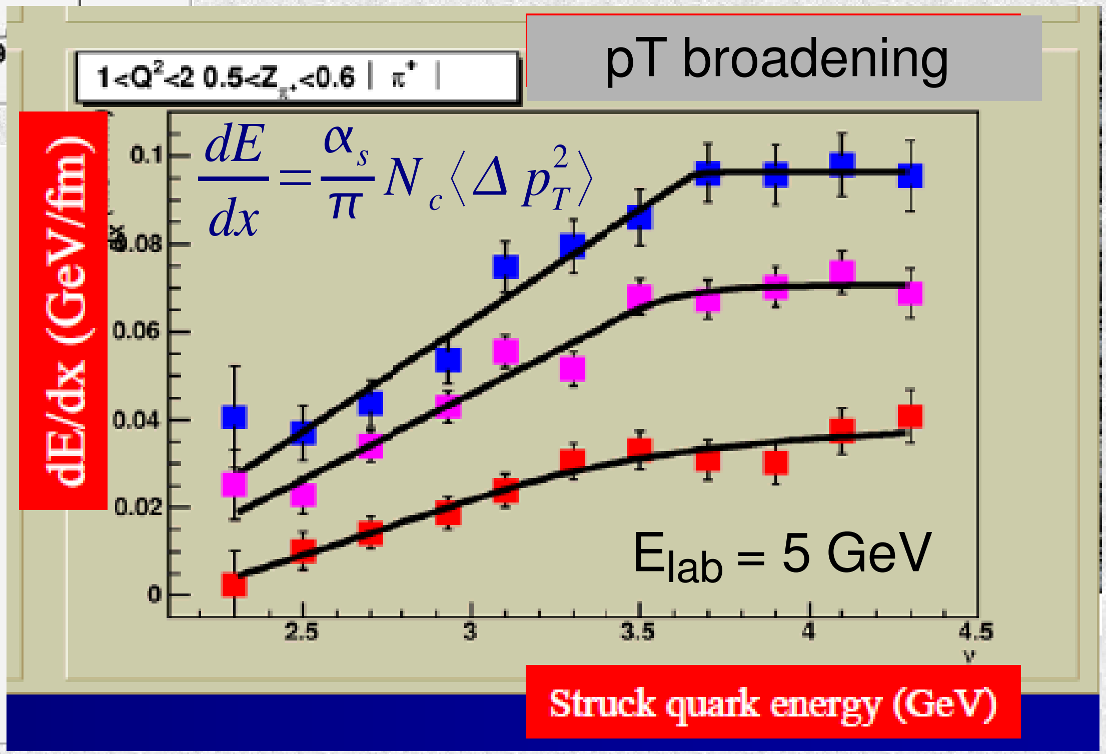


- 6 (12) GeV beam
- huge luminosity
  - multi-differential binning !!
  - γ+h correlations
  - and much more...

K.Hafidi, nucl-ex/0609005

Brooks, Hicks, talks at Trento Workshop



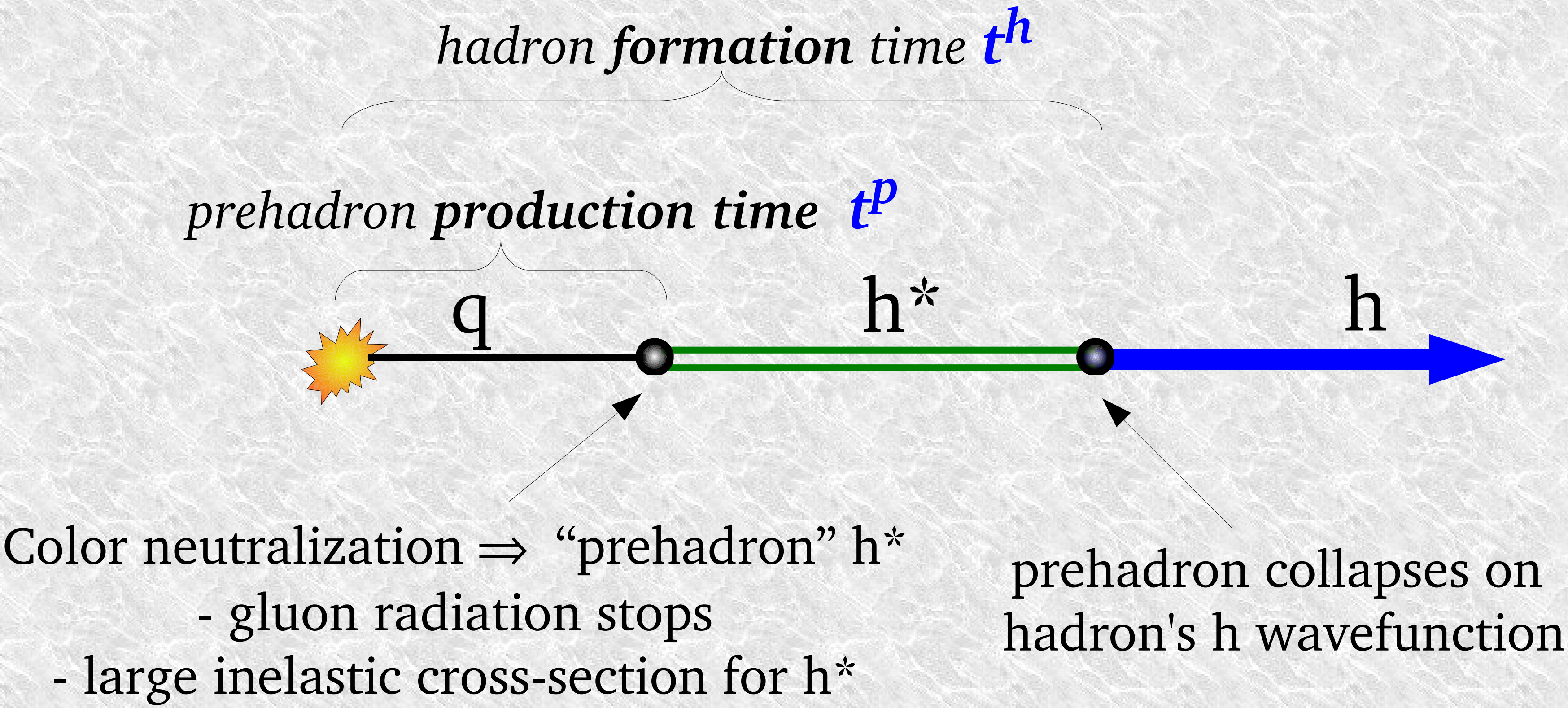


Hadron formation time:
a review of theory models

see A.A., EPJC 2007 for a mini review

The (naïve) framework : prehadron vs. hadron

- Hadronization is non perturbative $\Rightarrow$ (many) models
- General features:

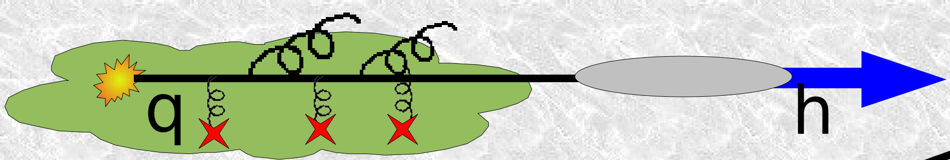


- *Caveats:*
  - It's tricky to rigorously define t^p , t^h: consider them as working tools
  - Leading-order pQCD mindset ($\gamma^* + q \to q$), but NLO may be large

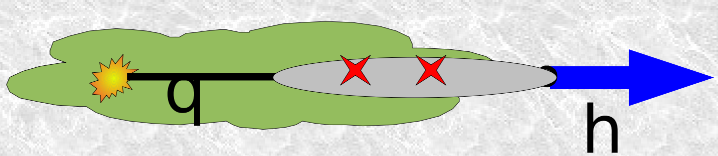
Hadron attenuation in nDIS

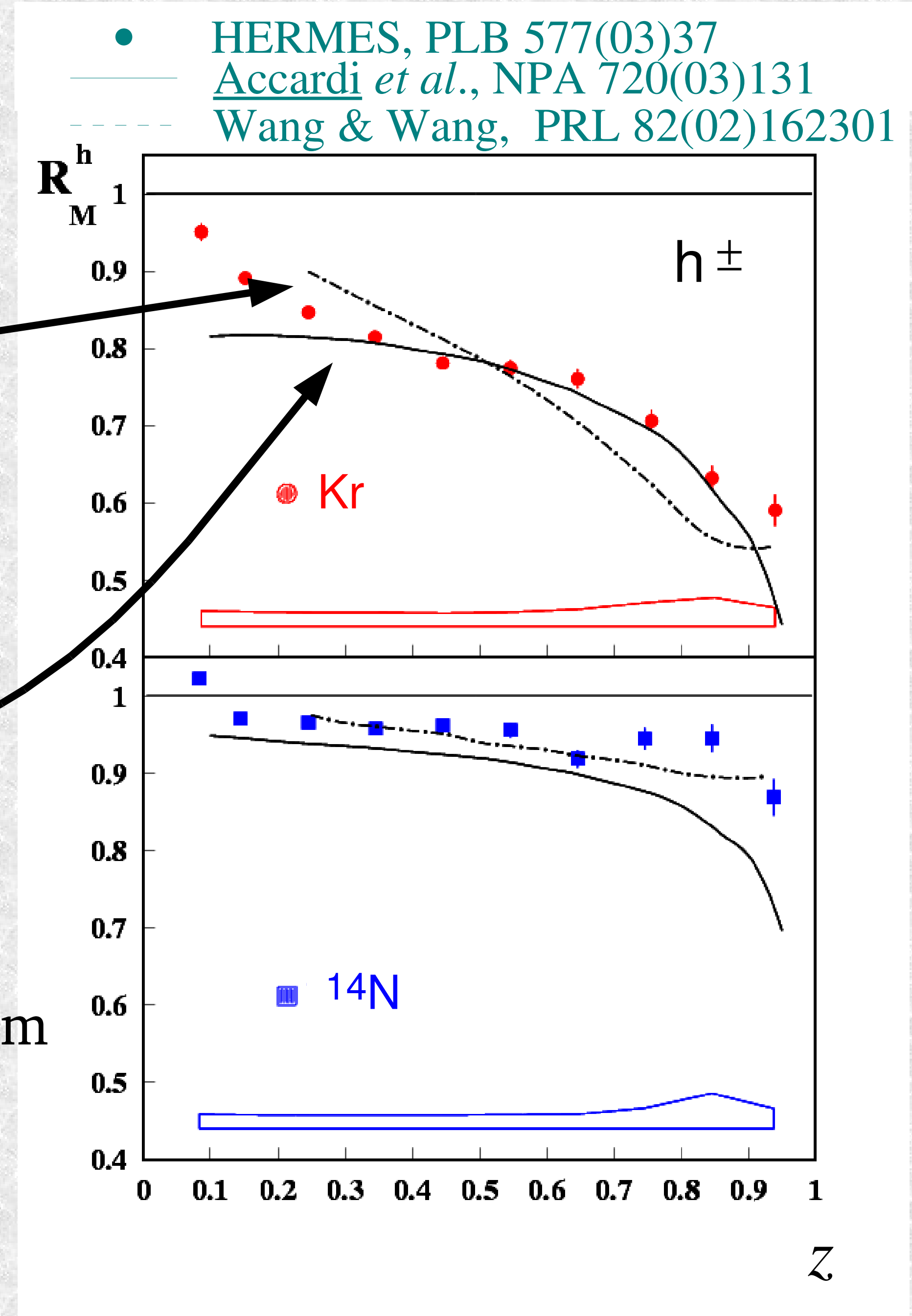
$$R_M^h(z) = \frac{\frac{1}{N_A^{\mathrm{DIS}}}\frac{dN_A^h(z)}{dz}}{\frac{1}{N_D^{\mathrm{DIS}}}\frac{dN_D^h(z)}{dz}}$$

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



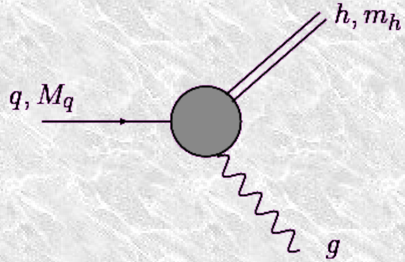
- **Prehadron absorption**
  [Accardi *et al.*;
  Falter *et al.*; Kopeliovich, *et al.*]
  - color neutralization inside the medium
  - prehadron-nucleon scatterings

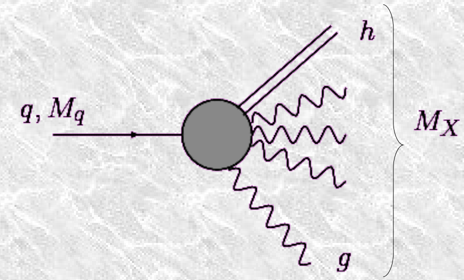




Formation time estimates 1 – pQCD estimate

- pQCD estimate [see Vitev, QM'05]

assume, 

more probably, 

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

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

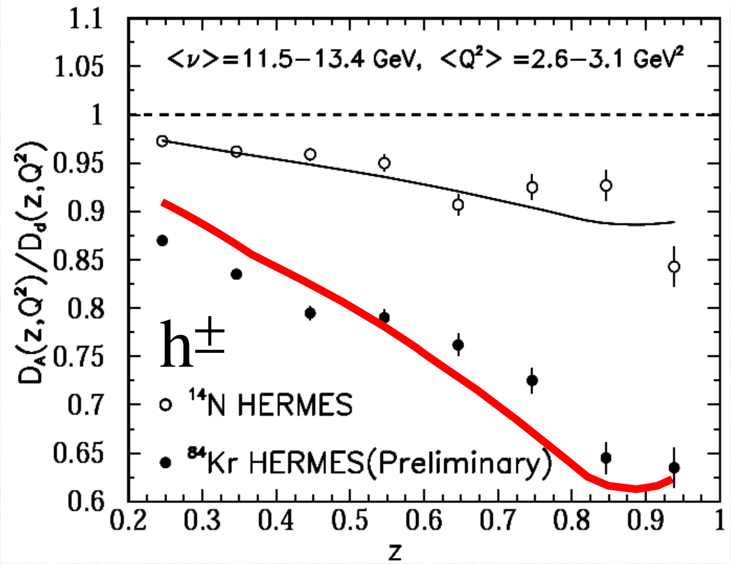
	π	K	p	D	B
HERMES (ν~13 GeV, z~0.5)	37 fm	11 fm	4 fm	1.2 fm	0.1 fm
RHIC (p_T^h ~ 7 GeV z~0.7)	26 fm	6 fm	4 fm	1.2 fm	0.1 fm

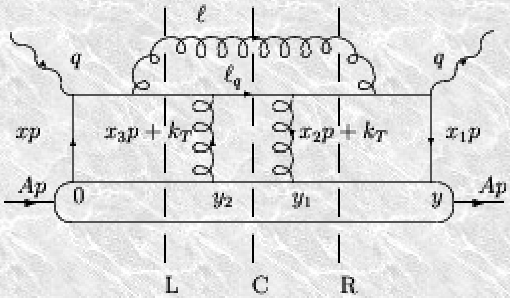
~ inside the medium !!

