Between the brick and the QGP

Alberto Accardi
Hampton U. & Jlab

Joint CATHIE/TECHQM workshop
BNL, 14-18 December 2009

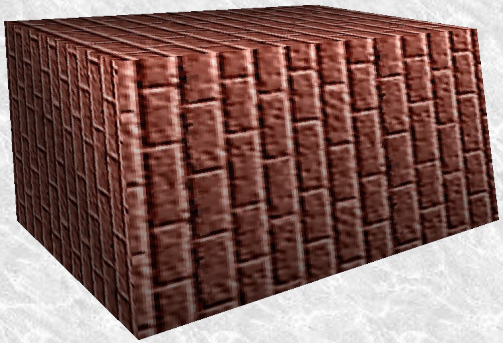
Outline

- **Between the brick and the QGP**
  – cold nuclear matter
- **Energy loss in cold nuclear matter**
- **Hadronization in cold nuclear matter**
- **Interplay of cold and hot**
  – examples
  – EIC primer

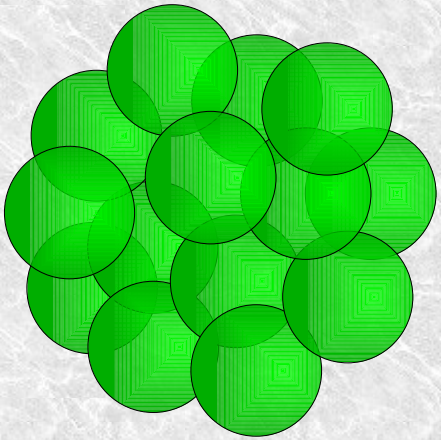
Review: Accardi, Arleo, Brooks, d'Enterria, Muccifora
"Parton propagation and fragmentation in QCD matter"
arXiv:0907.3534

Next talk: Abhijit Majumder

The characters



The Brick

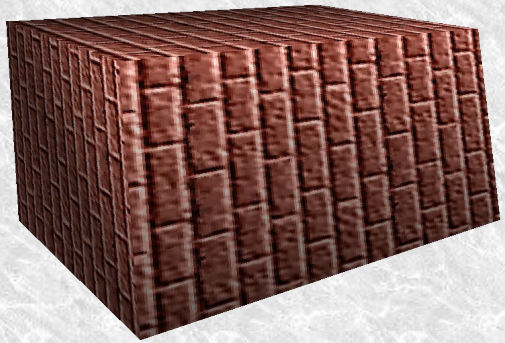


the nucleus

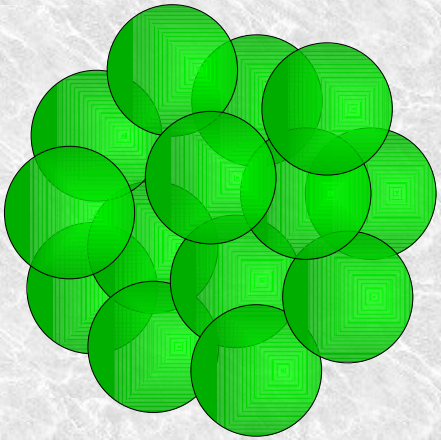
the QGP

- **Cold nuclei as experimental benchmark for theory and Monte Carlo implementations**
  - known density, not expanding
  - nucleons as femto-detectors
  - enrgy-loss, hadronization

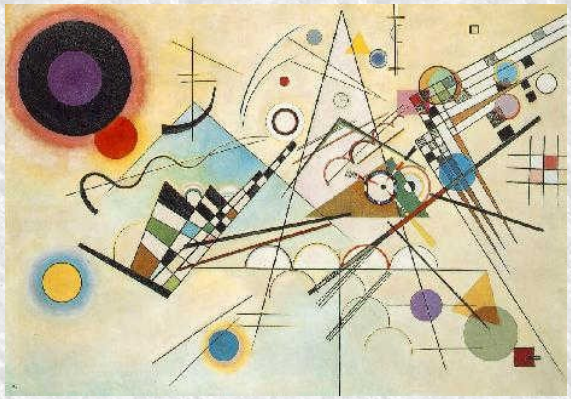
The characters



The Brick



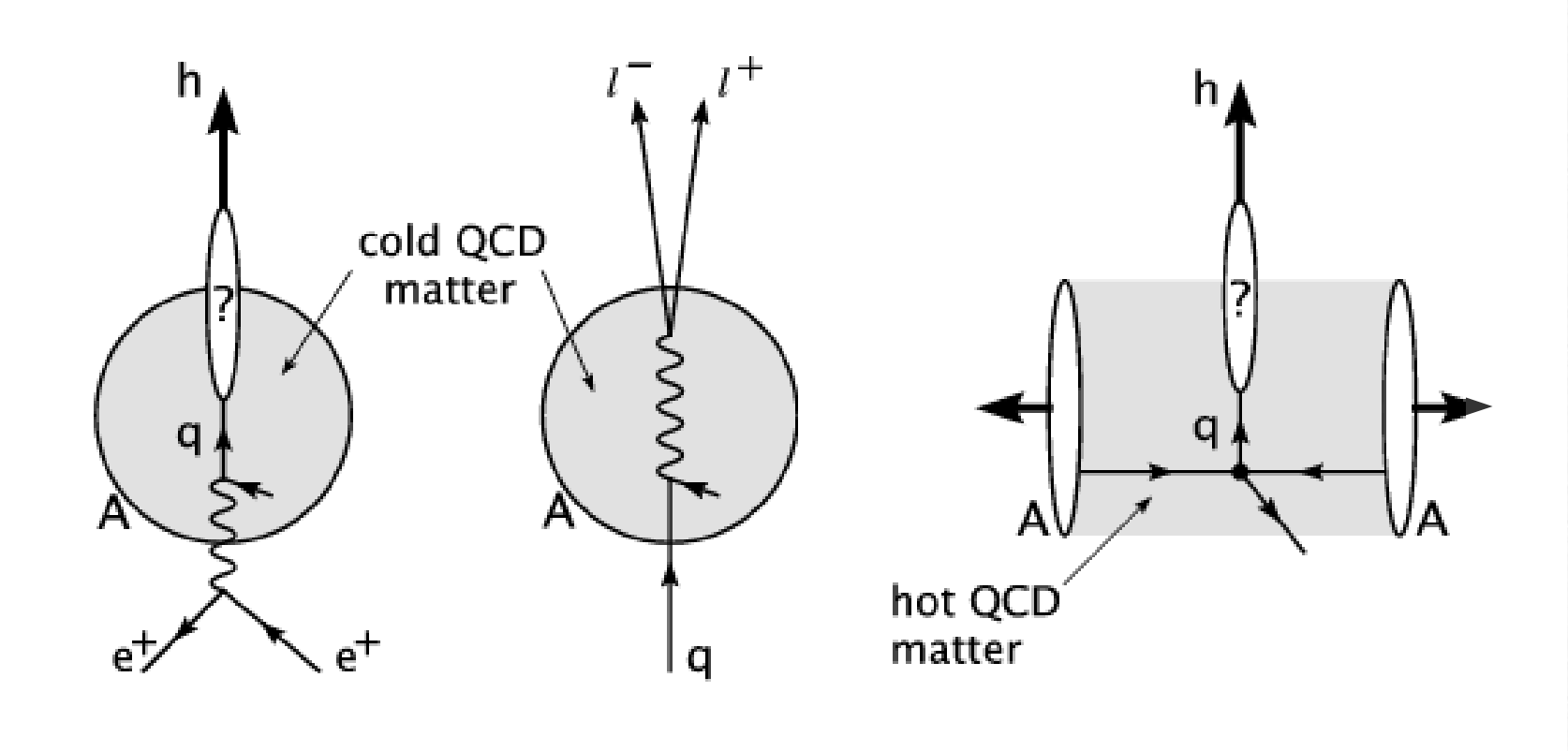
the nucleus



the QGP

Cold nuclei are necessary to reveal QGP's true nature!!

Cold vs. hot



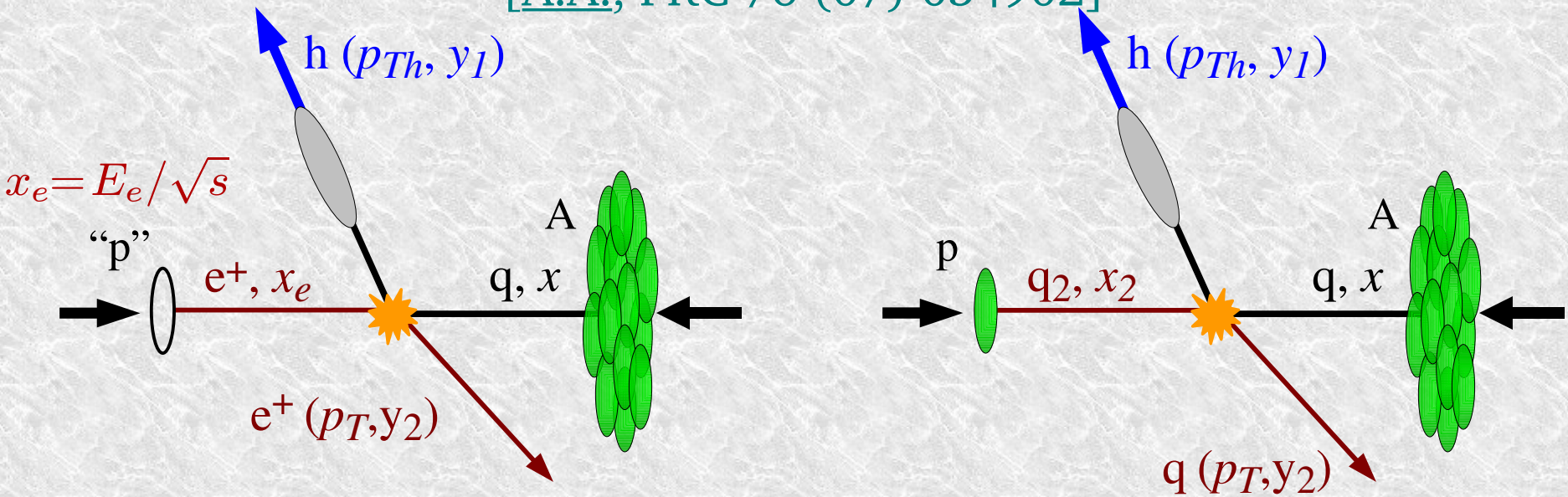
DIS
Hadronization
+ FS energy loss

DY
IS energy loss
+ nuclear PDFs

properties of the QGP

Kinematic comparison

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

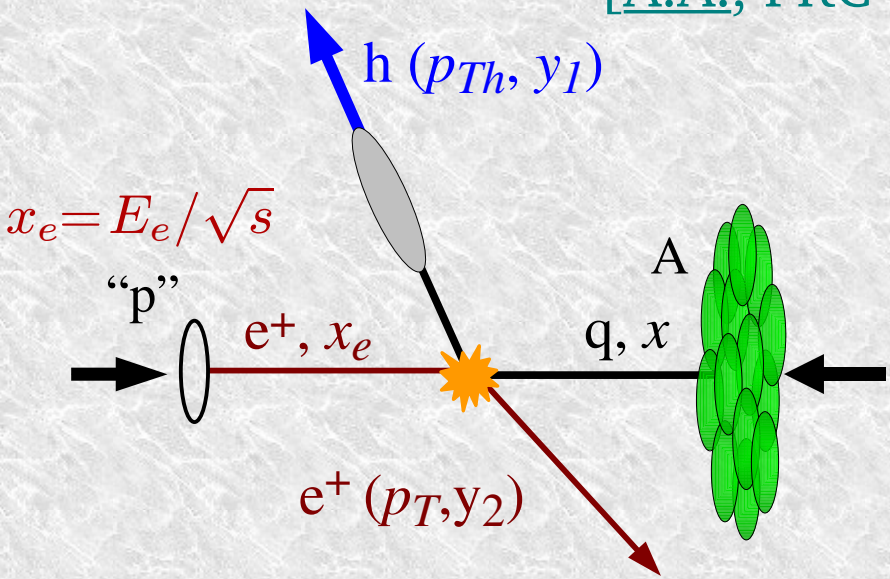


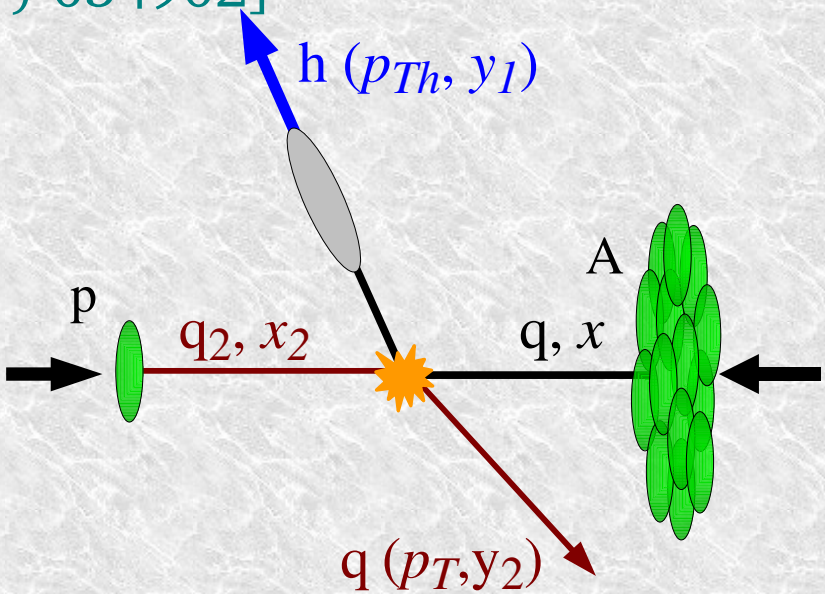
- At LO:

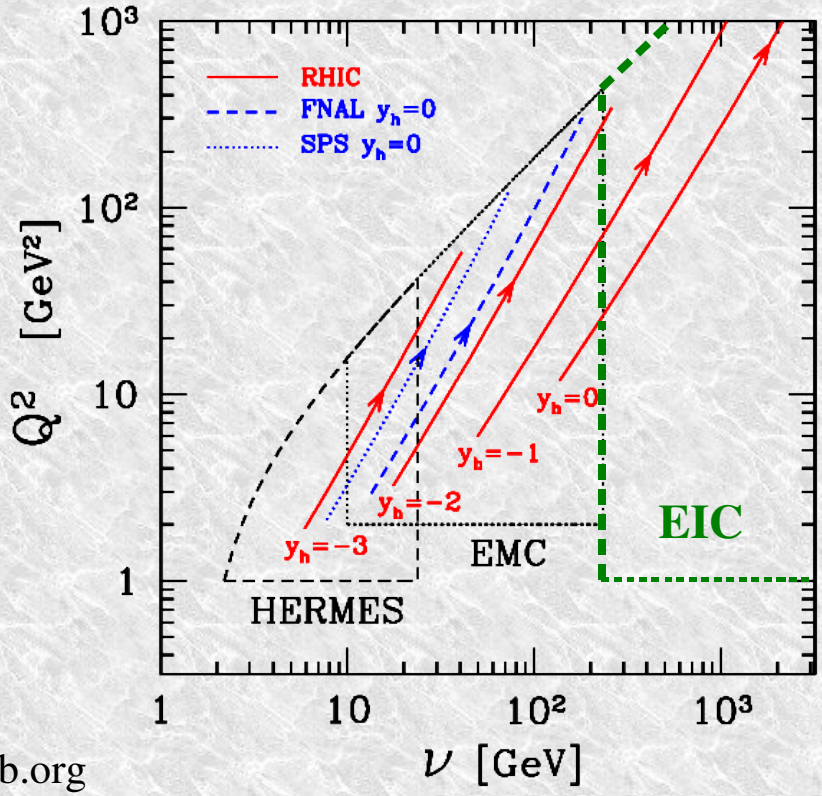
	fixed target	p+A equivalent
$Q^2 = -(p_e - p'_e)^2$		$= p_T^2(1 + e^{y_1 - y_2})$
$\nu = E_e - E'_e$		$= \frac{p_T\sqrt{s}}{2M} e^{y_1}$
$y = \nu/E$		$= \frac{1}{1 + e^{y_2 - y_1}}$
$z_h = E_h/\nu$		$= z$

Kinematic comparison

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







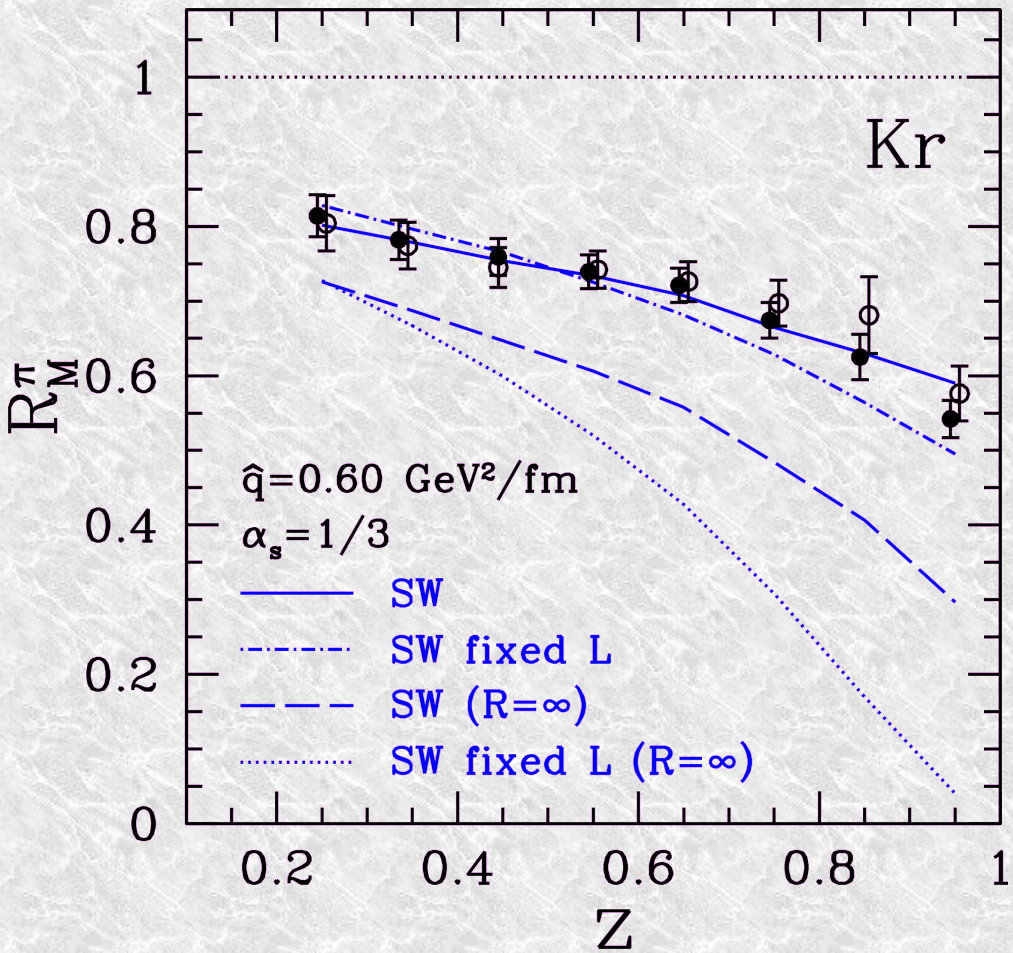
NOTE: Q^2 very different at HERMES and RHIC !

Energy Loss

Benchmarking theory with nuclear DIS

- **Example**: energy loss model with SW quenching weights

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



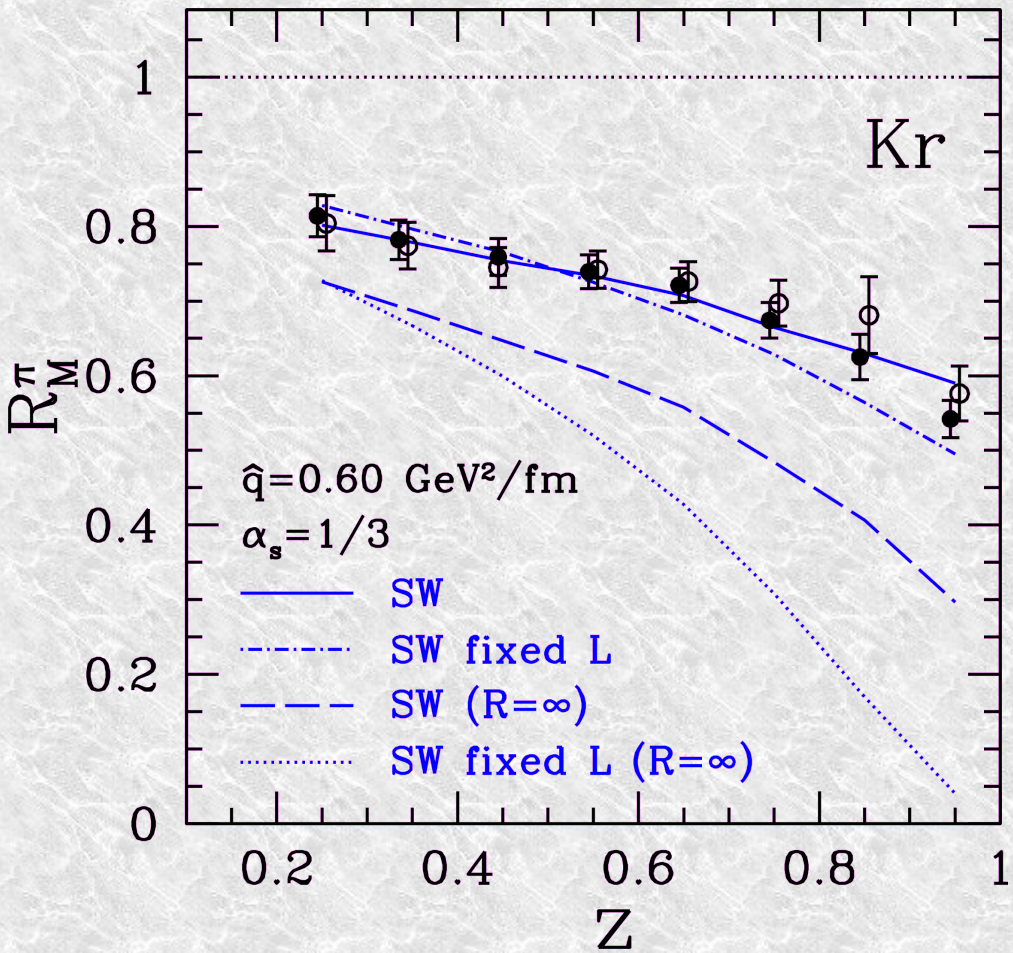
- Hadron attenuation in nuclear DIS:

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

  - nuclear PDFs largely cancel
  - exposes modified fragmentation

Benchmarking theory with nuclear DIS

- **Example**: energy loss model with SW quenching weights
  [A.A., Acta.Phys.Hung. '06 & PRC '07; Big Review]



Fixed vs. variable path length:

$\Rightarrow$ change in slope

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

Asymptotic vs. finite size:

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

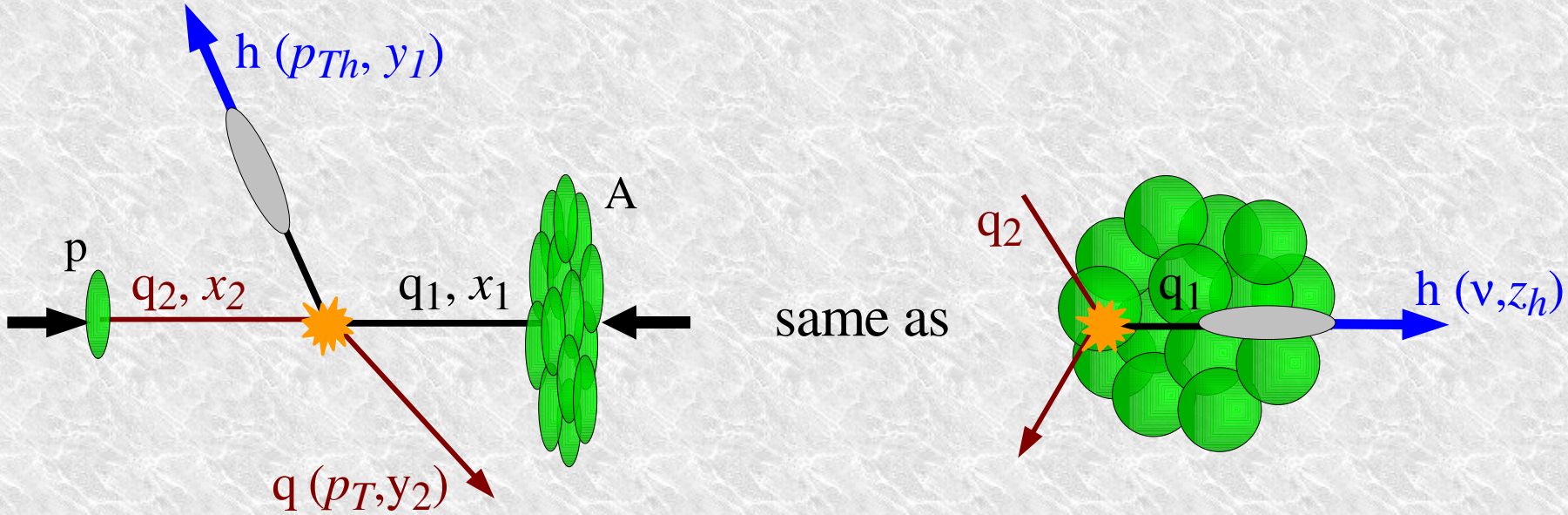
$\Rightarrow$ thick: $\hat{q} \approx 0.2\ \mathrm{GeV}^2/\mathrm{fm}$