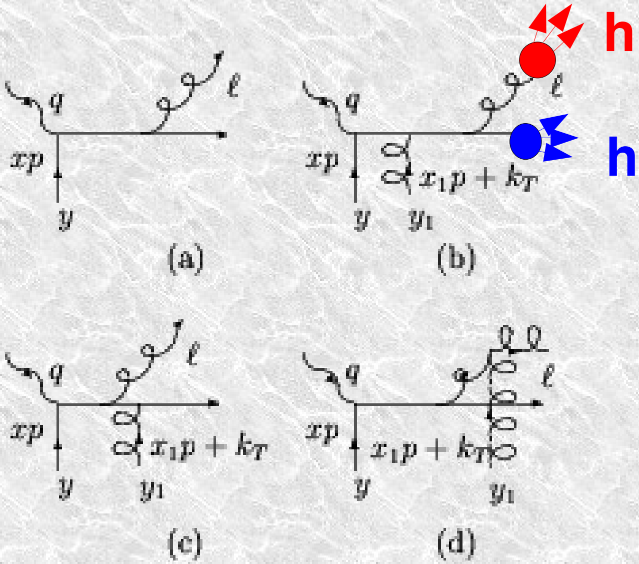
- Large π formation time, used in en. loss models to justify assumptions, but **neglect interactions of forming color field with the medium**

Formation time estimates 1 – energy loss models

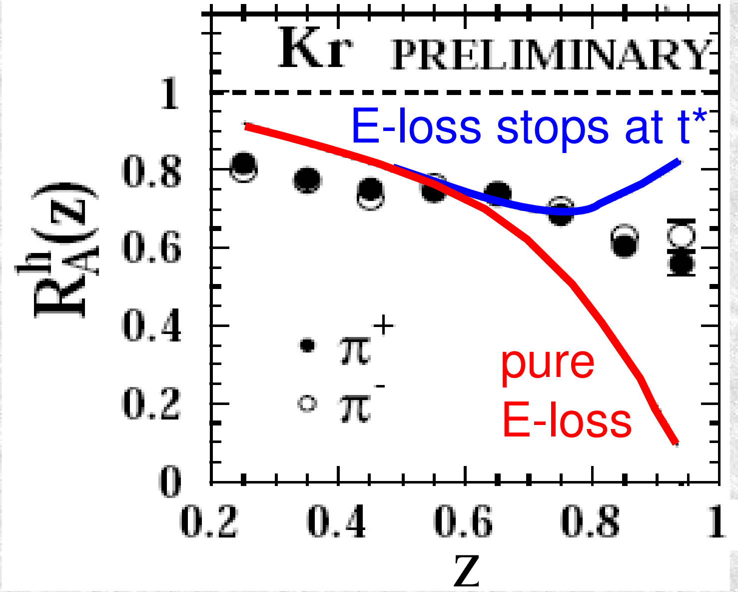
- Twist-4 modified Fragmentation Fns. [Wang&Guo '00, Wang & Wang '02]

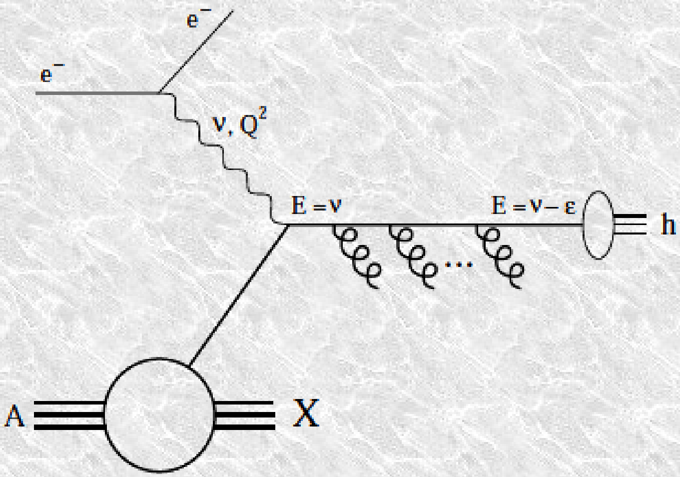






- Quark energy loss *à la* BDMPS [Arleo '02]



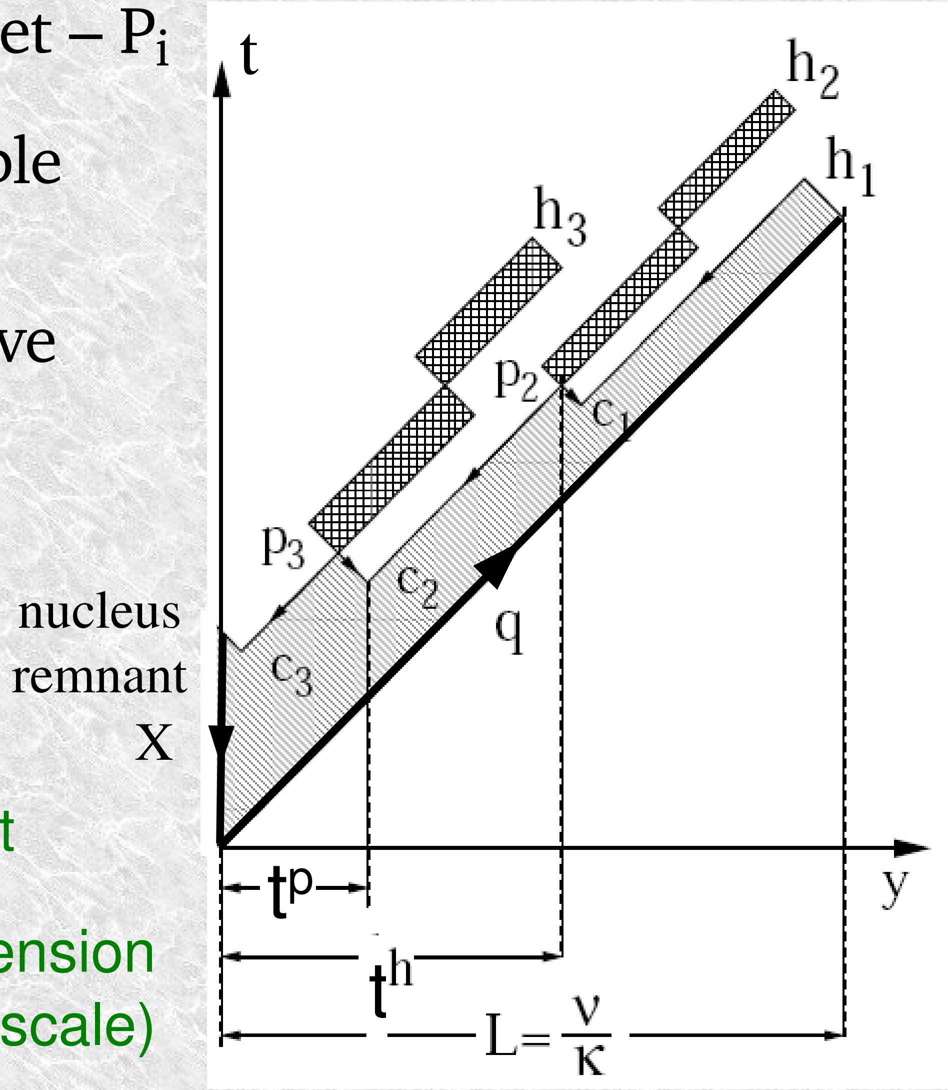


Formation time estimates 2 – Lund model

- 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: $\langle t^p \rangle \to 0$

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

boost
string-tension (non pert. scale)
energy conservation



Formation time estimates 2 – Lund model

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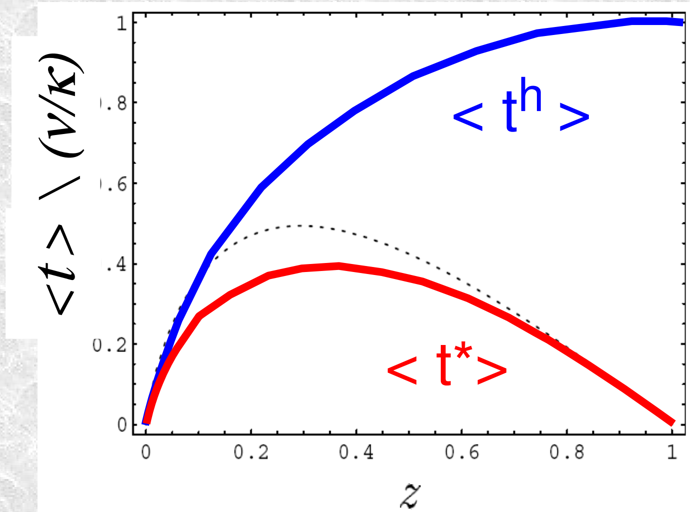
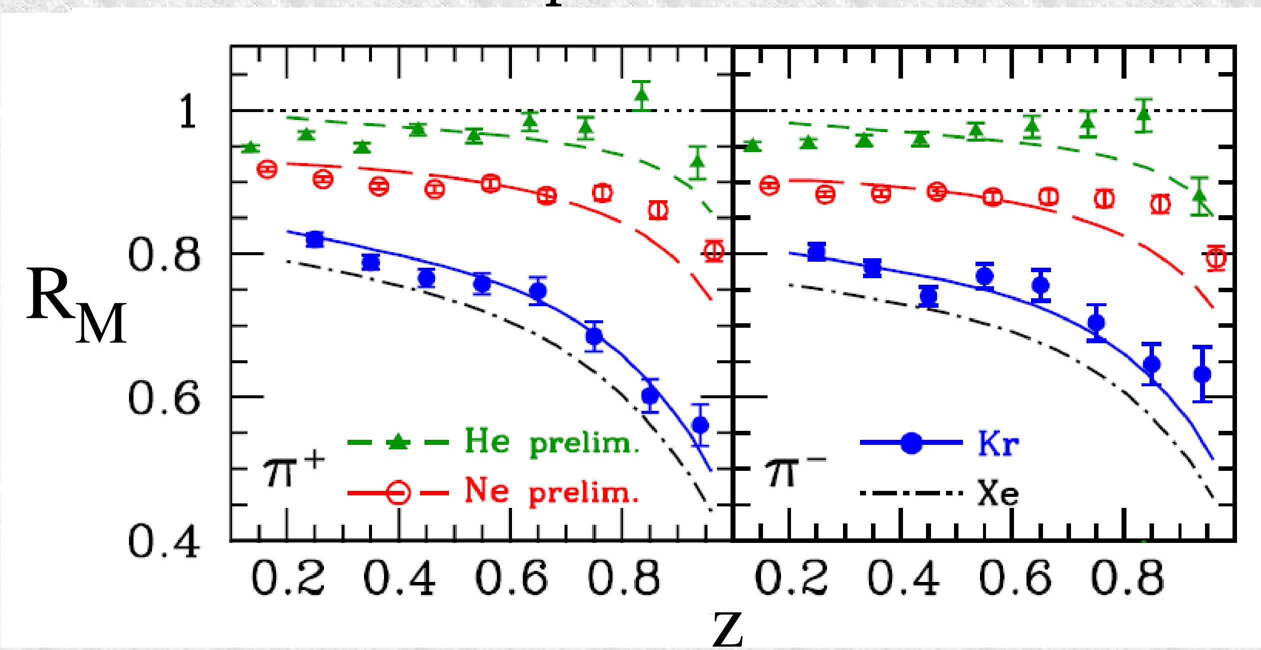


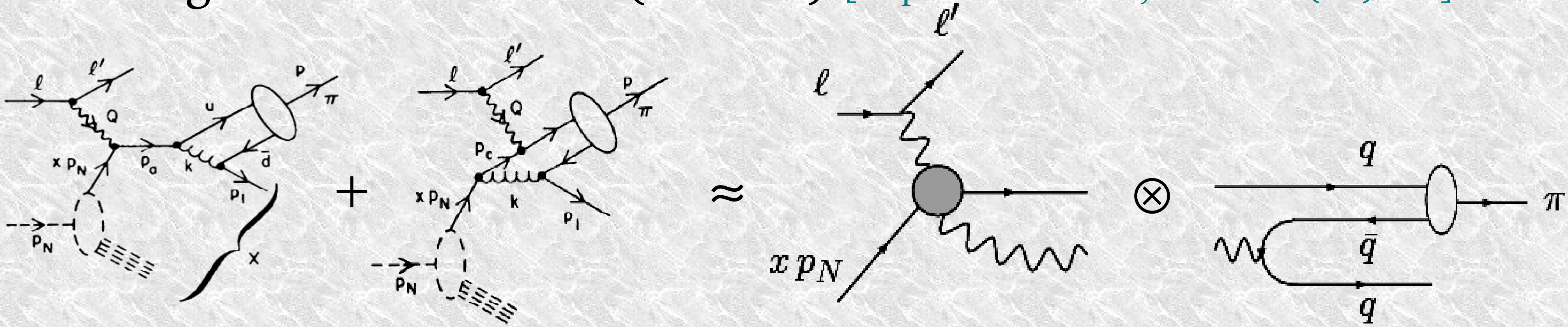
- For a $\nu = 14$ GeV pion at Hermes,
  $\langle t^p \rangle < 5$ fm ~ $O(R_A)$ $\langle t^h \rangle \sim 10$ fm $> R_A$
- Prehadron absorption with this estimate [A.A. et al., NPA 761(05)67]



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

Formation time estimates 3 – Dipole model

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



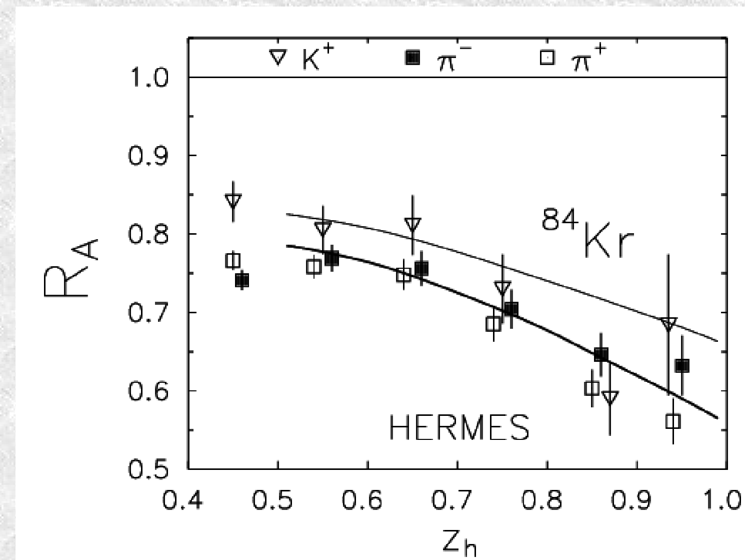
- Prehadron production time t^p
  = time at which gluon becomes decoherent with parent quark
- At large $z \to 1$, $E_h \to \nu$ $\Rightarrow$ quark must be short-lived
  (or radiates too much energy)

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

boost

energy conservation

virtuality (perturbative scale)



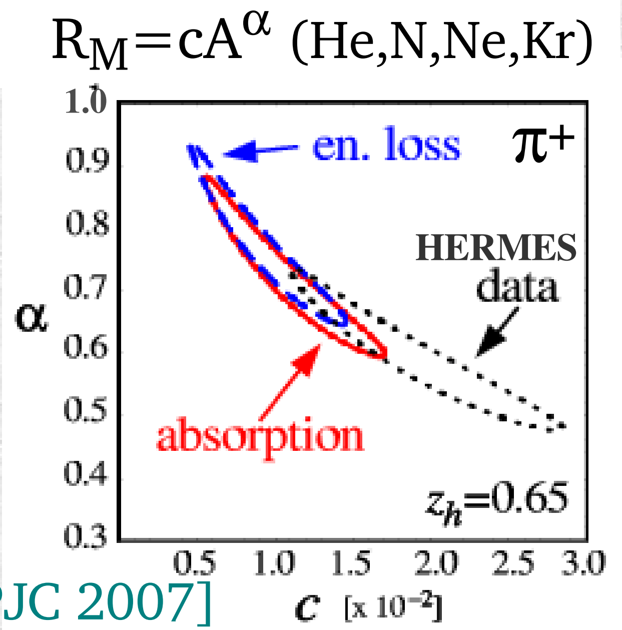
- Evolution to hadron by path-integral formalism
  - usually $\langle t^h \rangle \gg R_A$

Can we measure the production time = quark lifetime?