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

Correct geometry needed at qualitative & quantitative levels

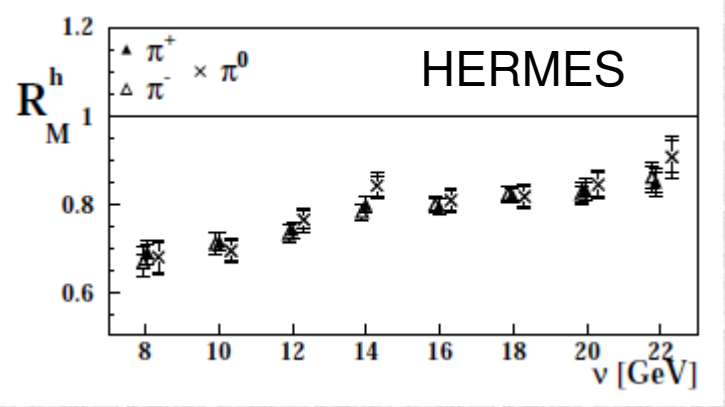
Cold quenching in p+A and A+A collisions

A.A., PRC76 (07) 034902



- At low $\sqrt{s}$ or negative η , the equivalent ν is small

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



  - parton travels slowly through the nucleus when seen in the nucleus rest frame
  - **quenching in the cold nucleus by same mechanism of nDIS**

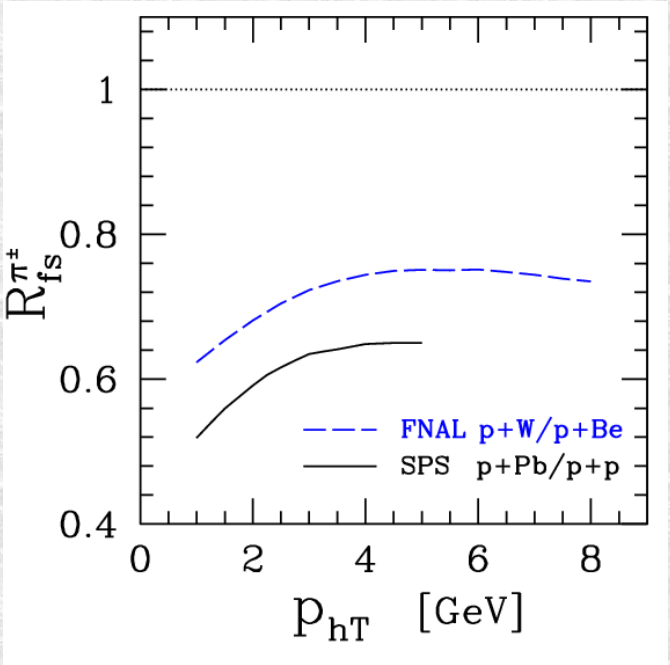
Cold quenching in p+A and A+A collisions

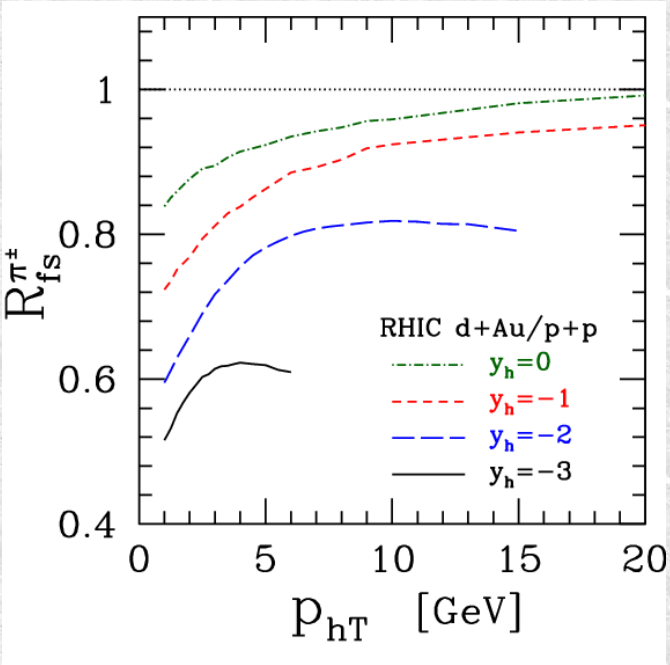
A.A., PRC76 (07) 034902

- 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, ...]





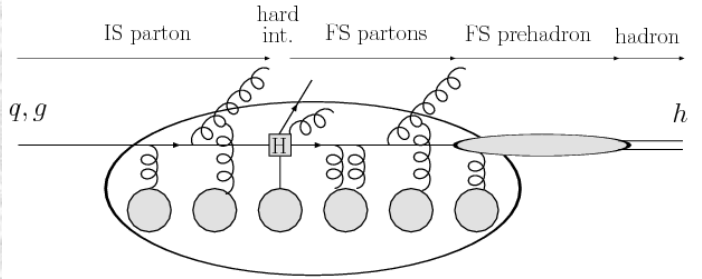
- For **A+A at $\eta = 0$**, suppression comes from both nuclei $\Rightarrow$ ~ squared:

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

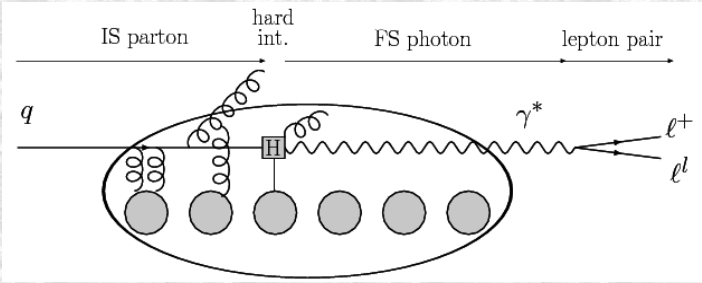
Initial state parton energy loss in p+A / A+A

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

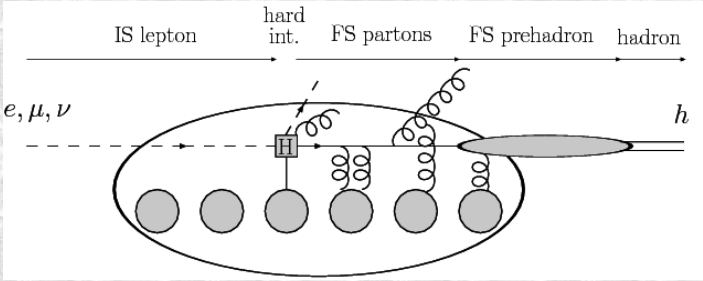
p+A (A+A)



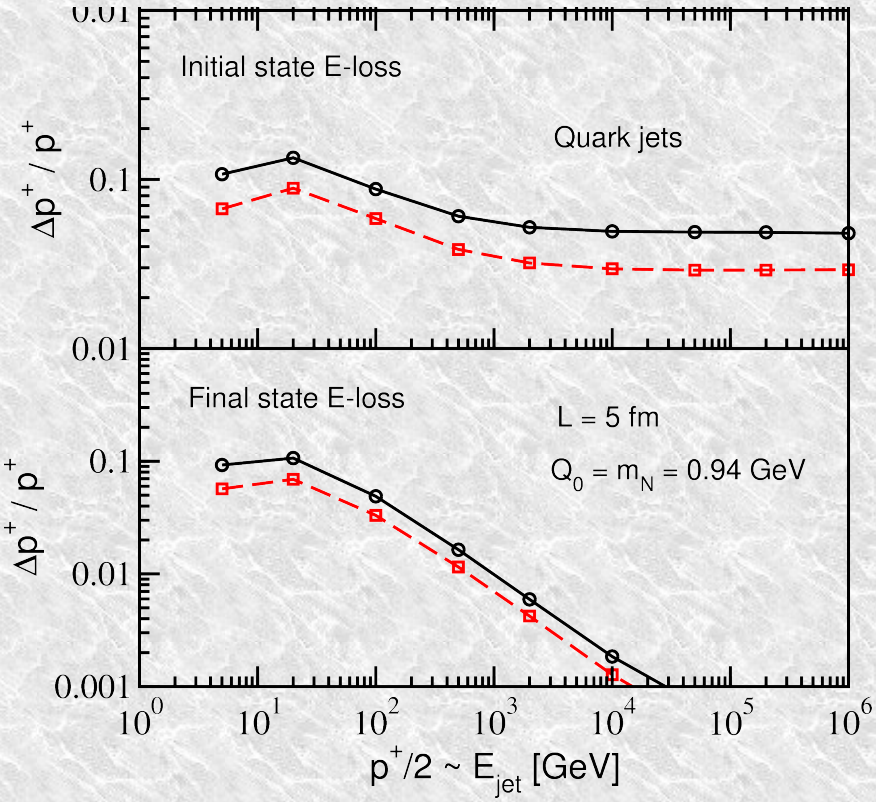
DY



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.)

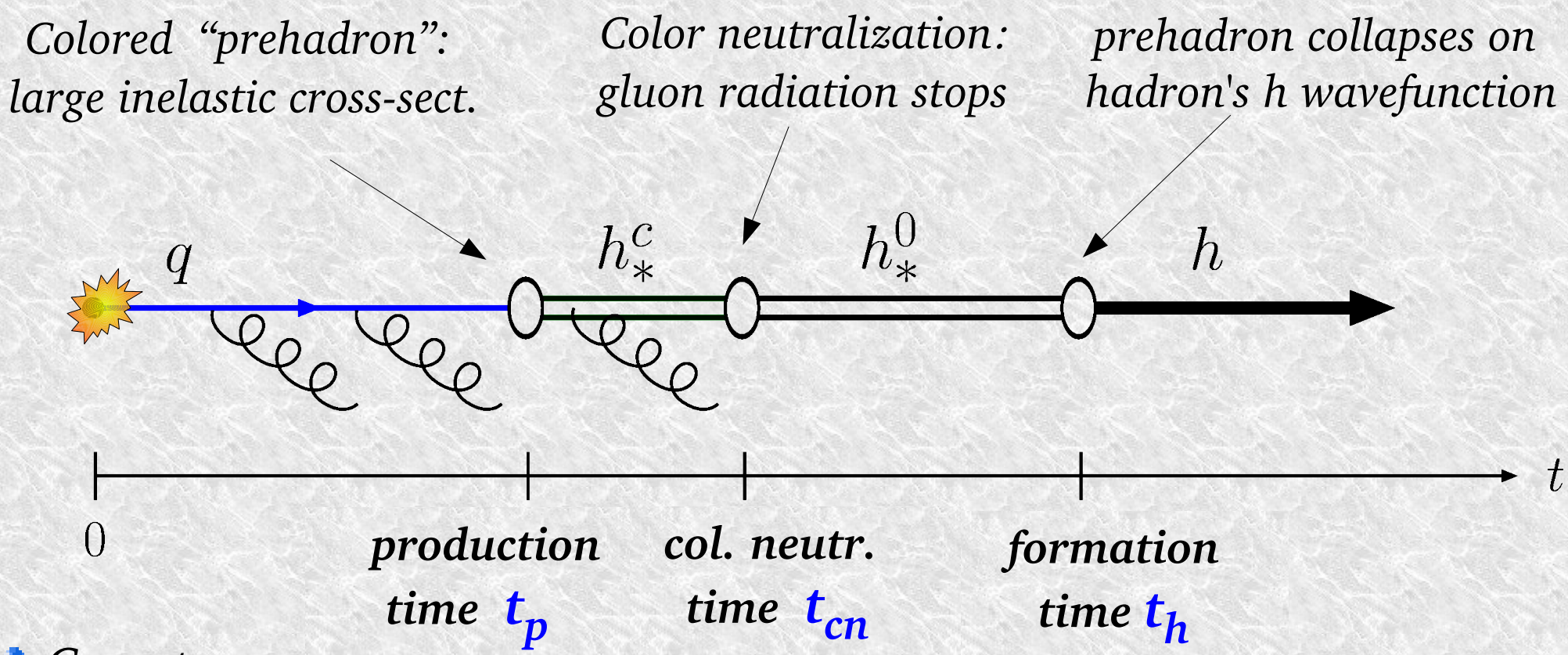
Needs unified energy loss formalism for DY, nDIS, h+A

Hadronization

(parton fragmentation)

The (naïve) framework : quark, prehadron, hadron

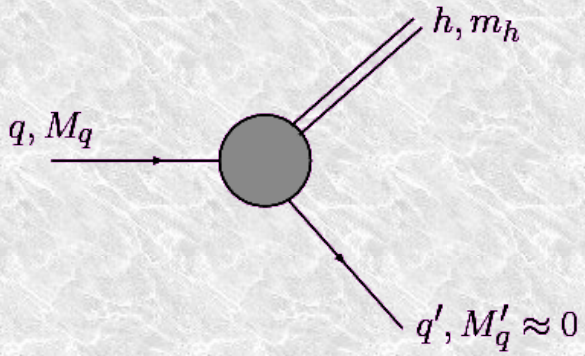
- Hadronization is non perturbative $\Rightarrow$ (many) models
- General features:



- *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

Parton lifetime 1 – pQCD estimate

- pQCD estimate [see Vitev, Adil '07]



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

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

	π	K	η	p	D	B
HERMES (ν~13 GeV, z~0.5)	28 fm	9 fm	7 fm	3 fm	0.8 fm	0.1 fm
RHIC (p_T^h ~ 7 GeV z~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

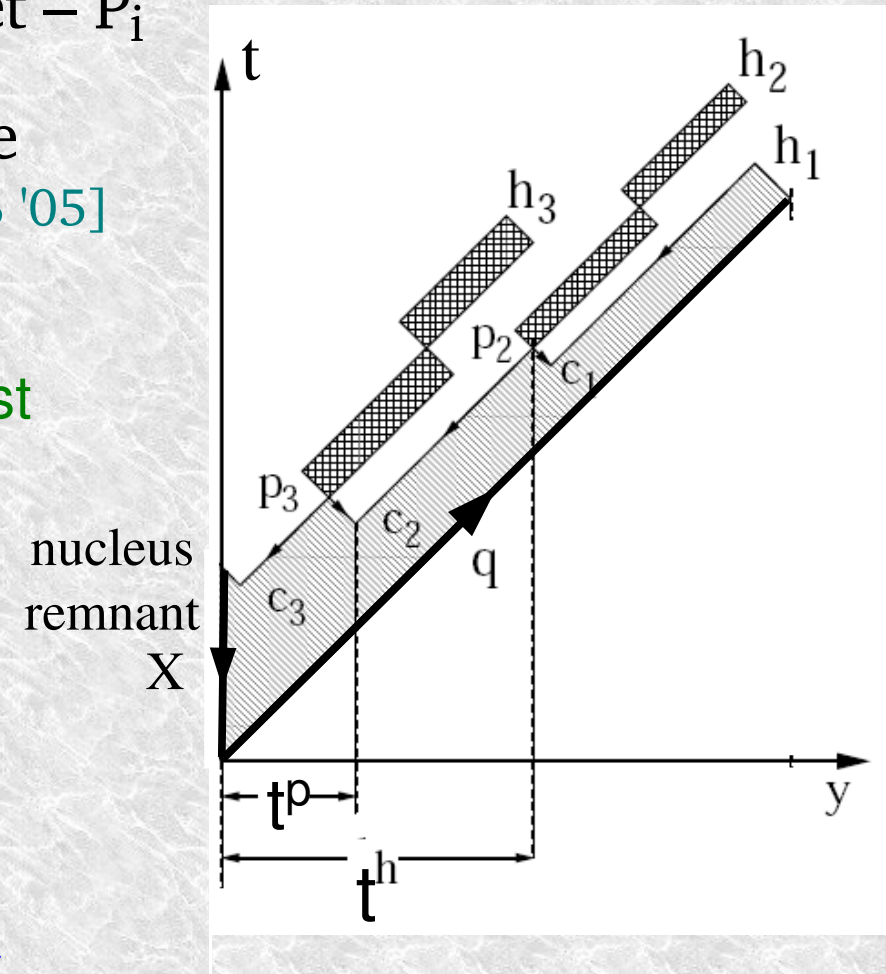
- Inside-out cascade [Bialas-Gyulassy '87]
  - Prehadron formed at $\bar{q}q$ creation (string breaking) – C_i
  - Hadron h_i formed when q and q meet – P_i
- Average formation times are computable [Accardi et al., NPA '02; Gallmeister, Falter, PLB '05]

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

boost

string tension

energy conservation



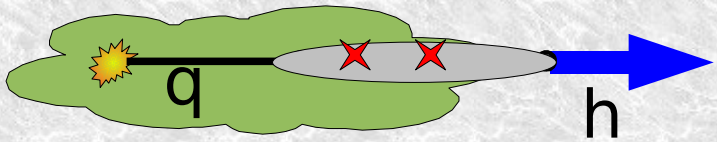
- For a $\nu = 14$ GeV pion at Hermes,

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

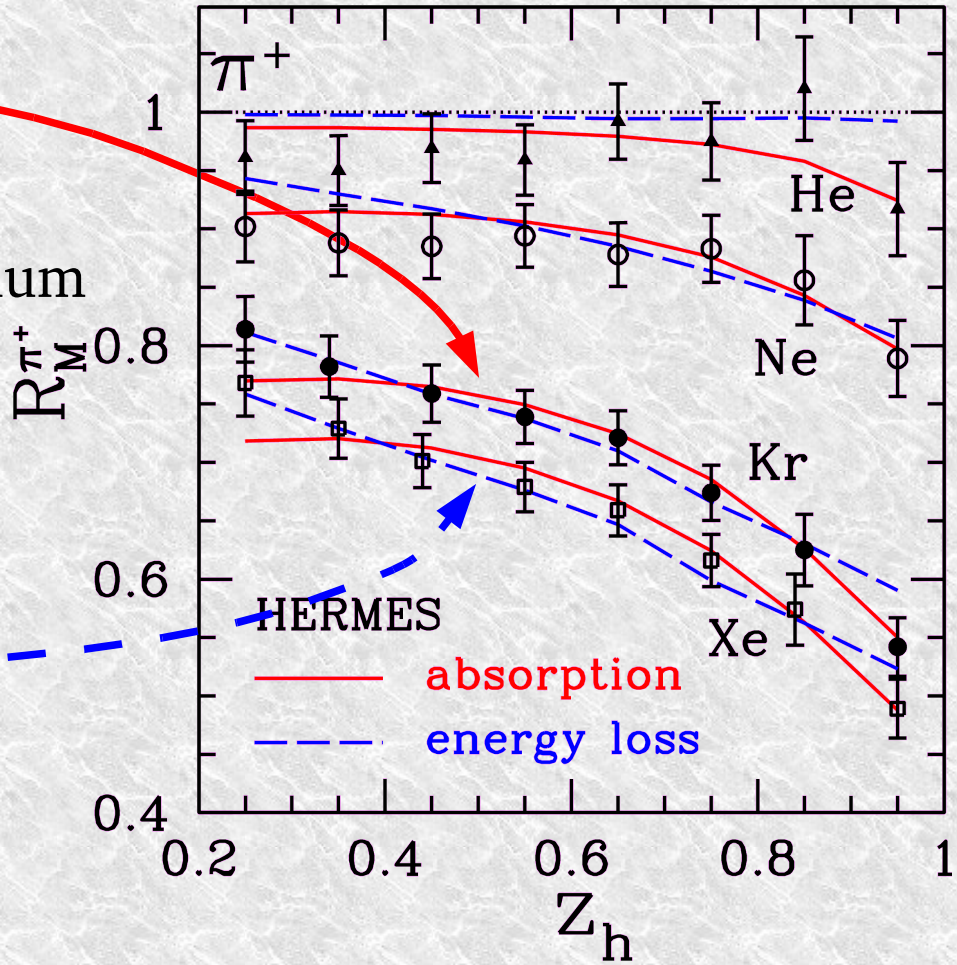
  - **shorter time scales than in pQCD estimates**

1) Hadron quenching in nDIS

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



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



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

1) Hadron quenching in nDIS

Red: **absorption model**

$(\sigma_p = 0.65\,\sigma_h)$

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

Blue: **energy loss model**

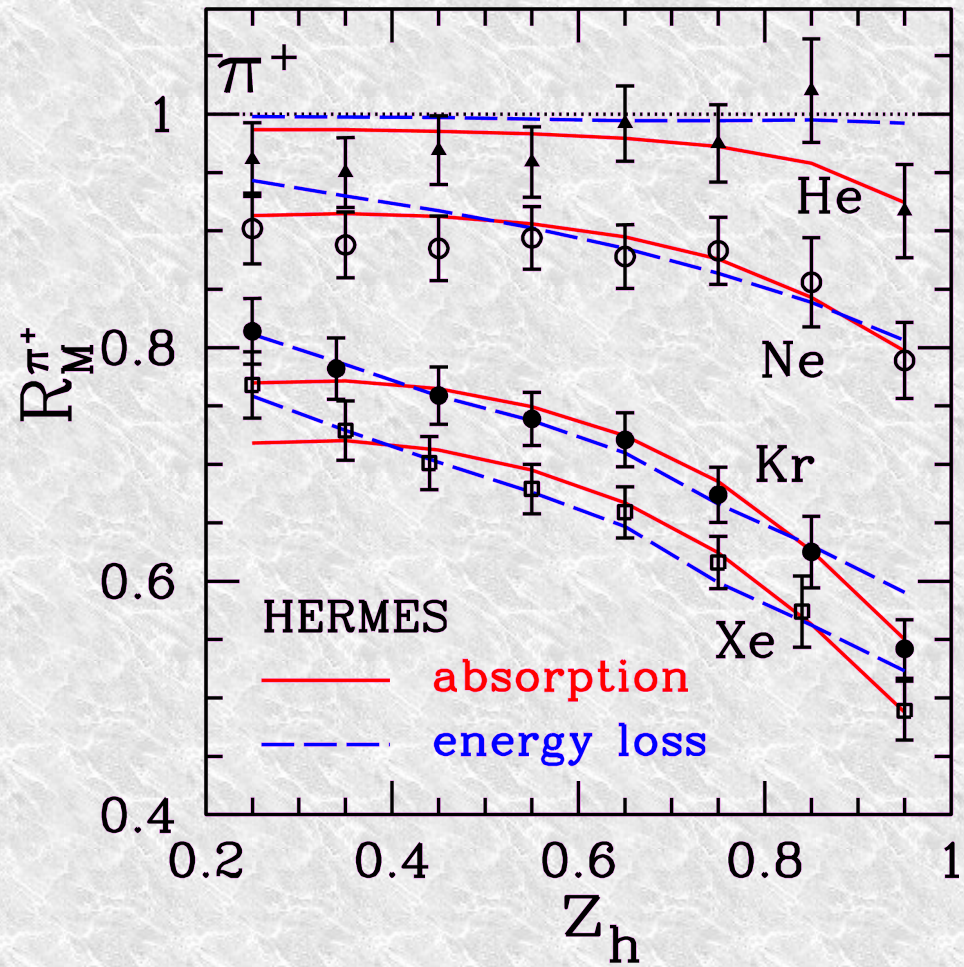
with SW quenching weights

$(\hat{q} = 0.6\ \mathrm{GeV}^2/\mathrm{fm})$

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

Detailed medium geometry:

same in both computations



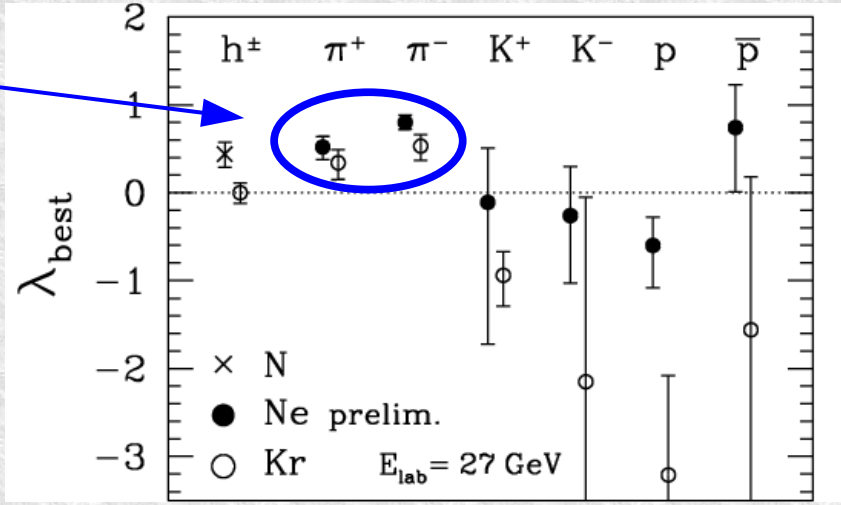
Both describe the data:
no info on parton lifetime

2) Scaling of R_M [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
  - 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. et al., review]

- Assume very long production times: pure energy loss models

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

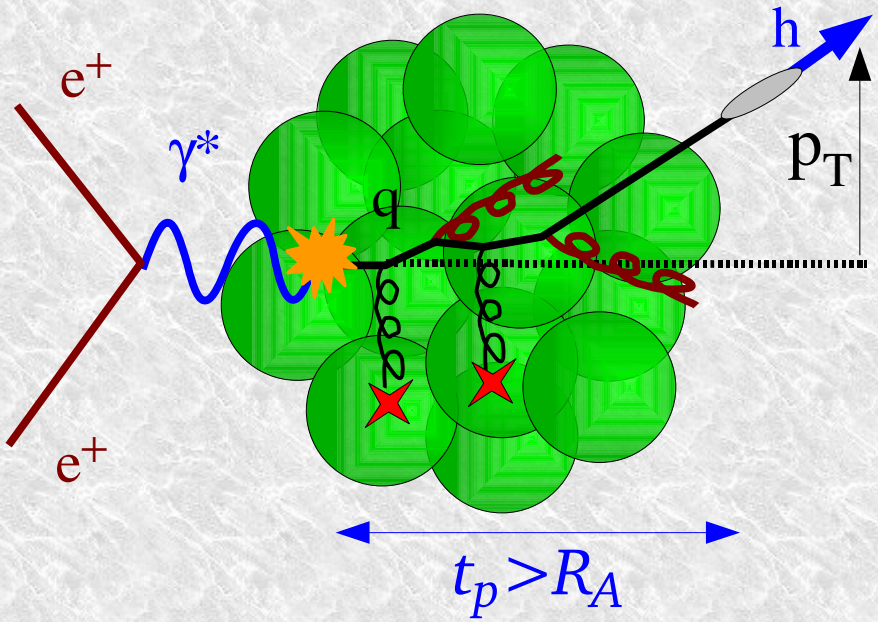
- Use the extracted

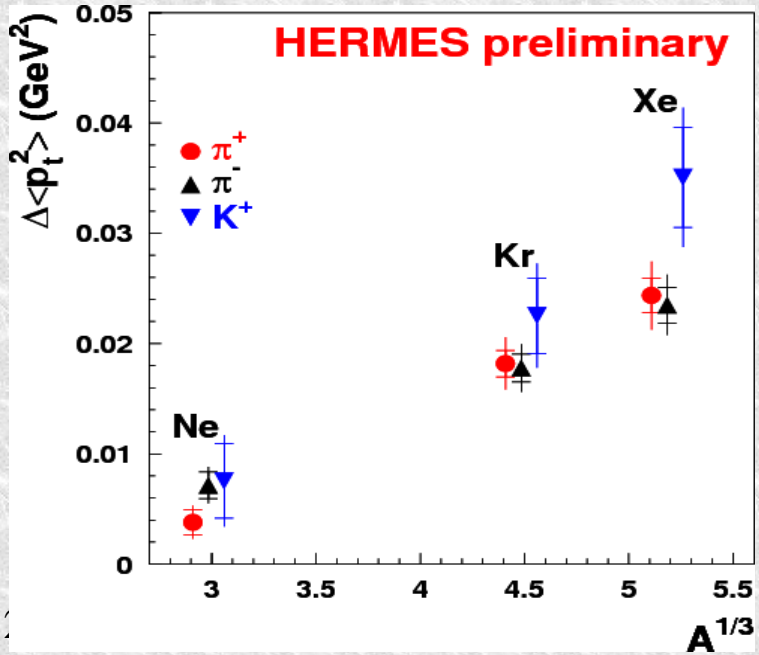
$$\hat{q} = 0.6 \text{ GeV}^2/\text{fm}$$

- **Obtain too large broadening!!**

	$\langle \Delta k_T^2 \rangle$	$\langle \Delta p_T^2 \rangle = \langle \Delta (z_h k_T)^2 \rangle$
Ne	1.4 GeV^2	0.23 GeV^2
Kr	2.2 GeV^2	0.35 GeV^2
Xe	2.6 GeV^2	0.42 GeV^2

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



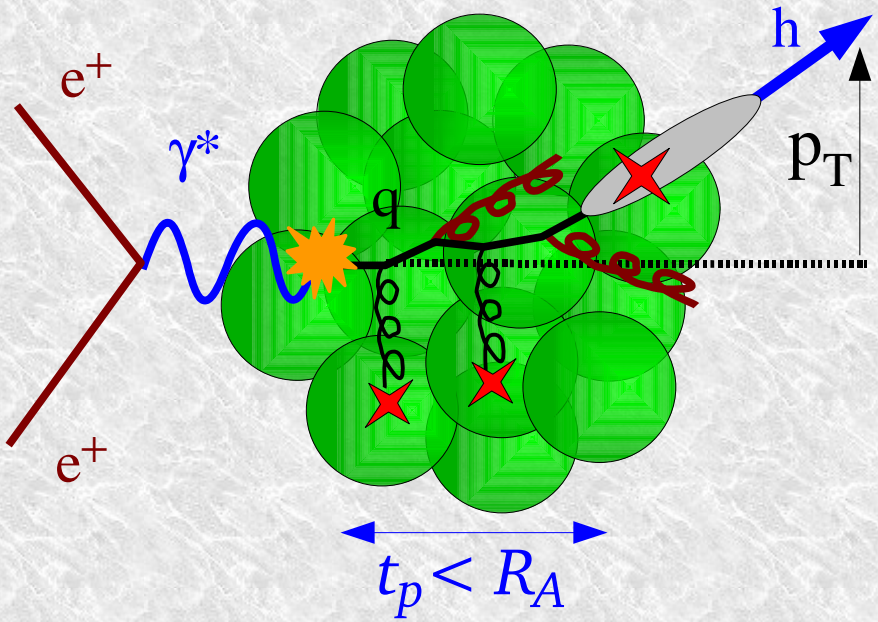


3) p_T – broadening [A.A. et al., review]

- **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

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

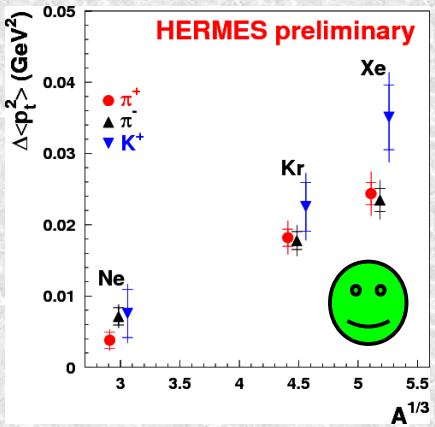
$$\Delta\langle p_T^2\rangle = \langle p_T^2\rangle_A - \langle p_T^2\rangle_D$$

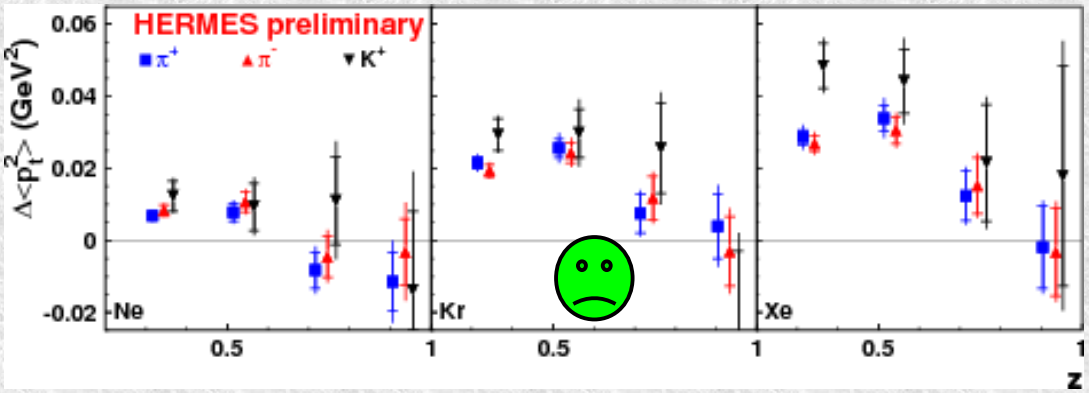


- p_T-broadening should:
  1) rise with $A^{1/3}$ until $\langle t_p\rangle \sim R_A$, then level off
  2) decrease as $z_h \to 1$
  3) rise with ν, then level off
  4) possibly, decrease with Q^2 if $\langle t_p\rangle \propto \nu/Q^2$ as claimed by Kopeliovich et al., NPA 740(04)211

3) p_T – broadening [A.A. et al., review]

- **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 $\langle t_p\rangle \approx \frac{4}{3} R_{\mathrm{Xe}}$ at $z_h = 0.4$ $\nu = 14$ GeV

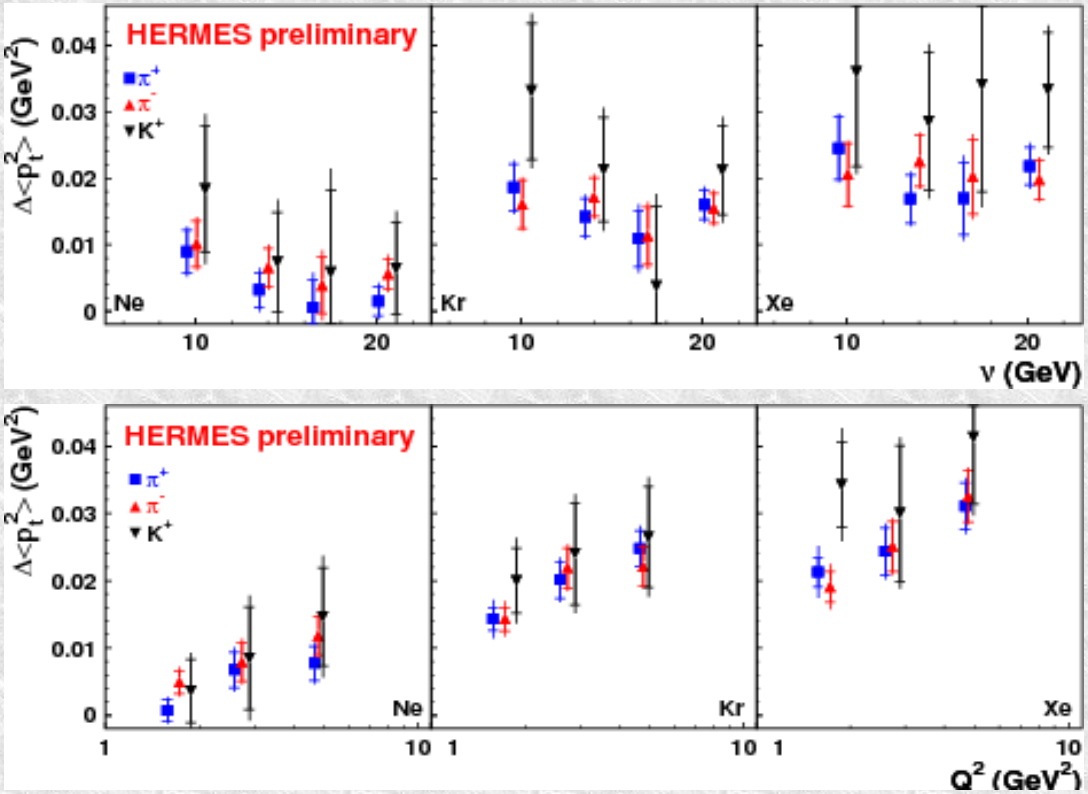
$$\Delta\langle p_T^2\rangle \propto \langle t_p\rangle \approx (0.8\ \mathrm{GeV}) \times z_h^{0.5}(1-z_h)\,\nu$$

	$\langle Q^2\rangle$ [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. et al., review]

- **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 $\langle t_p\rangle \propto \nu/Q^2$)

at strong variance with Kopeliovich et al.

- **Partonic dynamics beyond production time & multi-scattering**
  - **modified DGLAP evolution ?**
  - **NLO effects ? Uncommon prehadron t_p , inelastic σ ?**
  - **Role of virtuality ?**

Interplay of cold and hot matter

(with EIC glimpses)

Parton lifetime in hot QCD matter – 1

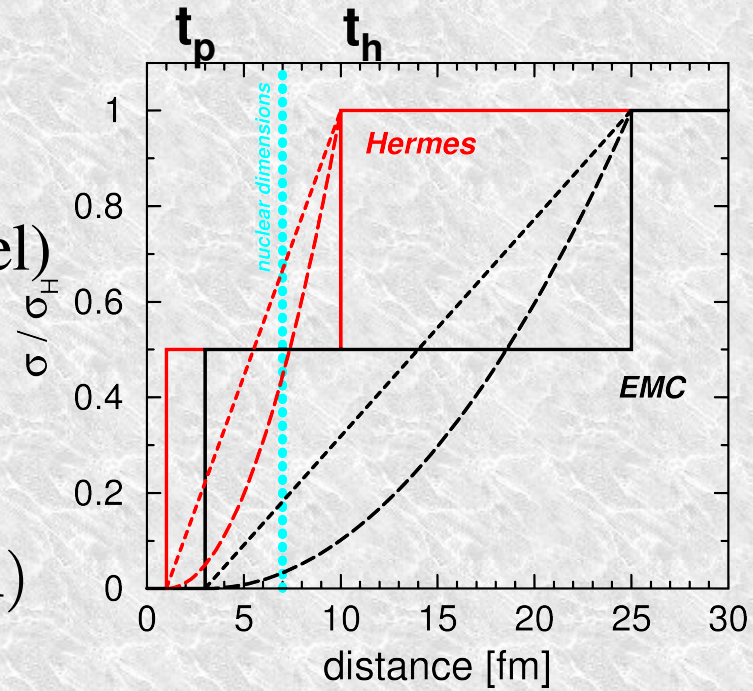
- **GiBUU absorption model:**
  [Falter et al. PRC '04, Gallmeister, Mosel NPA '08]

  Formation times: t_p from PITHYA (Lund model)