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

- Conventional (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: ~~$1\text{-}R_M \sim \langle \text{no. of nucleons seen} \rangle \sim L \sim A^{1/3}$~~ **WRONG!**

- $A^{2/3}$ also for absorption models!
  [A.A., et al., NPA 761(2005)67]
  - extra dimensionful scale:
    prehadron production length $\langle t^p \rangle$
  - neutralize it ⇒ extra power of A
    $$(R_A / \langle t^p \rangle)^n \sim A^{n/3}$$
  - typically $n=1$



[A.A.,EPJC 2007]

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

2) Scaling of R_M – basic idea

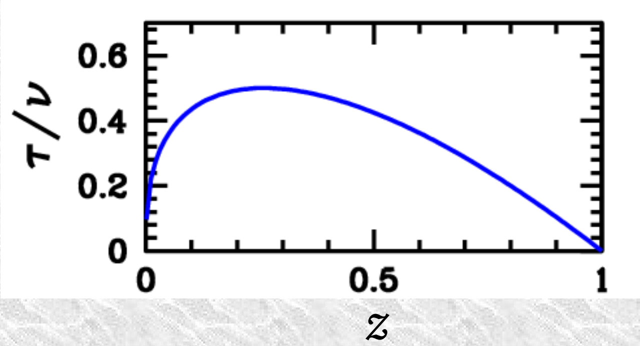
A.A., PLB B649 (07) 384

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

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

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

  - **Short quark lifetime, absorption**: $\lambda > 0$



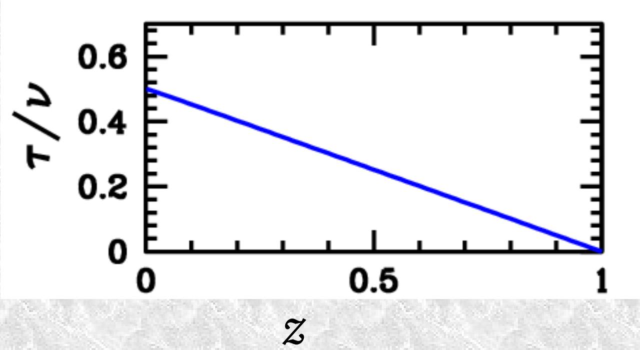
$$\langle t^p \rangle = f(z_h)(1-z_h)\frac{z_h\nu}{\kappa} \approx \tau(z_h,\nu)$$

energy conservation

Lorentz boost

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

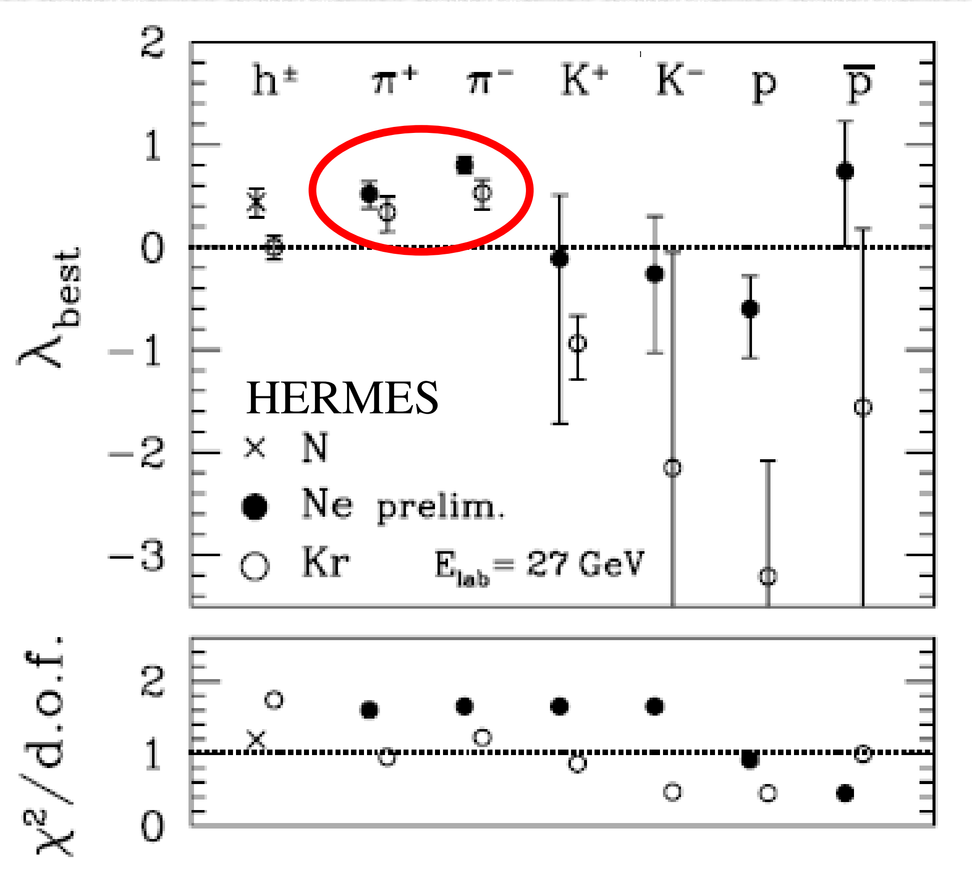
    radiated energy: $\varepsilon < (1-z_h)\,\nu$



energy conservation

2) Scaling of R_M – χ^2 fits

A.A., PLB B649 (07) 384



- Formation-time scaling for pions!

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

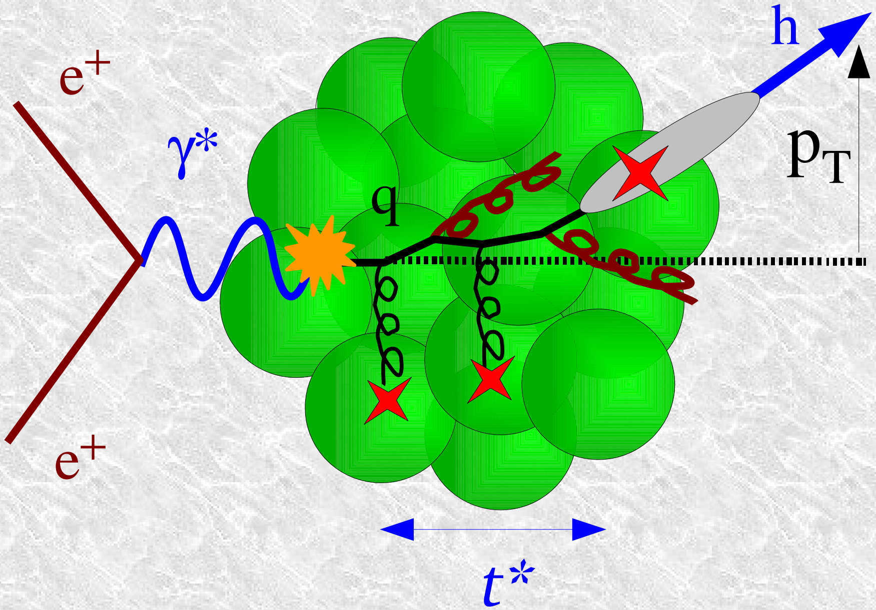
Hadronization starts inside the nucleus!

How much inside?

3) p_T – broadening

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

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



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

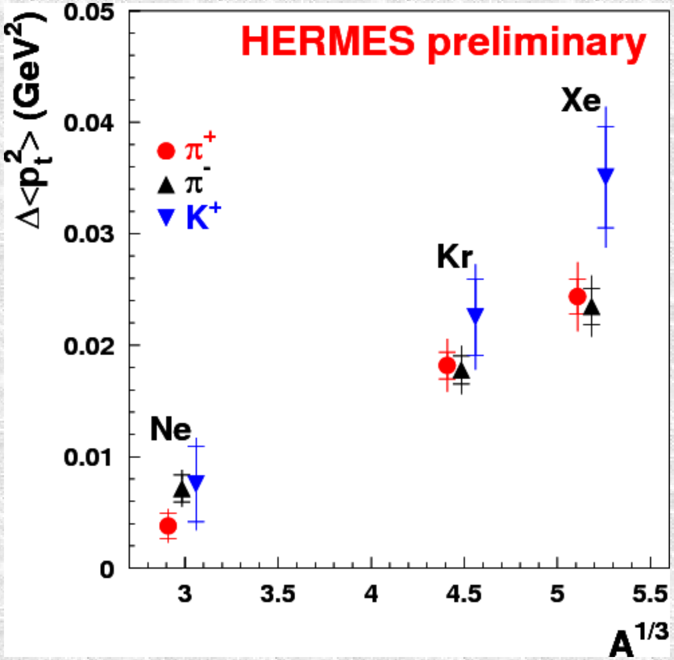
- It should:
  1) rise with $A^{1/3}$ until $\langle t^p\rangle \sim R_A$, then level off
  2) decrease as $z_h \to 1$
  3) rise with ν, then level off
  4) decrease with Q^2 (if $p_T^2 \propto 1/Q^2$)

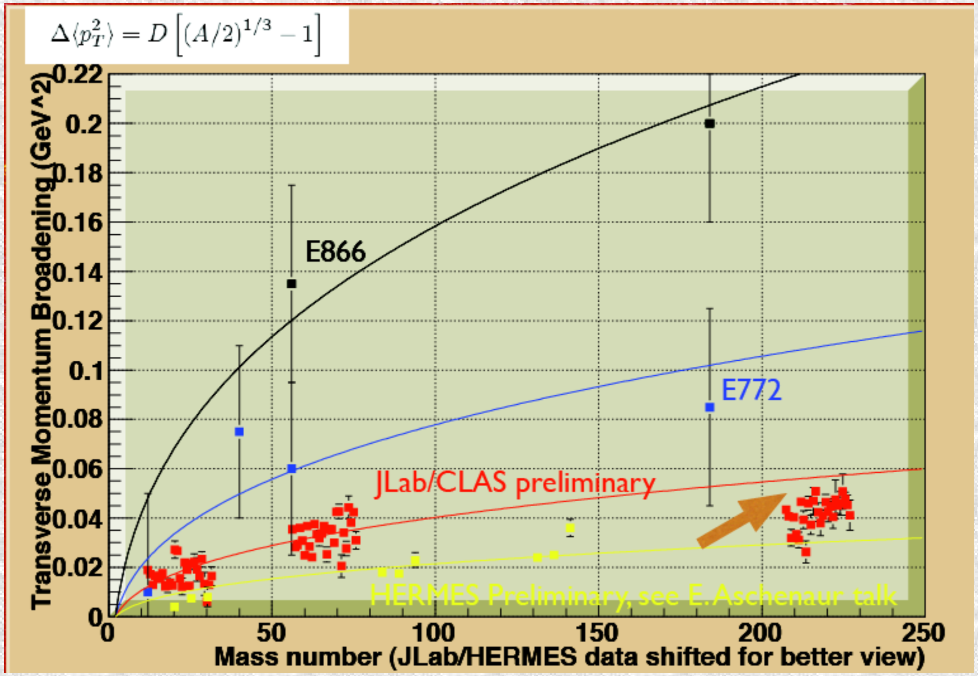
3) p_T – broadening

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

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

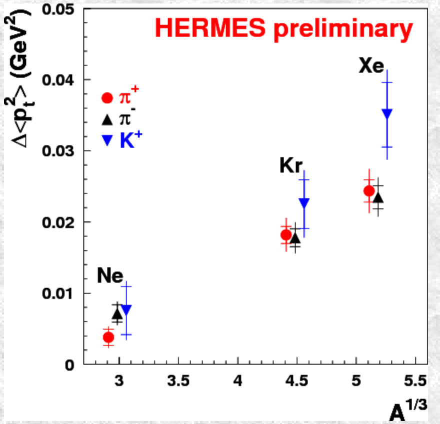
- It should:
  1) rise with $A^{1/3}$, then level off





JLAB preliminary, Will Brooks, Trento workshop

3) p_T – broadening



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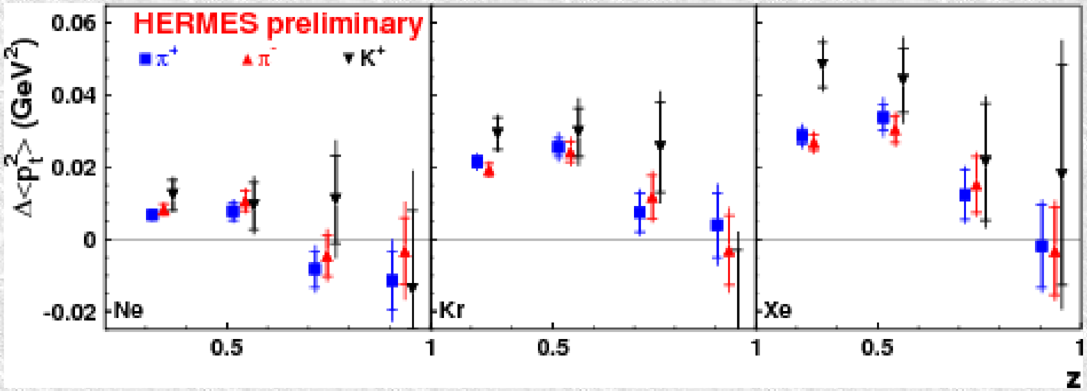
$$\Delta\langle p_T^2\rangle = \langle t^p\rangle \approx C\, z_h^{0.5}(1-z_h)\,\nu$$



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

- Let's assume: $\langle t^p\rangle \approx \frac{4}{3}R_{\mathrm{Xe}}$ at $z_h = 0.4$ $\nu = 14$ GeV

→ $C \approx 1.4$ GeV/fm

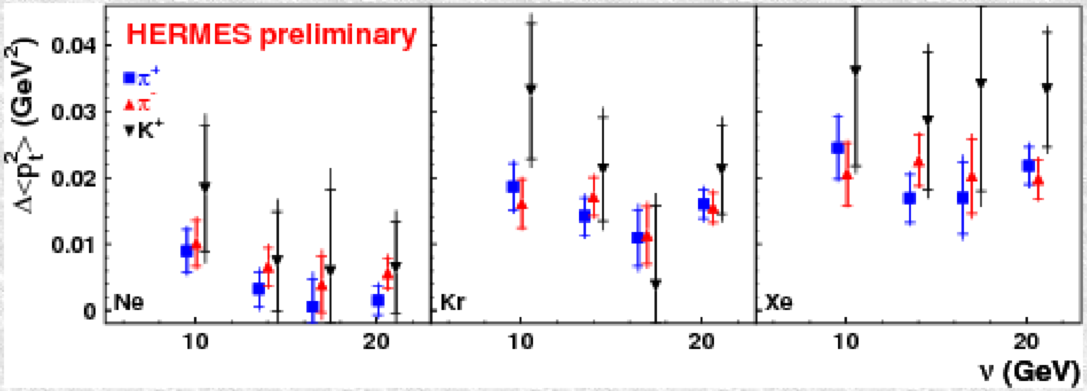
prehadrons formed on short time scales!