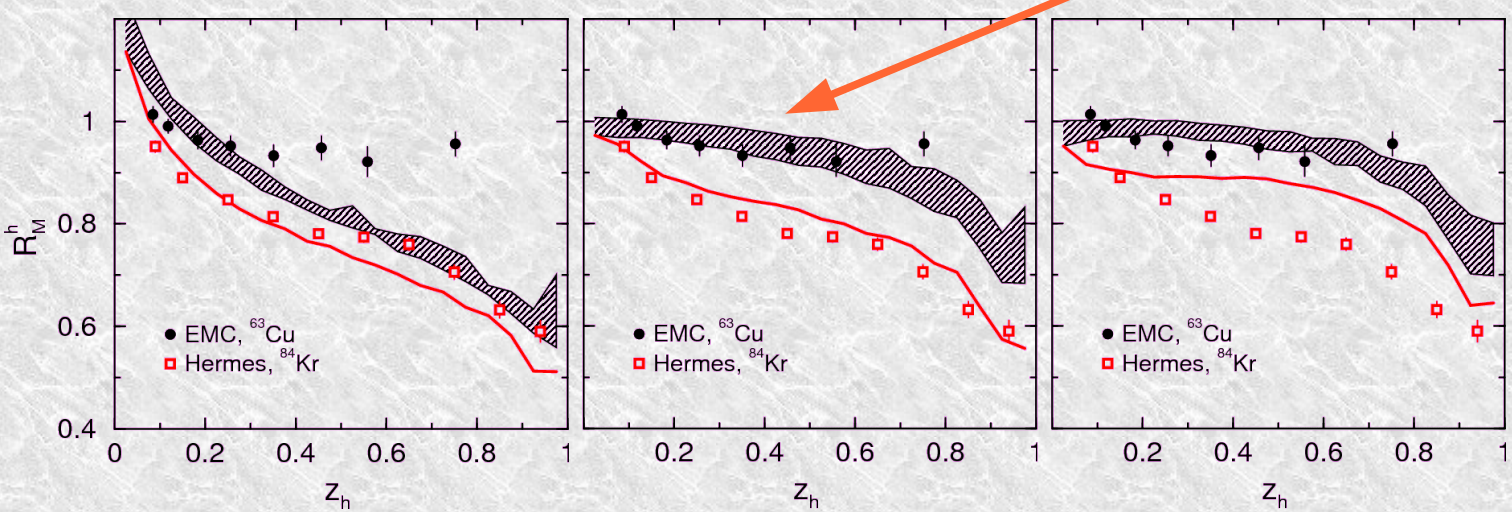
  Cross sections: leading h: $\sigma_* = f(t)\,\sigma_h$

  subleading h: $\sigma_* = 0$

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

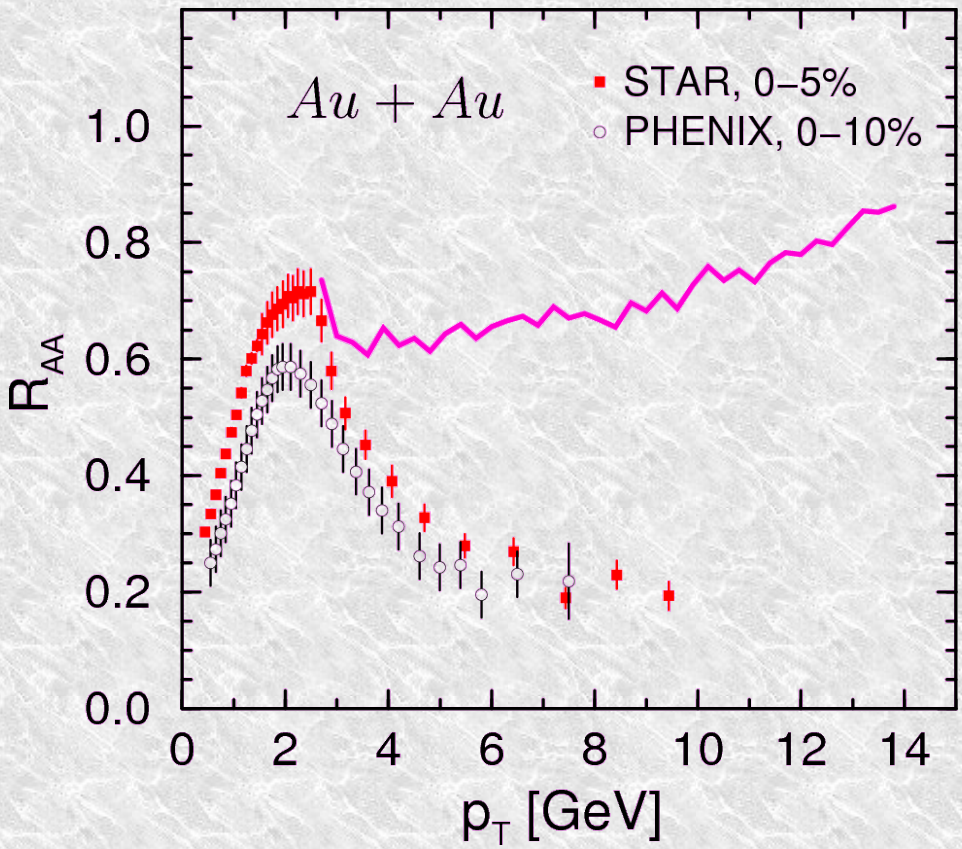


- Consistency of HERMES + EMC data selects linear $f(t) \sim t$
  [Gallmeister, Mosel NPA'08]



Parton lifetime in hot QCD matter – 2

- Apply $f(t) \sim t$ to Au+Au collisions at RHIC:
  [Cassing, Gallmeister,Greiner NPA '04; Cassing, Gallmeister NPA '05]

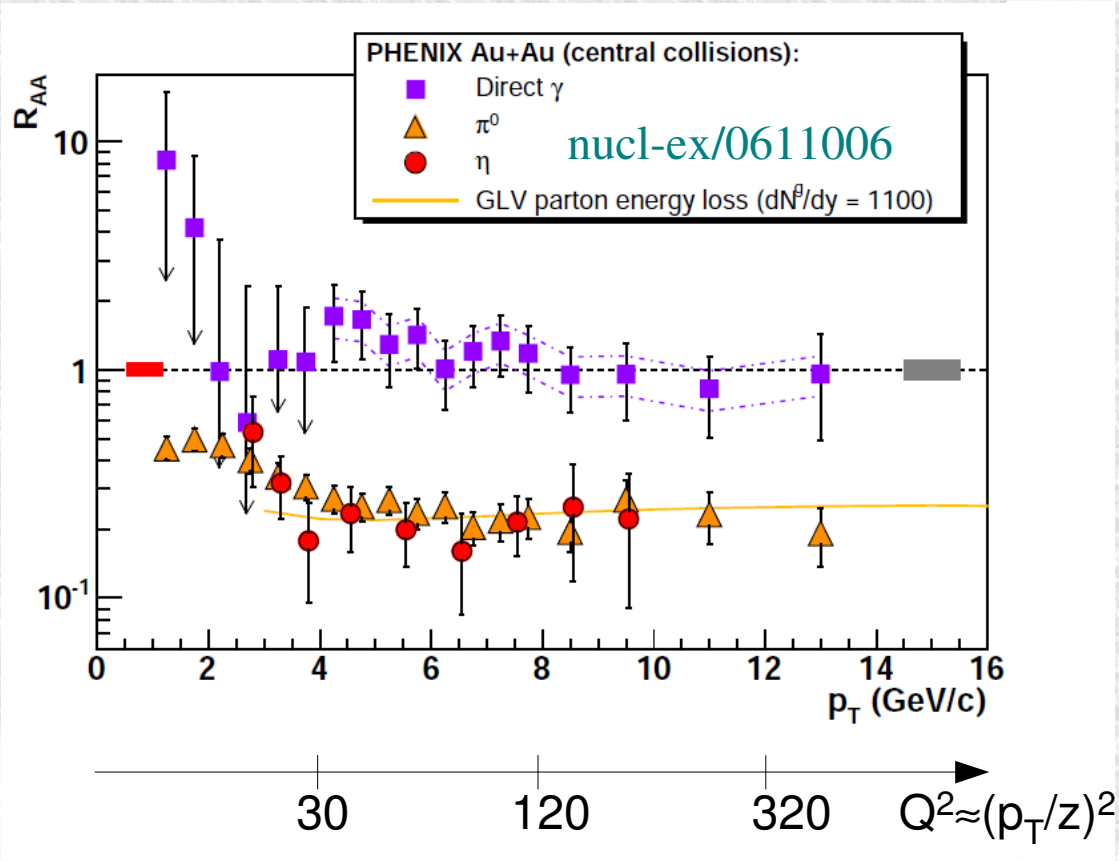


Way too little suppression:
long lived partons in QGP?

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

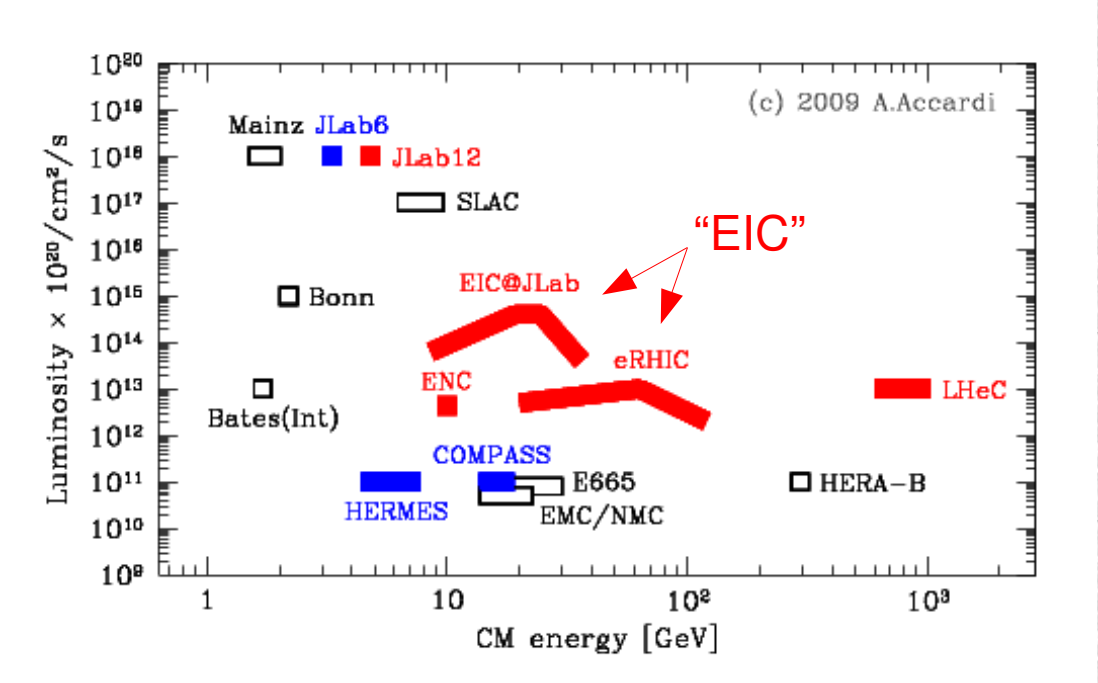
π^0 vs. η

- **Why is η as much suppressed as π in Au+Au ?**
  - **long lived partons in QGP?**
  - 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)

An Electron-Ion Collider primer



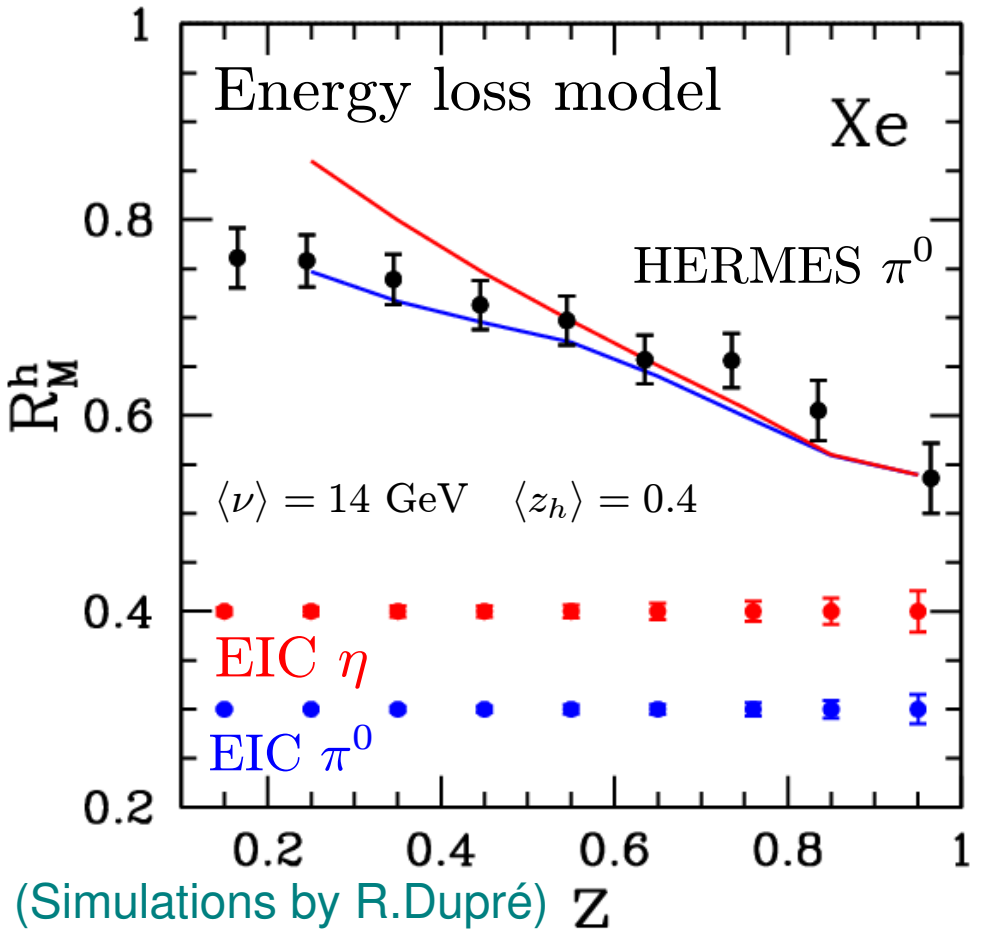
- high luminosity ≈ 10^2-10^4 × HERMES
- small x, large ν, large Q^2 reach
- **Test /extend HERMES**
  - cross-check results
  - multi-differential observables
  - 2-particle correlation (h-h, γ-h, ...)
- **Unique**:
  - **tests of parton dynamics** (energy loss, DGLAP)
  - **heavy flavors**
  - **jets** (1st time in nDIS !)
  - **baryon fragmentation, target fragmentation**

π^0 vs. η at EIC – attenuation

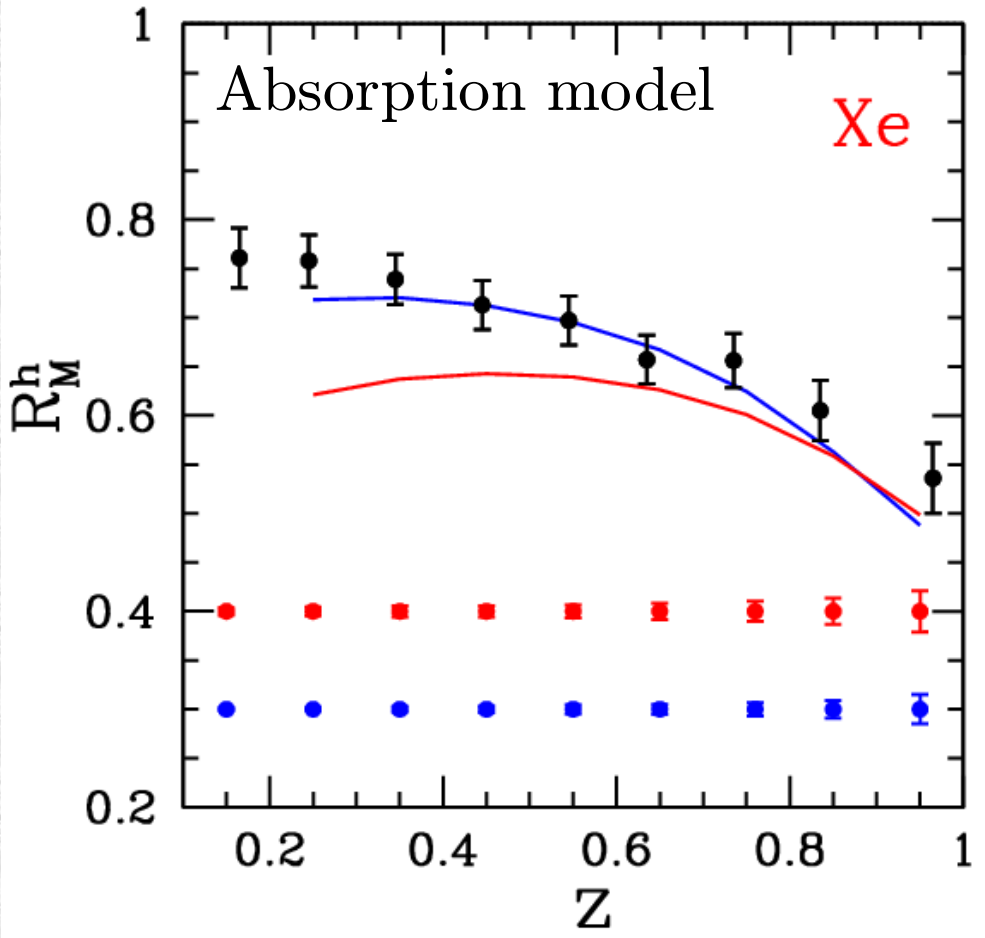
[Accardi, Dupré, Hafidi, EIC e+A note]

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

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



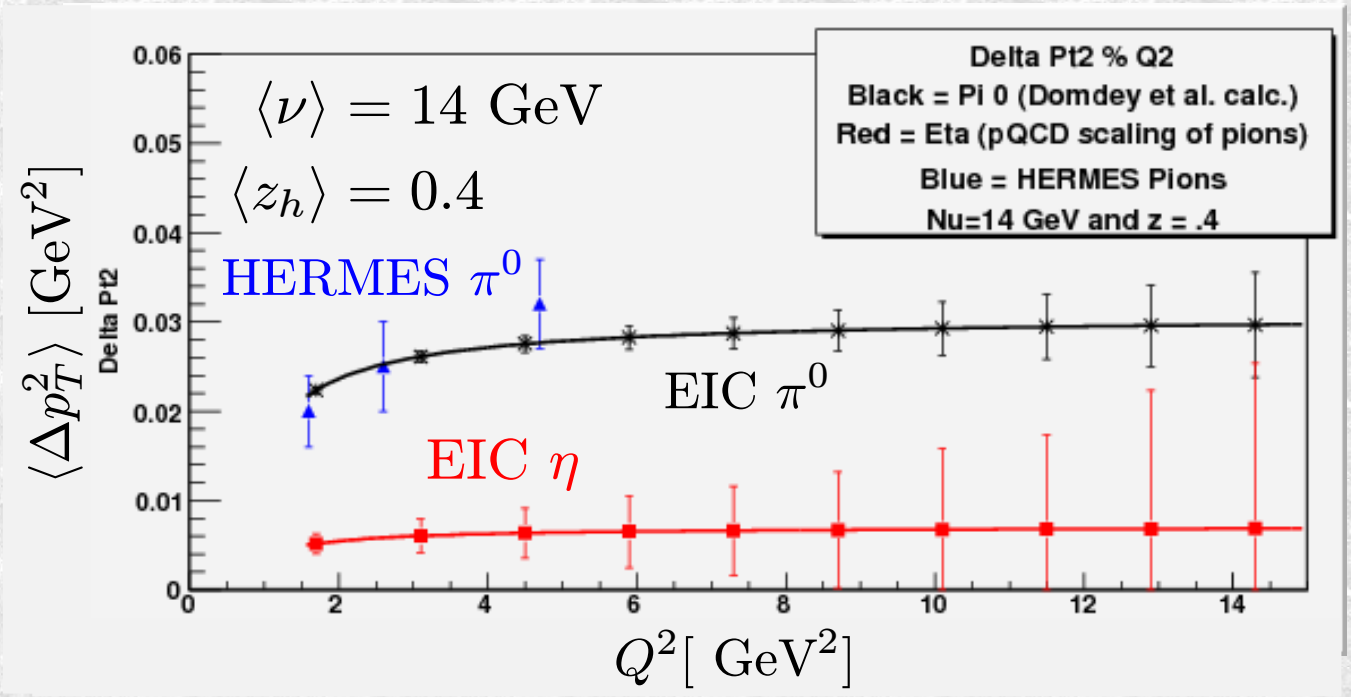
(Simulations by R.Dupré)



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.)

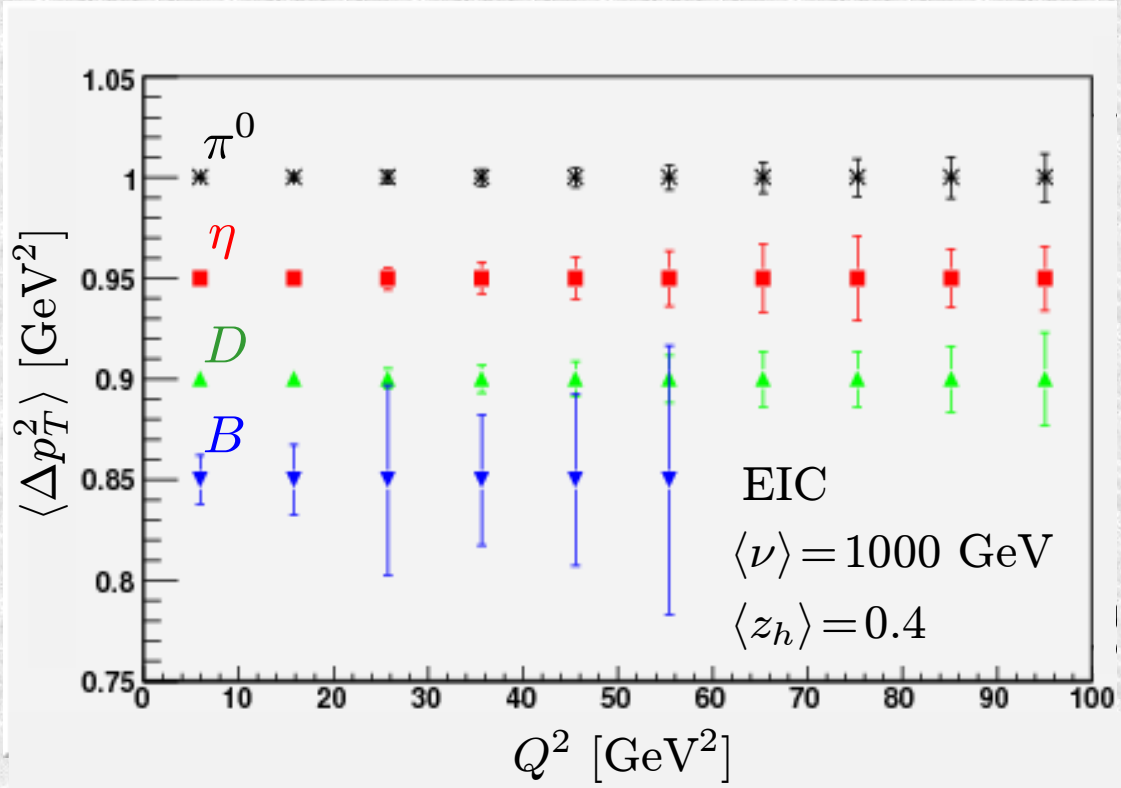
pQCD scaling of pions (slide 14)

(Simulations by R.Dupré)

Large ν, light vs heavy

[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



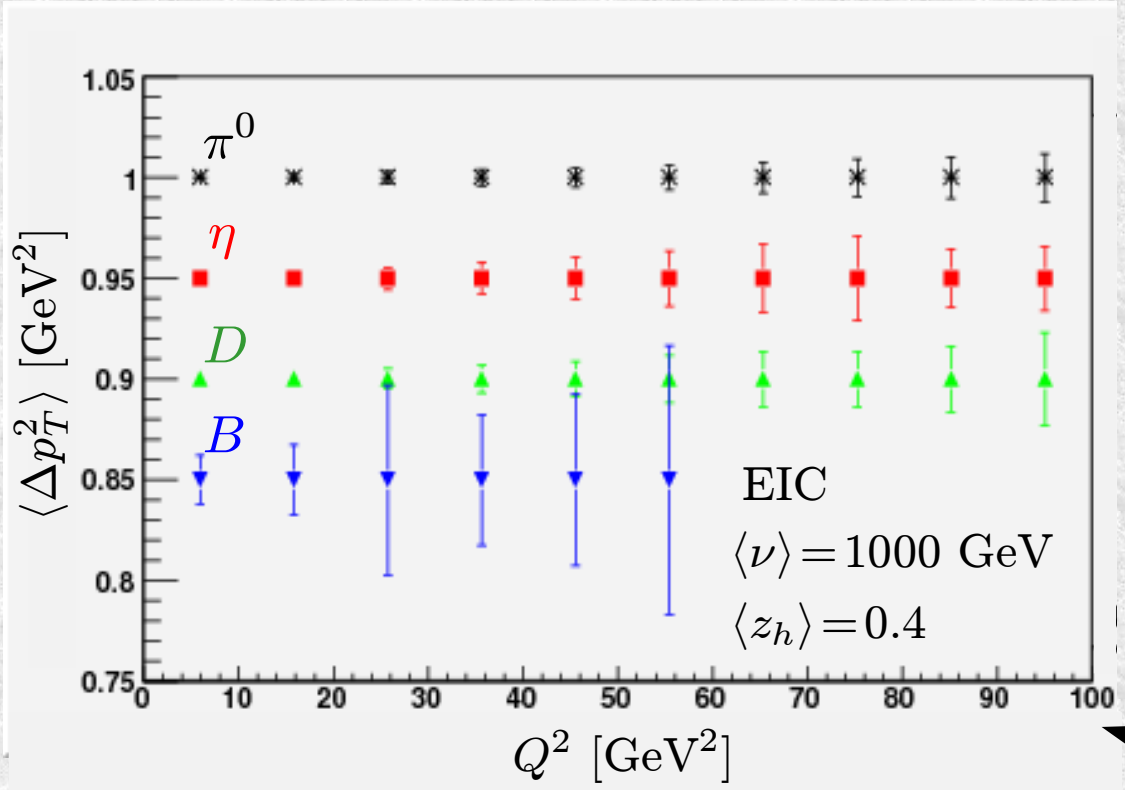
NOTE: p_T-broadening values are arbitrary
2% acceptance for heavy flavors