	$\langle Q^2\rangle$ [GeV²]	ν [GeV]	$\langle z_h\rangle$	$\langle t_p\rangle$ [fm]
$\langle\Delta p_{Th}^2\rangle$ vs A				
Ne (3.1 fm)	2.4	13.7	0.42	7.4
Kr (6.5 fm)	2.4	13.9	0.41	7.5
Xe (7.6 fm)	2.4	14.0	0.41	7.6
$\langle\Delta p_{Th}^2\rangle$ vs z	2.4	14.6	0.30	8.0
	2.4	13.3	0.53	6.5
	2.3	12.6	0.74	4.0
	2.2	10.8	0.92	1.2

3) p_T – broadening

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

$$\Delta\langle p_T^2\rangle = \langle t^p\rangle \approx 1.4\, z_h^{0.5}(1-z_h)\,\nu$$



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

3) p_T – broadening

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

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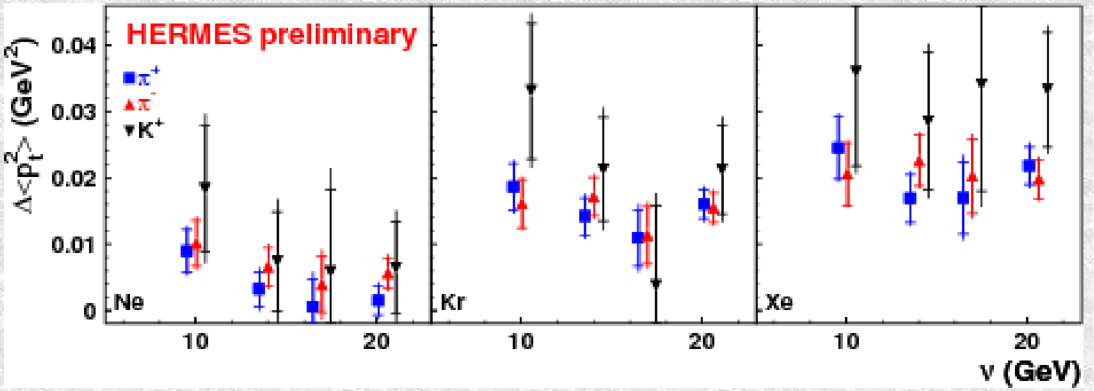
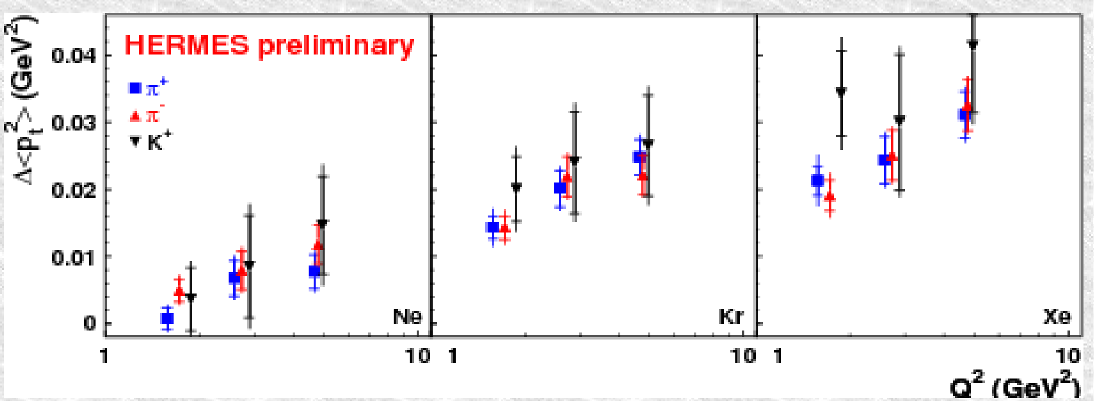




- It should:
  1) rise with $A^{1/3}$, then level off
  2) decrease as $z_h \to 1$
  3) rise with ν
  4) decrease with Q^2 (if $p_T^2 \propto 1/Q^2$)

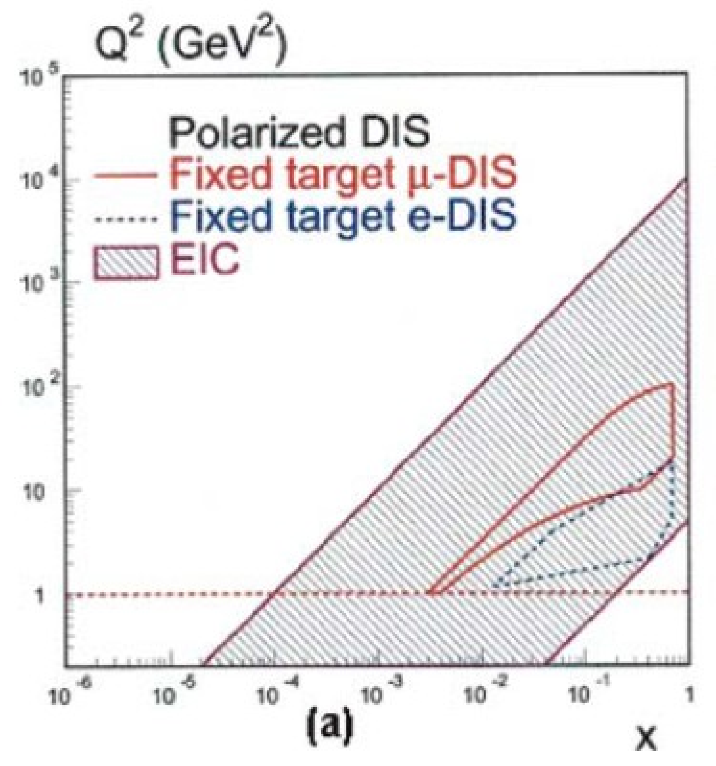
at strong variance with dipole model

- **Signals of partonic dynamics beyond production time & multi-scattering:**
  - medium-enhanced DGLAP evolution / soft gluon radiation ?

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

Perspectives at the EIC

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

	eRHIC				ELIC			
	high-E		low-E		high-E		low-E	
	Au	e	Au	e	Ca	e	Ca	e
E [GeV/A or GeV]	100	20	50	3	75	7	15	3
L [10^{33} cm^{-2}s^{-1}]	2.9		1.5		160		13	

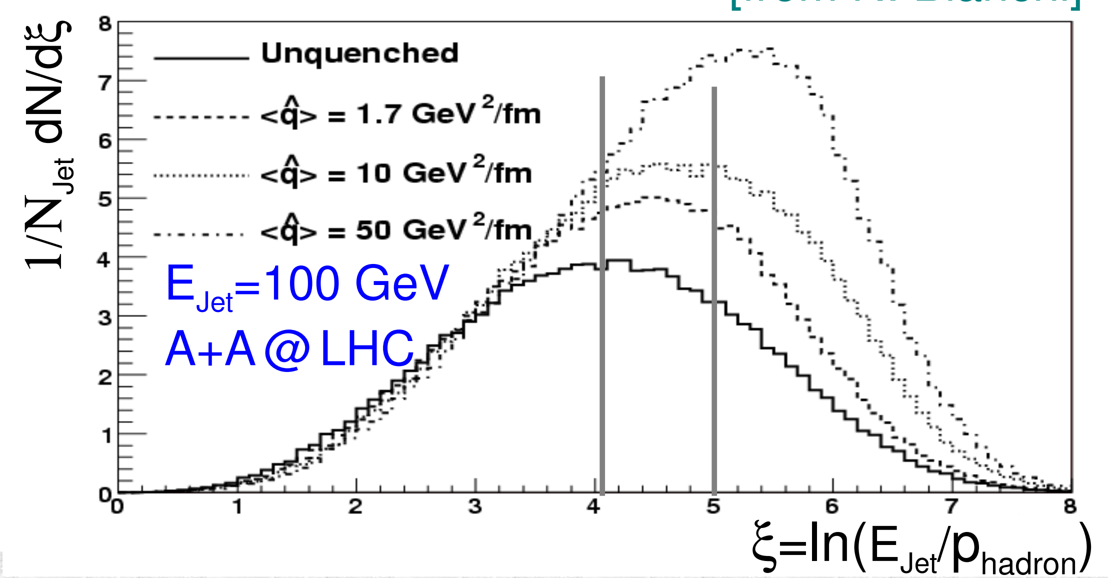
The EIC – large ν

- 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
- Interplay of radiative and collisional parton energy loss
  - big deal for heavy quarks at RHIC, LHC
- Study medium modification of DGLAP evolution
  - understanding of p_T-broadening
  - test parton showering algorithms in Monte-Carlo generators (!!)
- Test of factorization for Fragmentation Functions

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]

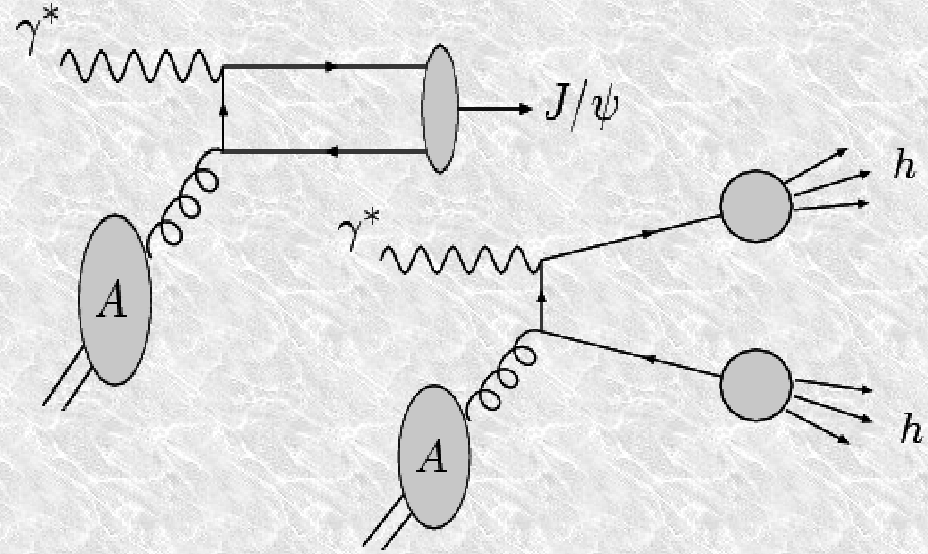
[from N. Bianchi]

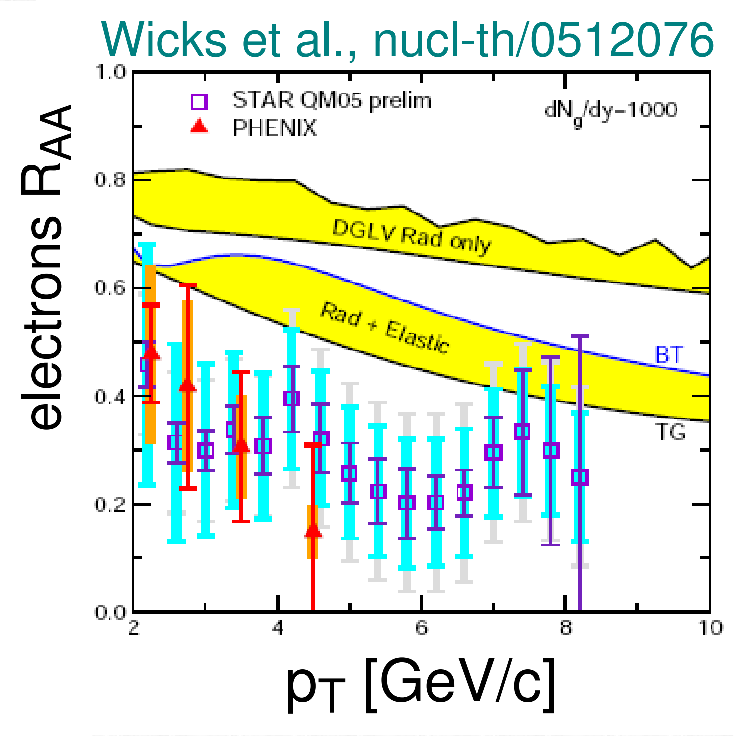


  - light-quark jets vs. heavy-quark jets vs. gluon jets
  - dijets, γ-jet correlations, ...

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

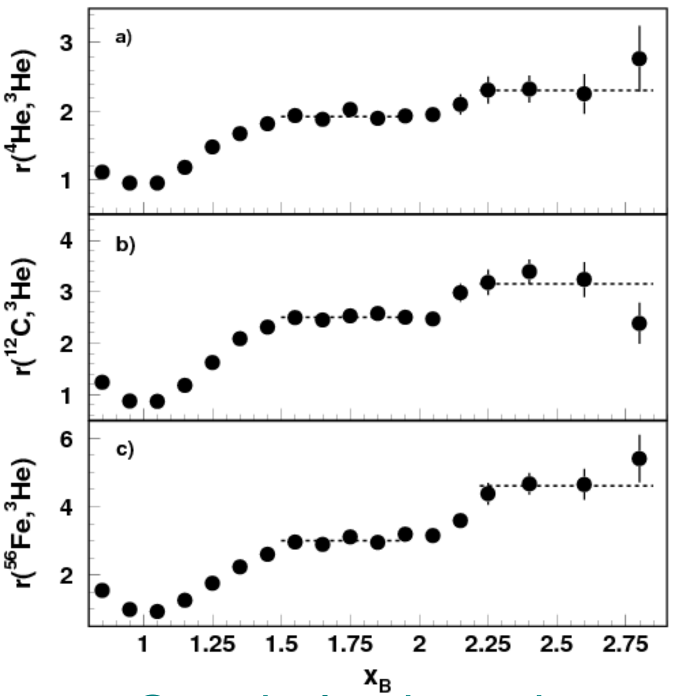




The EIC – large Q^2 range

- 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)

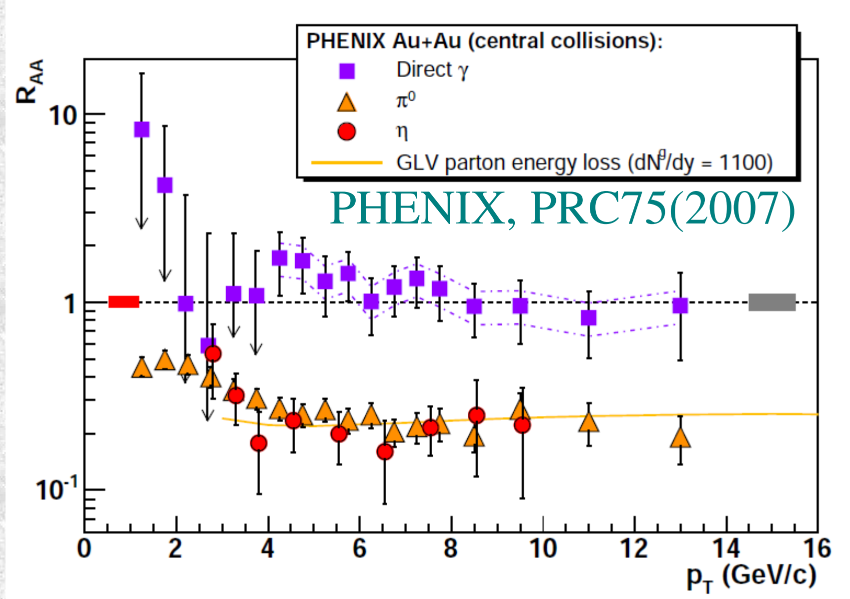


Quasi-elastic regime

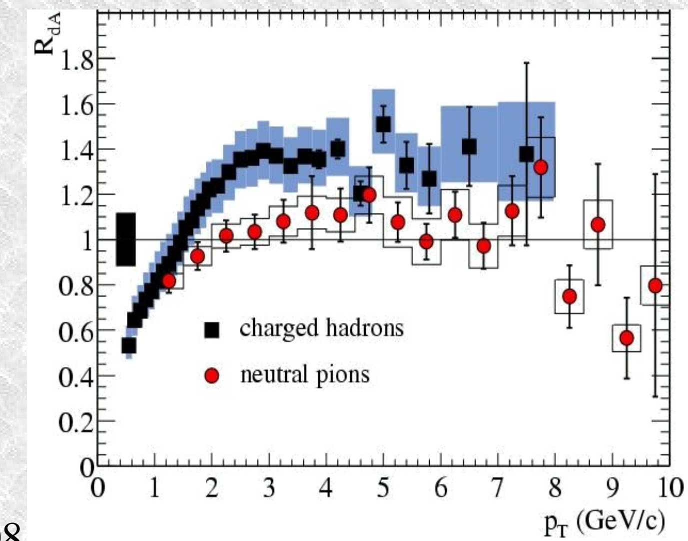
The EIC – large W^2

- 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

- 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)

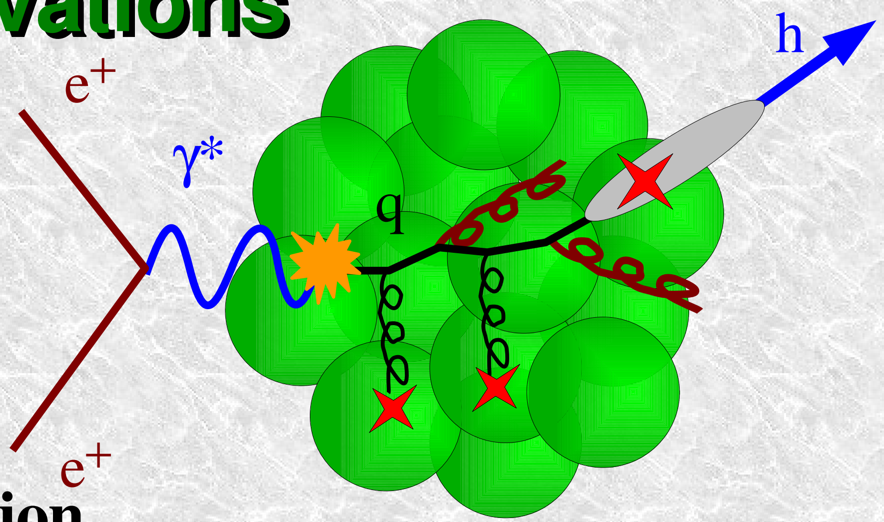


Homework: accelerator & detector

- **Accelerator requirements** – large physics program
  - ✔ not energy hungry
  - ✔ will benefit from high luminosity (jets, correlations, multi-diff.)
- **Detector requirements** - my personal, incomplete, wish-list:

1) PID – "minimal" requirements
   - ✔ $\pi^{\pm}$, π^0, η, (ϕ)
   - ✔ $K^{\pm}$, Λ
   - ✔ p, pbar, Δ
   - ✔ B, D – J/ψ , ψ', χ
2) Wide acceptance in (ϕ,y)
   - ✔ 2-particle correlations: e.g., h+h, γ+h, γ+jet
   - ✔ current vs. target fragmentation
3) Jet reconstruction: good calorimetry
   - ✔ Full hadron distribution in jet cone (charged and neutral)
   - ✔ Full distribution down to $p_T \sim 1$ GeV
   - ✔ PID for study of the jet composition ("jet hadrochemistry")

Physics motivations

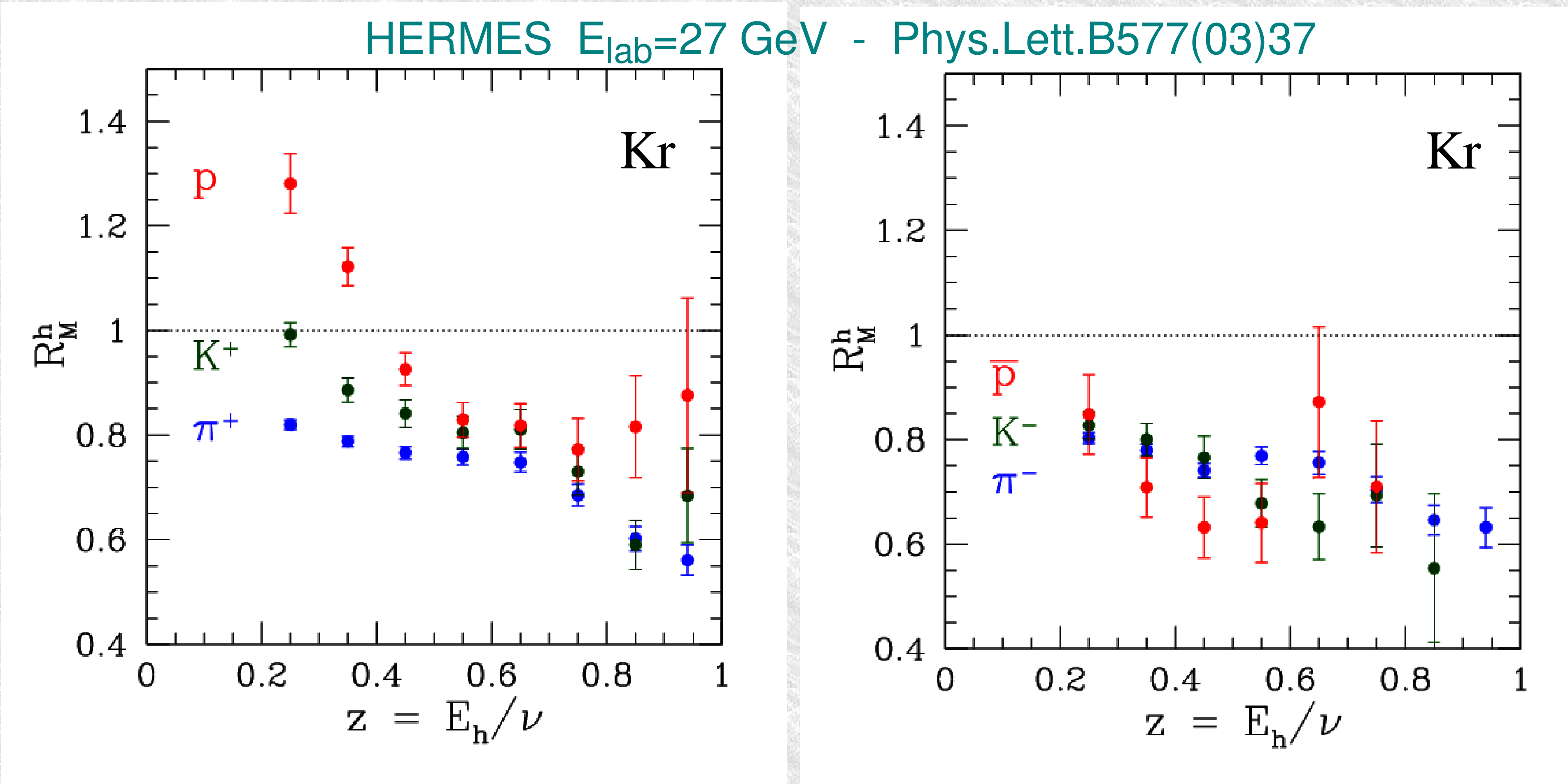


- **Nuclei as space-time analyzers**
  - nucleons as femto-detectors
  - medium rather well known
  - low final-state multiplicity
- **Non perturbative aspects of hadronization**
  - approaching microscopic understanding of Fragmentation Functions
  - how do partons dress up? Space-time evolution of hadronization
  - understanding of color confinement
- **Parton propagation in perturbative QCD**
  - QCD energy loss (LPM effect)**:** basic pQCD, only indirectly tested
  - 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

The end

Backup slides

Measurements at HERMES

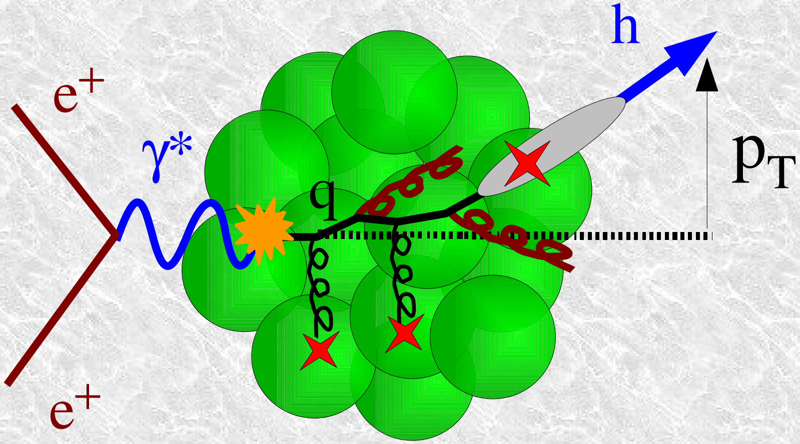


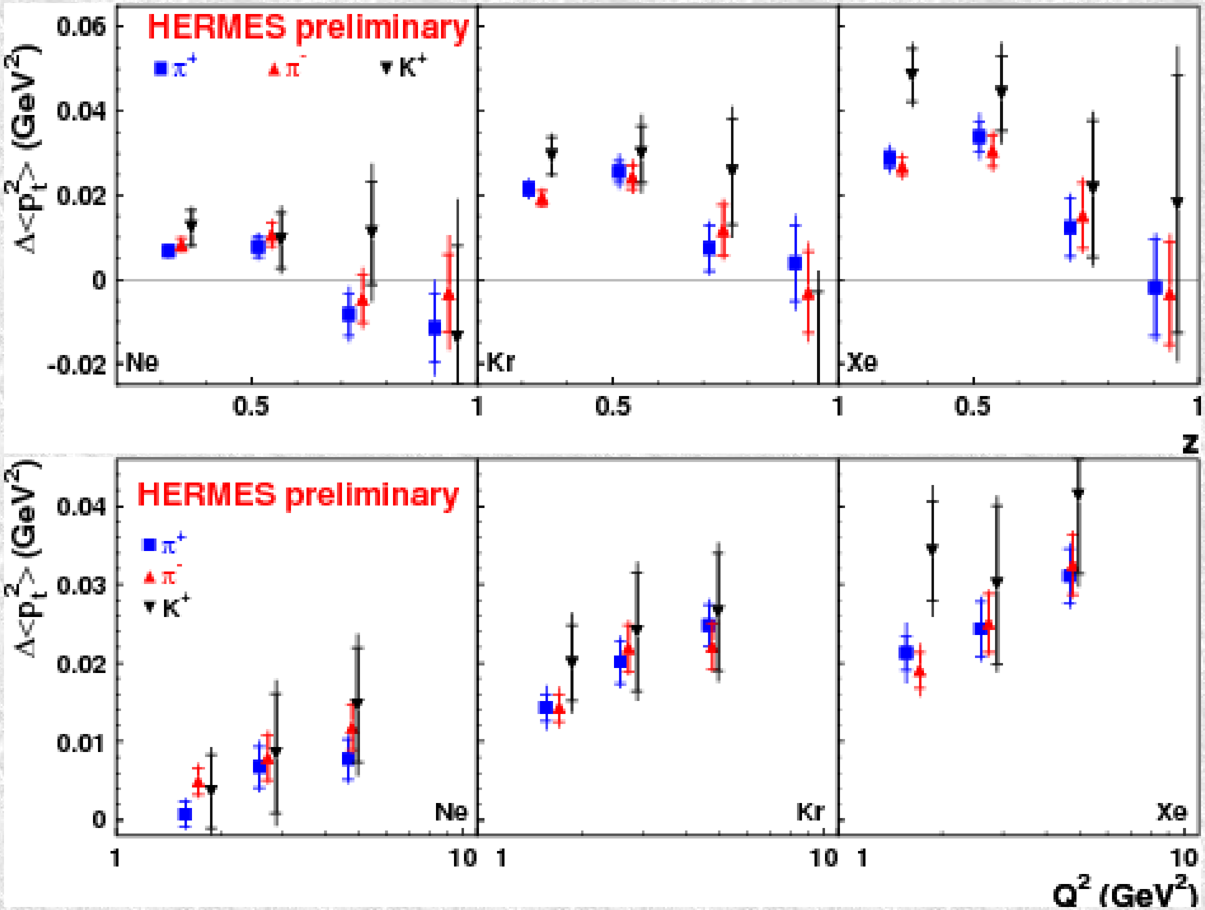
- **proton anomaly!**
- analogous to "baryon/meson anomaly" in p+p, p+A and A+A
  - what do they have in common, if anything?

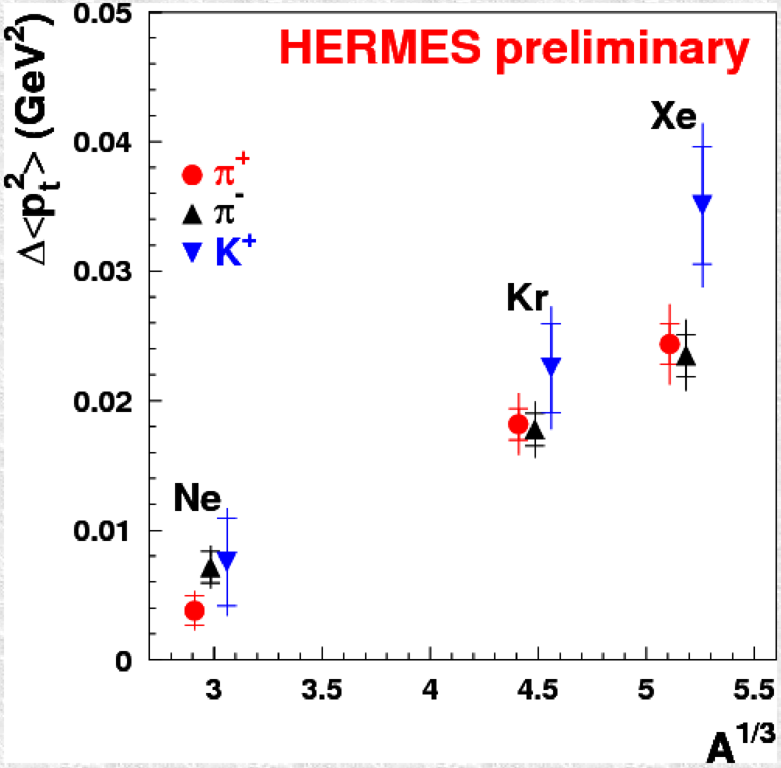
Measurements at HERMES

- **pT broadening**

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





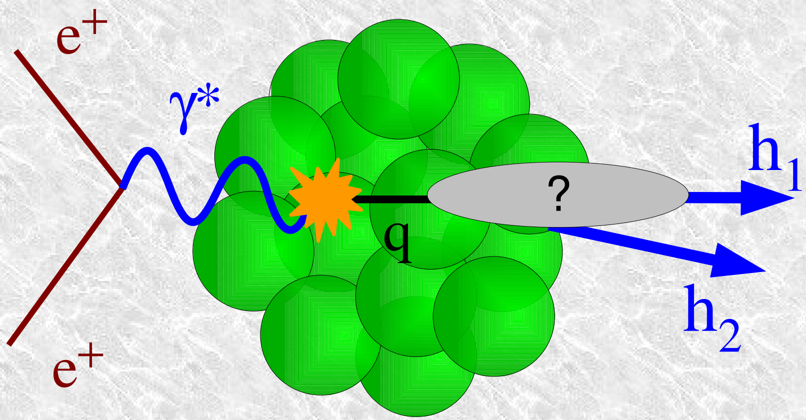


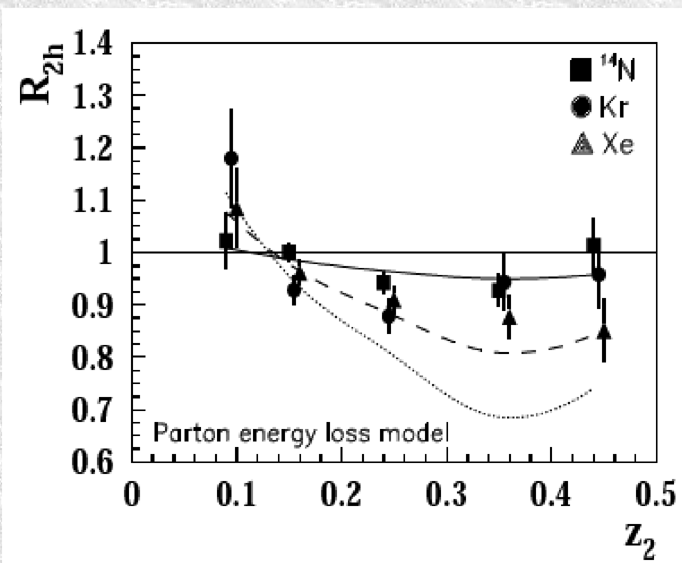
Measurements at HERMES

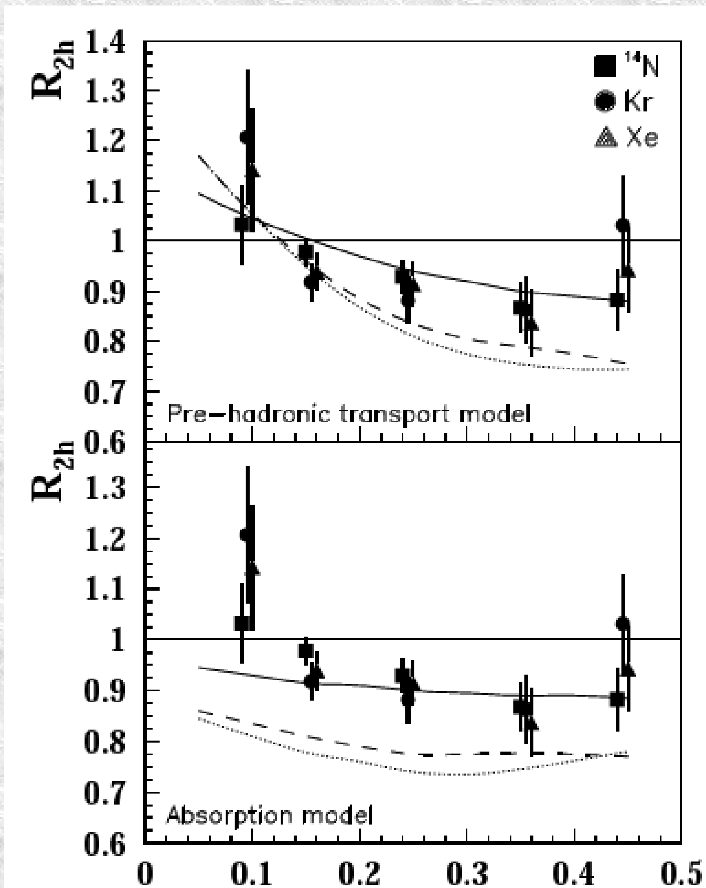
- **Double hadron attenuation** R_2
- in A+A: "same-side correlations"

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

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



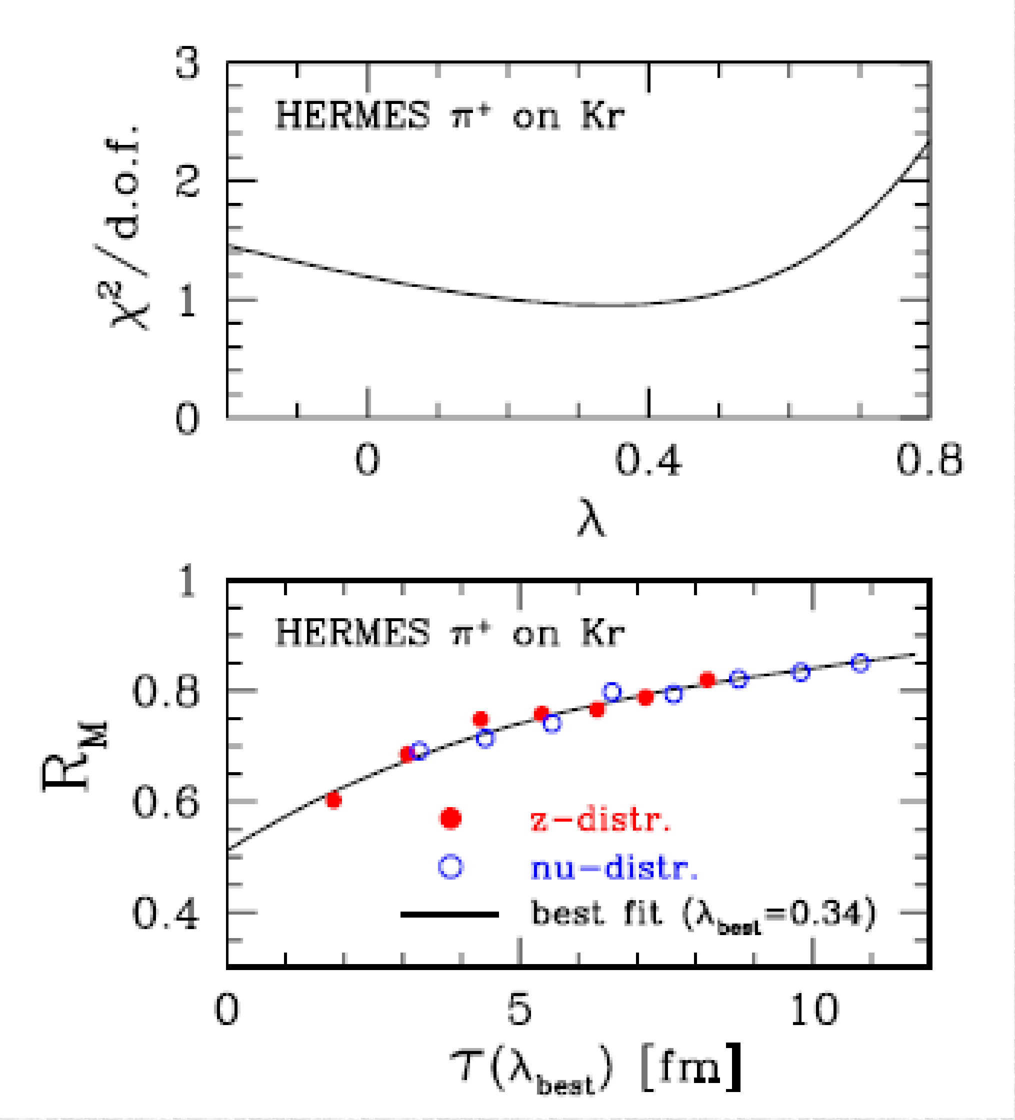




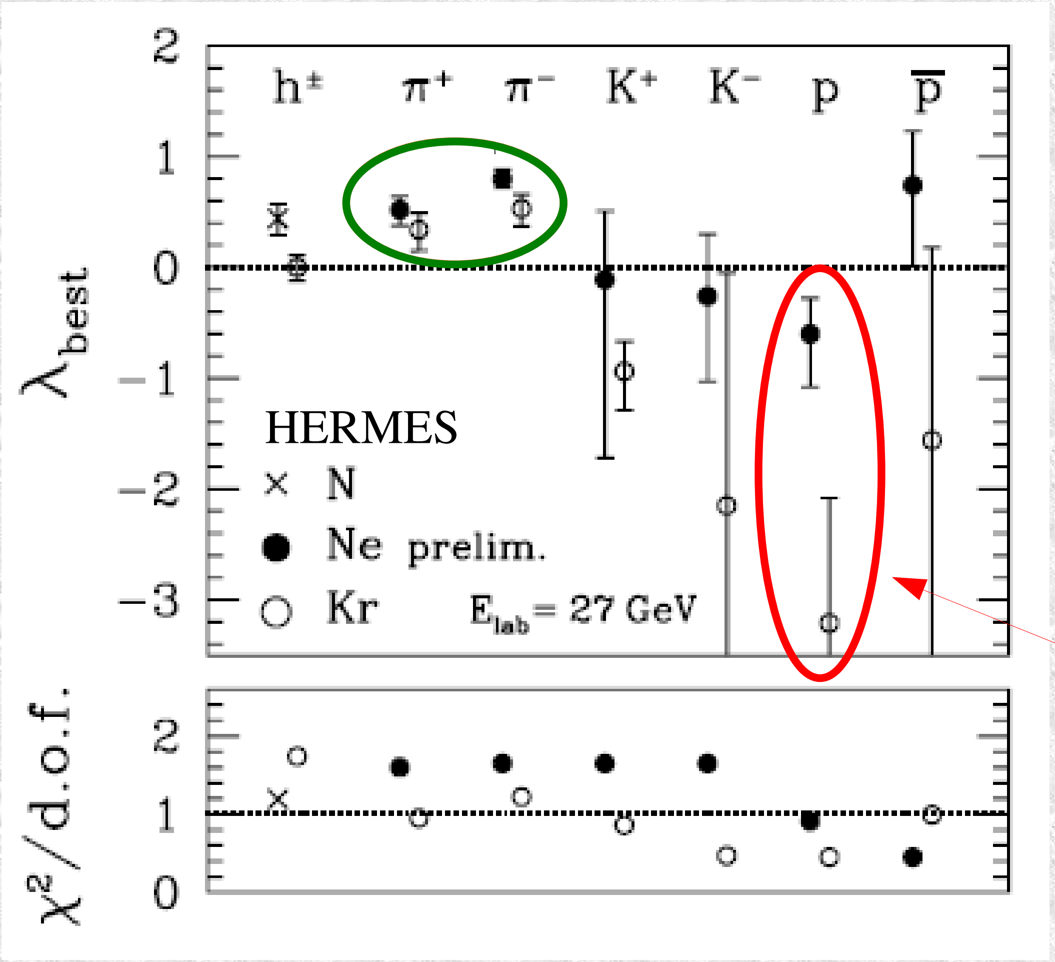
HERMES PRL96(06)162301

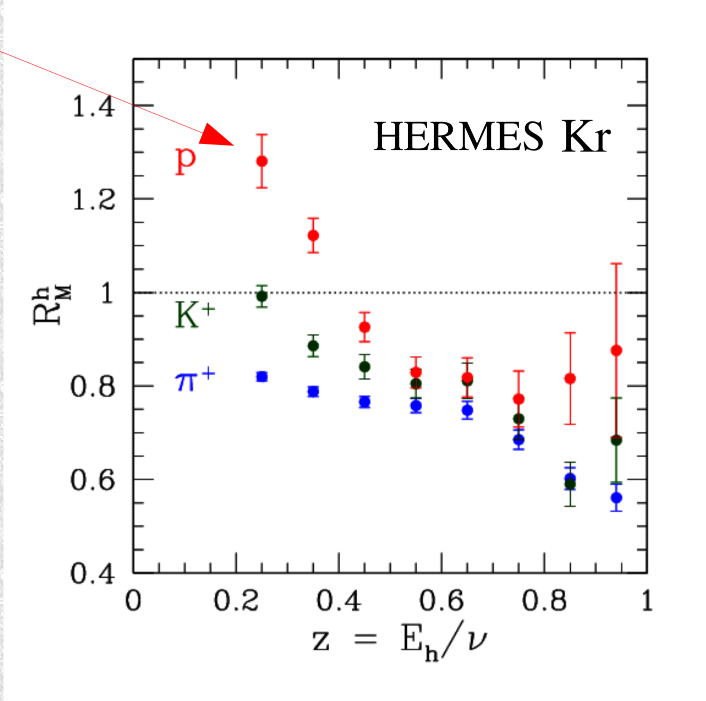
2) Scaling analysis - example

A.A., PLB B649 (07) 384



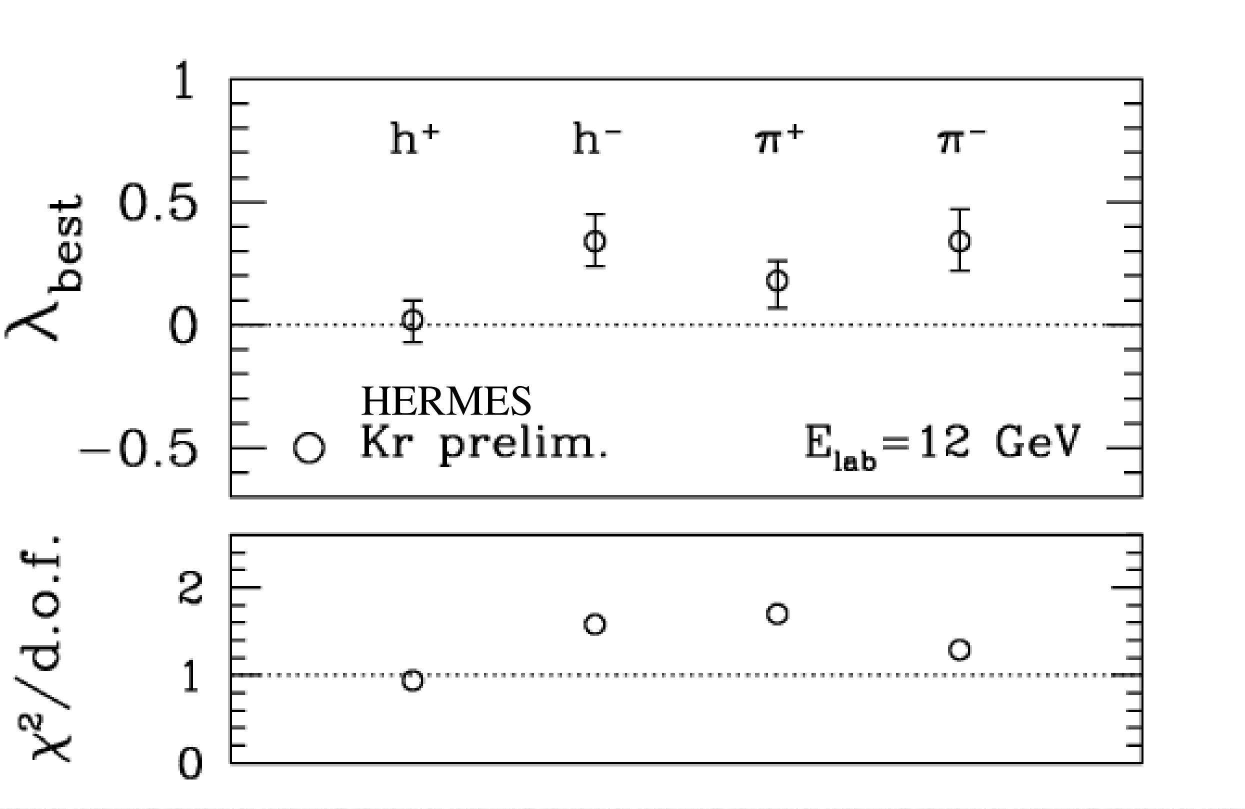
Results – E_{lab} = 27 GeV





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

Results – E_{lab} = 12 GeV



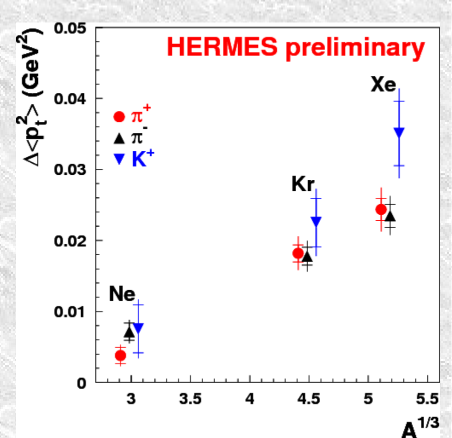
- pions are still positive! confirms results at 27 GeV
- $\lambda_{best}(h^+) \sim 0$ but $\lambda_{best}(h^-) > 0$
  - proton anomaly hypothesis confirmed!

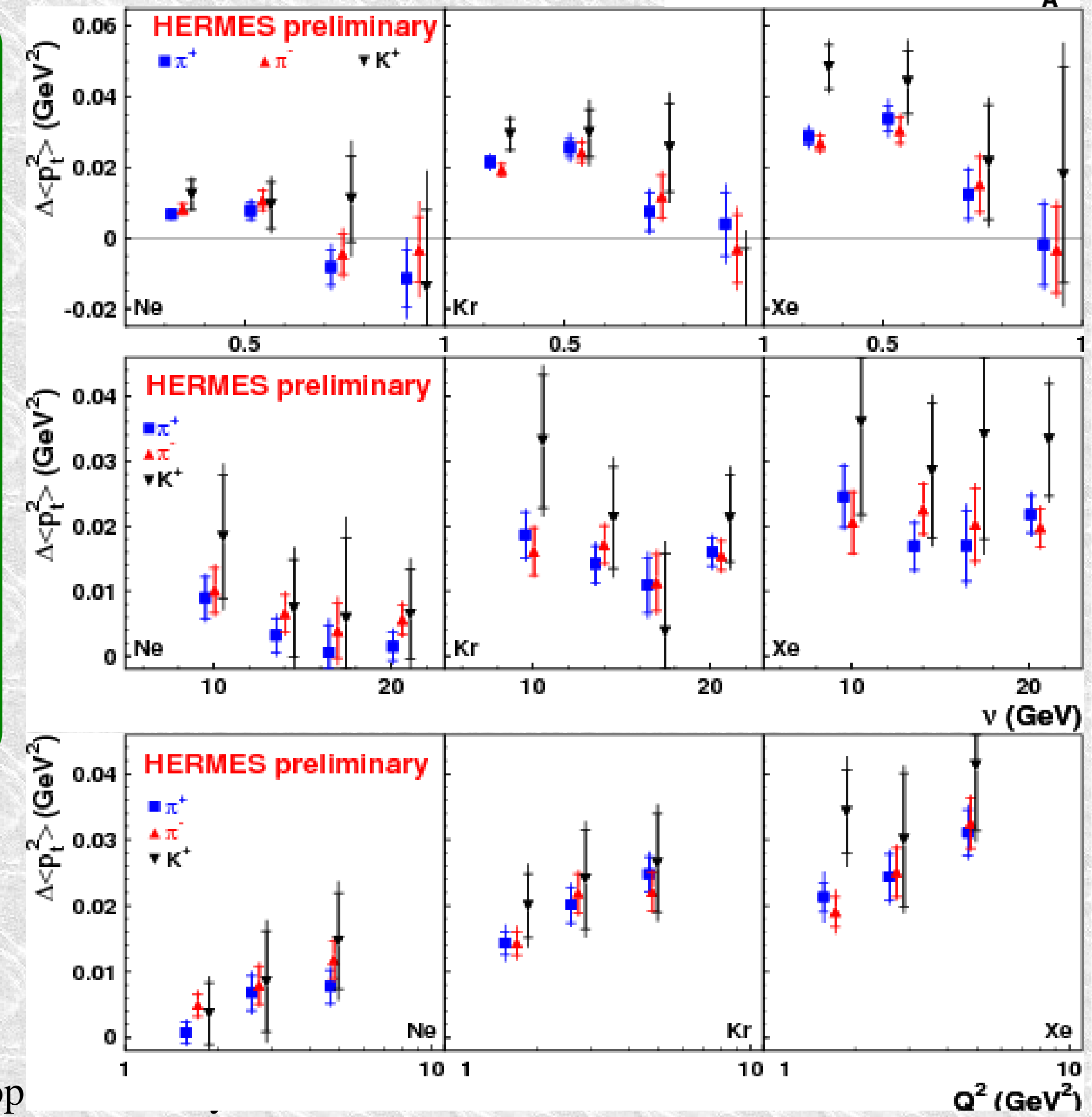
3) p_T – broadening

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

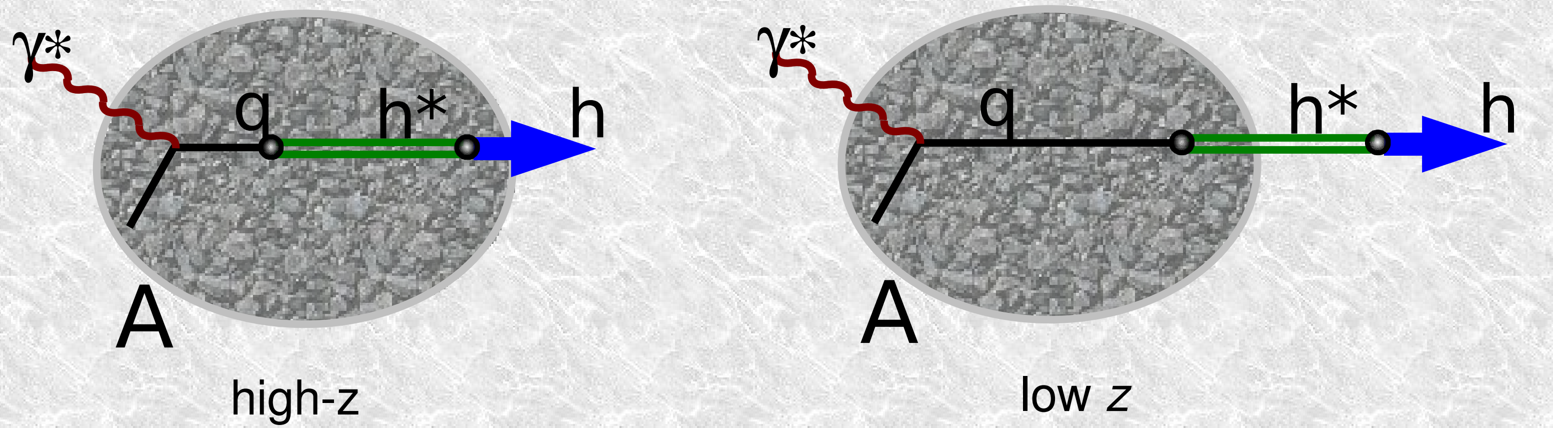
$$C \approx 1.4\ \mathrm{GeV/fm}$$

	$\langle Q^2\rangle$ [GeV^2]	ν [GeV]	$\langle z_h\rangle$	$\langle t_p\rangle$ [fm]
$\langle \Delta p_{Th}^2\rangle$ vs A				
Ne (3.1 fm)	2.4	13.7	0.42	7.4
Kr (6.5 fm)	2.4	13.9	0.41	7.5
Xe (7.6 fm)	2.4	14.0	0.41	7.6
$\langle \Delta p_{Th}^2\rangle$ vs z	2.4	14.6	0.30	8.0
	2.4	13.3	0.53	6.5
	2.3	12.6	0.74	4.0
	2.2	10.8	0.92	1.2
$\langle \Delta p_{Th}^2\rangle$ vs ν	2.1	8.1	0.48	4.2
	2.5	12.0	0.42	6.5
	2.6	15.0	0.40	8.1
	2.4	18.6	0.36	10.2
$\langle \Delta p_{Th}^2\rangle$ vs Q^2	1.4	14.0	0.41	7.4
	2.4	14.1	0.41	7.5
	4.5	14.5	0.39	7.6





3) p_T – broadening



- **$\langle p_T^2 \rangle$ 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]

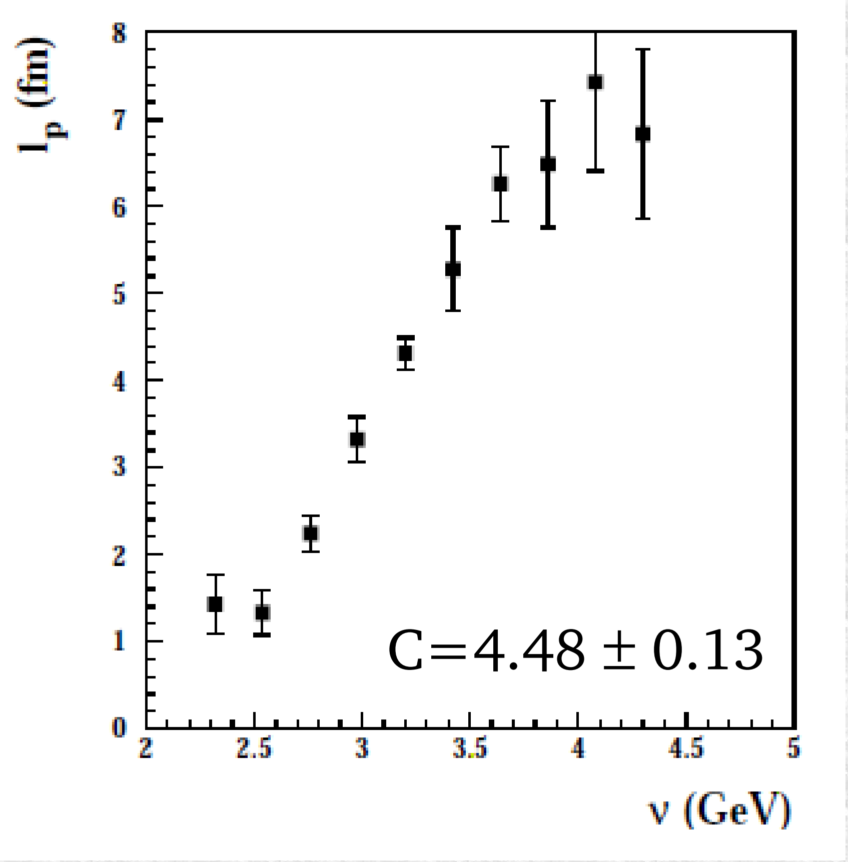
$$\Delta p_T^2 = \frac{2C z_h^2}{A} \int d^2b \int_{-\infty}^{\infty} dz\, \rho_A(b,z) \int_z^{z+l_p} dz'\, \rho_A(b,z')$$

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



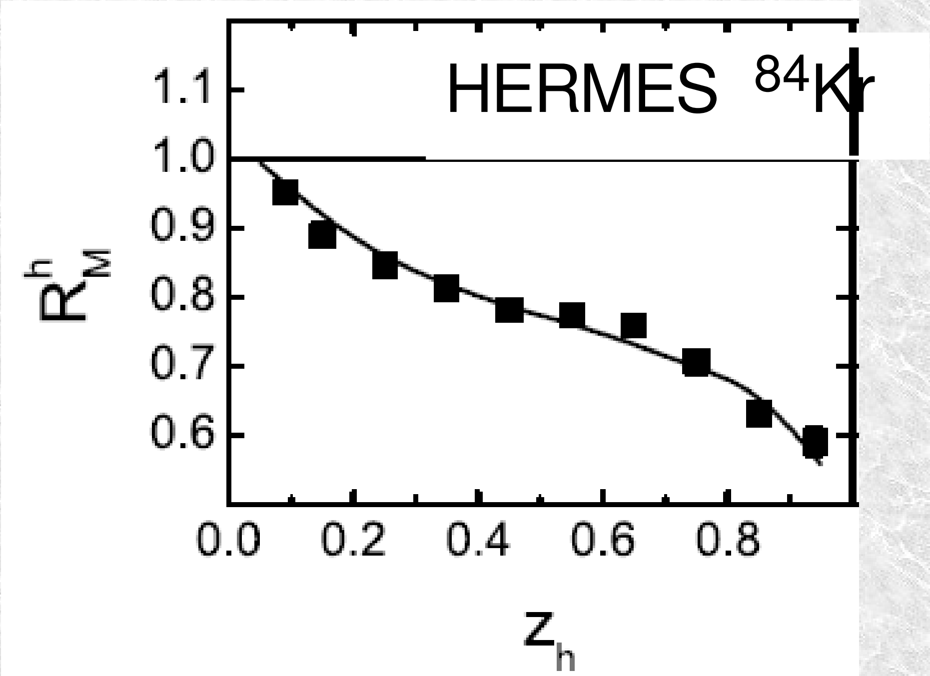
An absorption+transport model for Au+Au

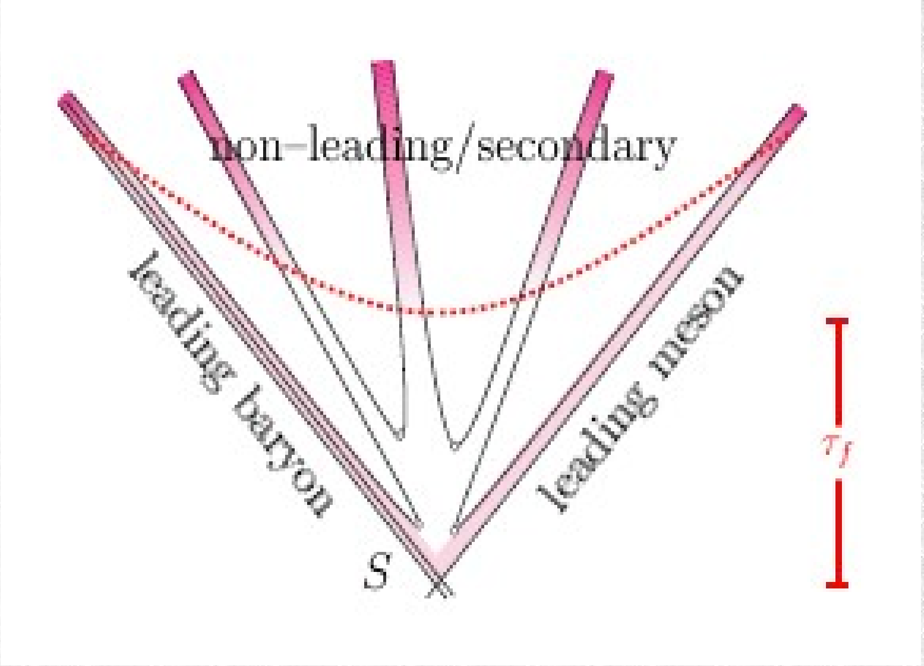
Falter et al., PRC 70(04)054609

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

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

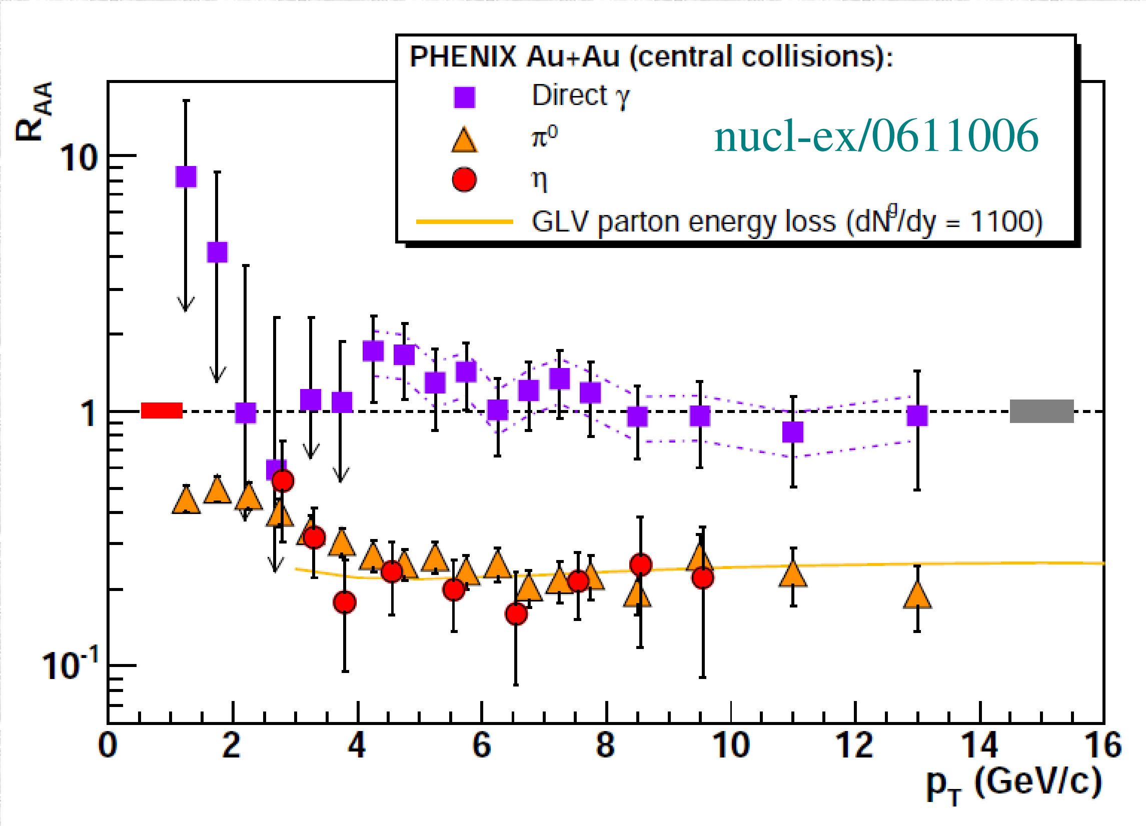
  subleading h: $\sigma_* = 0$ mbarn
- Final state X
  - by PYTHIA and FRITJOF
  - Fermi motion, Pauli blocking, shadowing
  - evolved by BUU transport equations





Perspectives 1 – mesons

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



- Is it so also in nDIS? [η is heavier ⇒ hadronizes earlier; lower Q^2]
  - measurement possible at HERMES, CLAS @ JLAB, EIC

Perspectives 2 – baryons

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

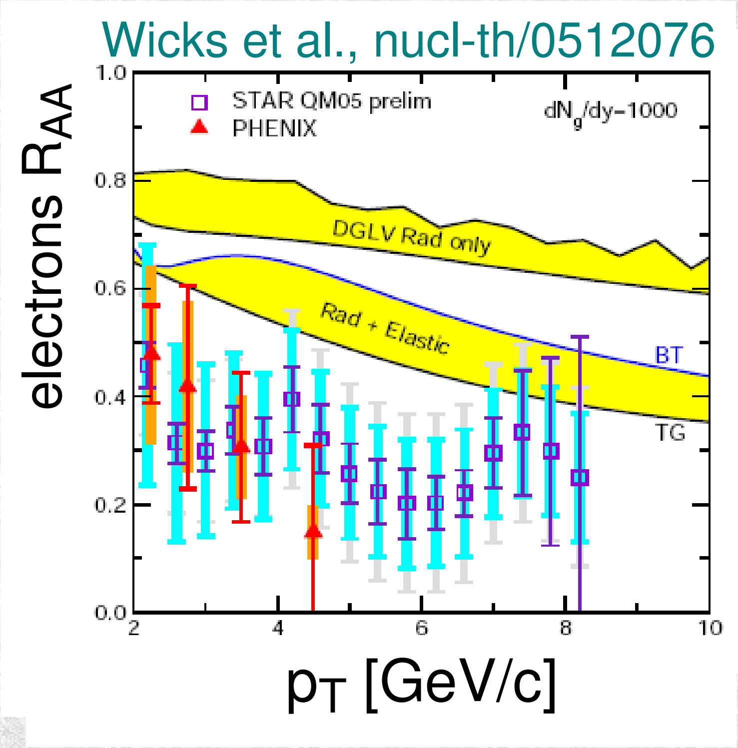
production rate @ CLAS++ 12 GeV (not folded with PID) [W.Brooks, FizikaB13(04)321]

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

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

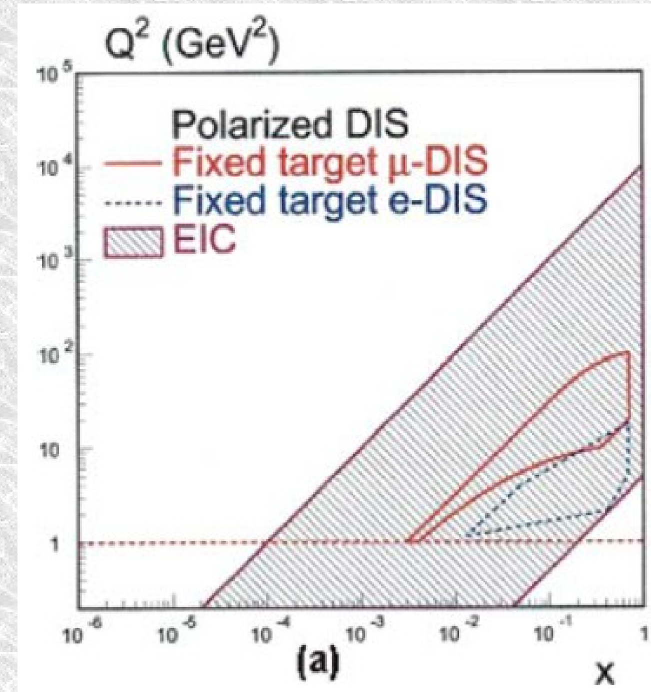
Perspectives 3 – heavy quarks

- Heavy-quark energy loss and hadronization of D, B mesons in the spotlight at RHIC
  - measure D, B in e+A !
- At HERMES
  - luminosity is 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!

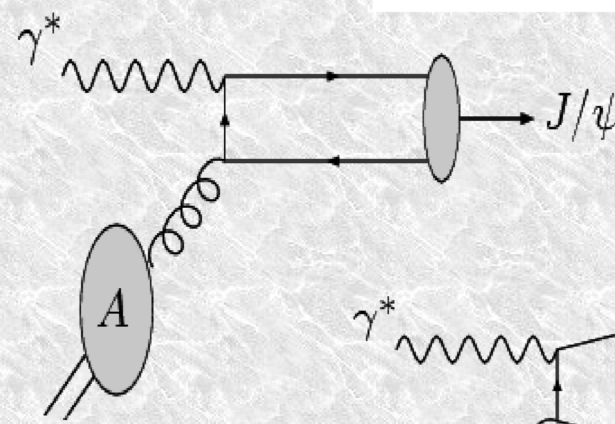


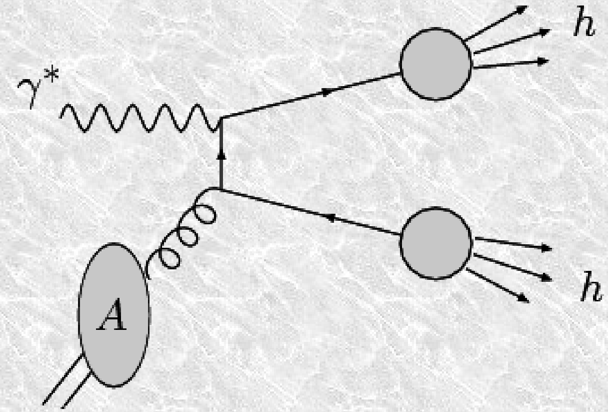
Perspectives 4 – eRHIC / ELIC

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



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

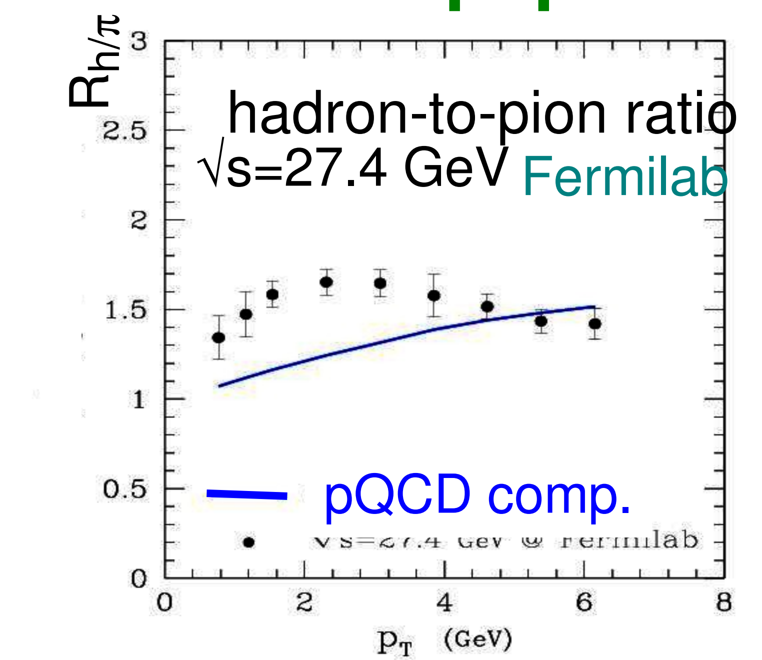




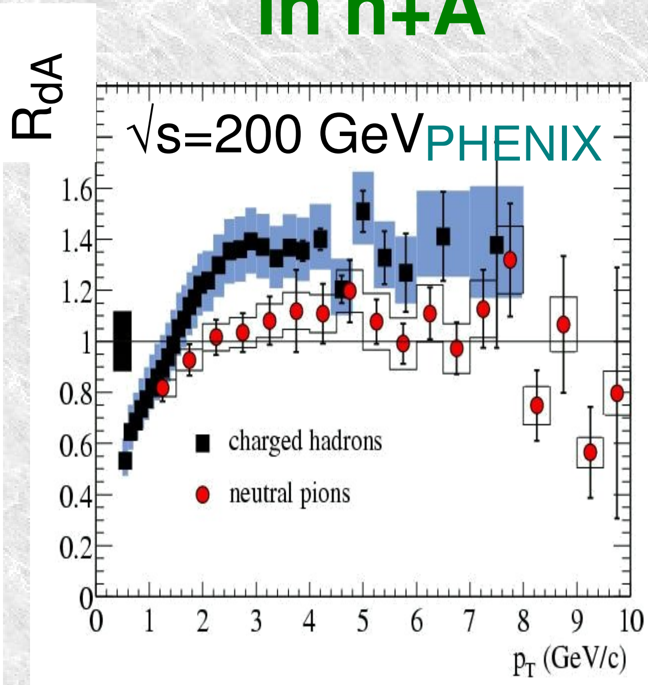
- Baryons from current fragmentation
  - baryon production and transport

Challenges: baryon anomaly

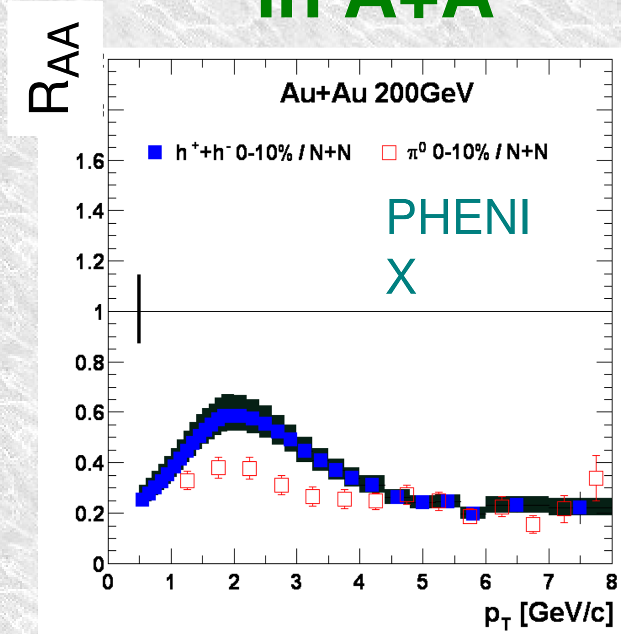
in p+p



in h+A



in A+A



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

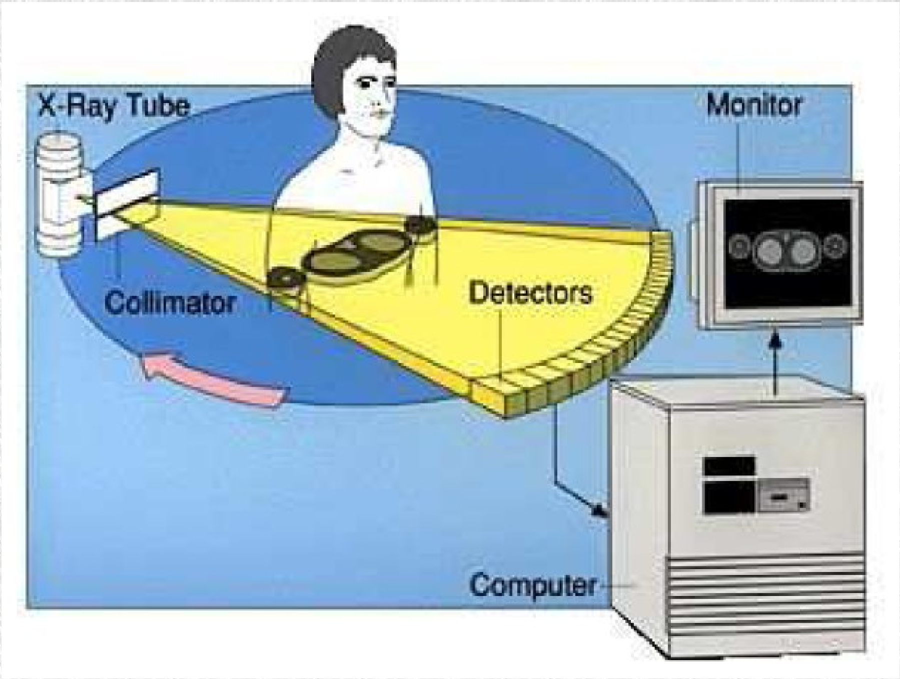
$$R_{BA} = \frac{1}{T_{BA}(b)} \frac{(dN^h/d^2p_T)_{d+A}}{(d\sigma^h/d^2p_T)_{p+p}}$$

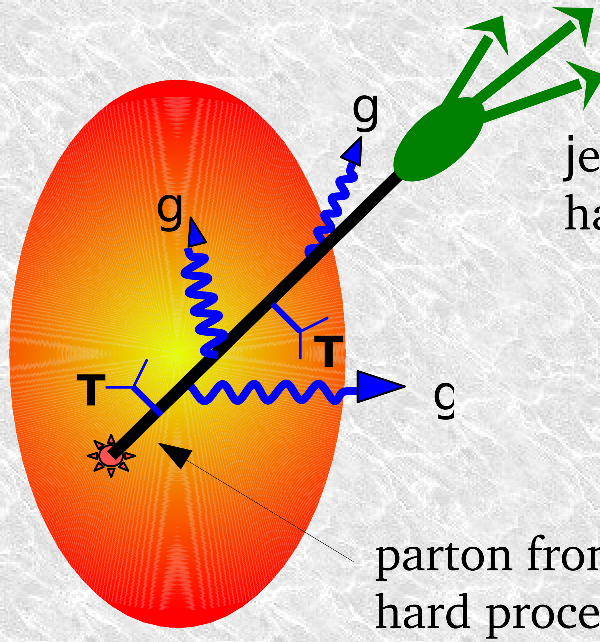
- **p+p, p+A:** difference in meson and baryon production at medium p_T not understood in pQCD + quark fragment.
- **A+A** : baryon anomaly persists – h/π ratio increases

The energy loss paradigm

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

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





Computed Axial Tomography

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

Single hadron tomography

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