(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 ⇒ ideal test of pQCD energy loss



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

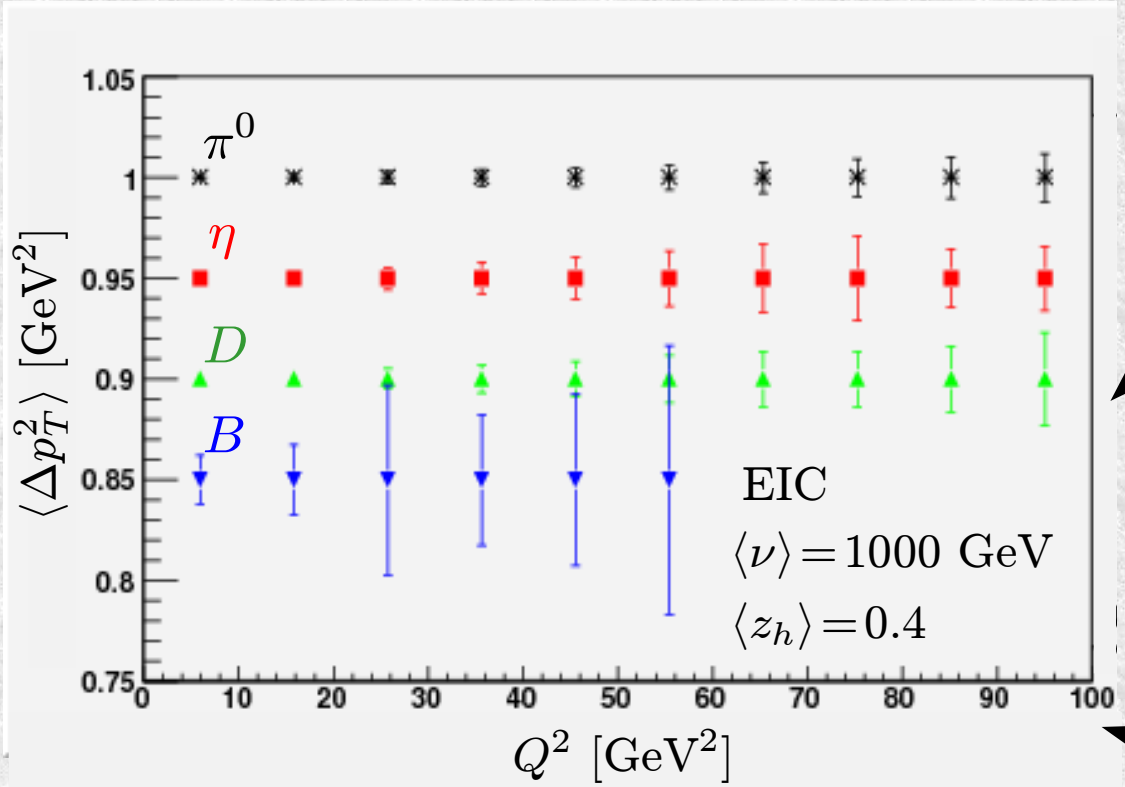
Q^2 range relevant to A+A

(Simulations by R.Dupré)

Large ν, light vs heavy

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

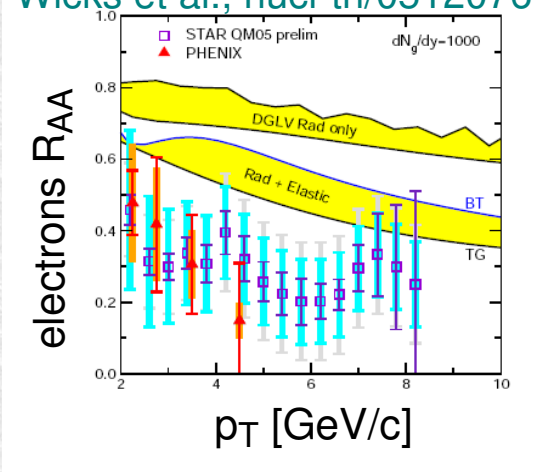
- At large ν
  - formation times are very long
  - attenuation disappears
  - pT-broadening little affected ⇒ ideal test of pQCD energy loss



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

Can solve RHIC's "heavy-flavor puzzle"

Wicks et al., nucl-th/0512076



Q^2 range relevant to A+A

(Simulations by R.Dupré)

Conclusions

- **Beyond the brick**
  - cold nuclei are the next best approximation to the QGP
- **Cold nuclei absolutely necessary:**
  - benchmark theory and MC models on real processes
  - hence, quantitatively extract QGP properties
- **Interplay of DIS, DY, hadrons in p+A**
  - requires unified formalism
- **Next theory challenge:**
  - p_T-broadening vs. z_h , ν , Q^2
- **Next experimental challenge:**
  - the Electron-Ion Collider

The end

Backup slides

The EIC parton energy loss and hadronization program

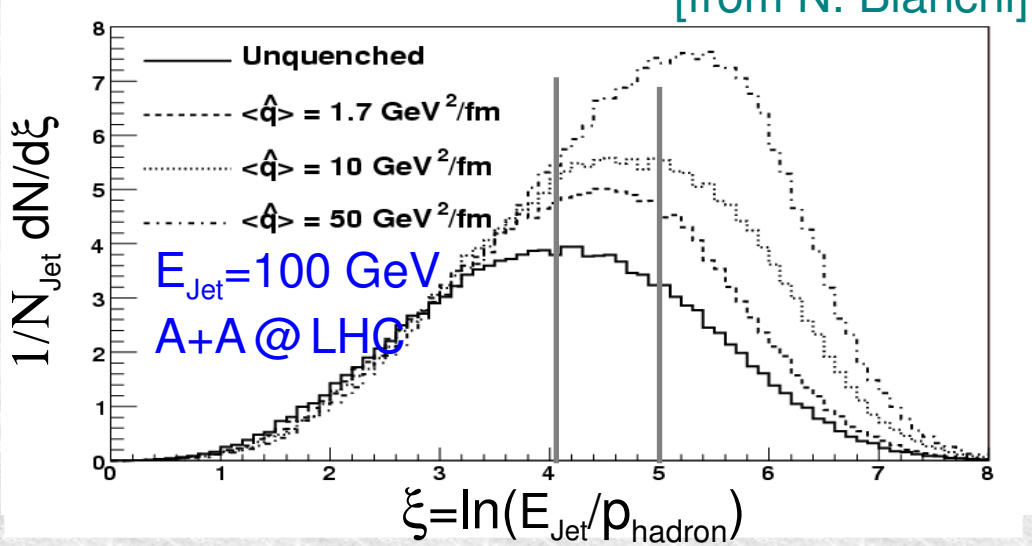
	EIC	fixed target
☆ Precision tests of pQCD energy loss, DGLAP showers	√	
☆ Jet event shape modifications, time evolution	√	
☆ Space-time picture of parton fragmentation (perturbative regime)	√	≈
☆ Hadronization from current to target region	√	≈

Not energy nor luminosity hungry (except B mesons, rare had's, 5D ?)
but **needs good PID, vertex detector**

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., jet distortion in cold matter [Borghini, Wiedemann, '06]

[from N. Bianchi]



- Jet shapes, time evolution → Sterman at EIC workshop, INT Seattle, Oct 09

So in a sense, E "tells a series of stories", of all possible emissions that take time t:

$$E(\nu,Q) = 2\int_0^\infty \frac{dt}{t}\Big[\int_{Q/t}^{1/t^2} \frac{dp_T^2}{p_T^2} A\left(\alpha_s(p_T)\right)\left(e^{-u\nu(p_T/Q)}-1\right) + \frac{1}{2}B\left(\alpha_s(\sqrt{u}Q)\right)\left(e^{-u(\nu/2)}-1\right)\Big]$$

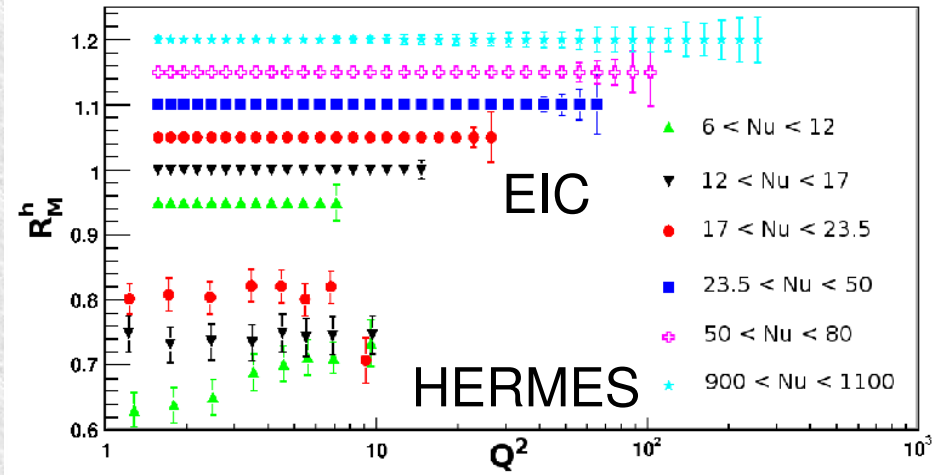
EIC vs. HERMES

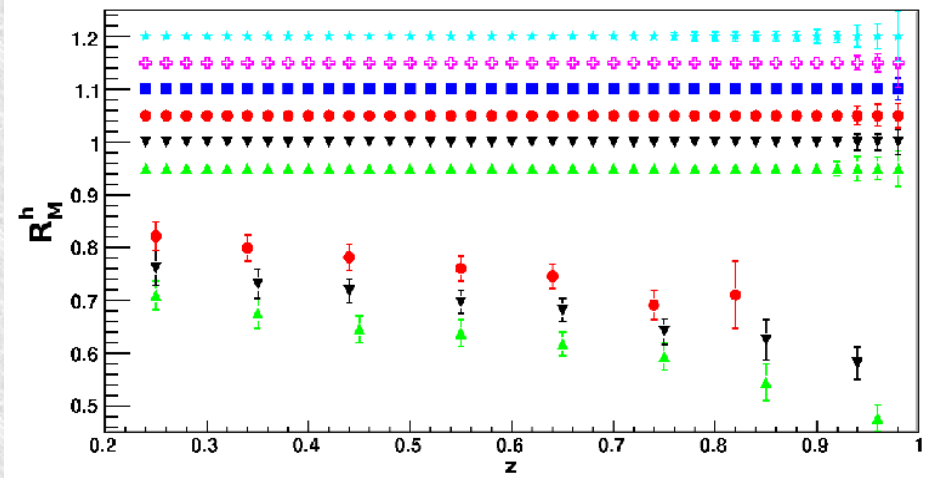
[Accardi, Dupré, Hafidi, EIC e+A note]

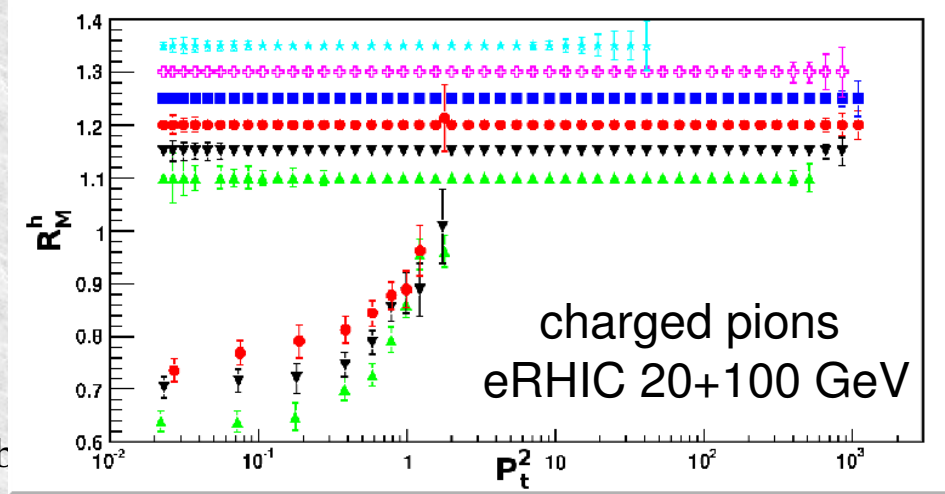
$$R_M^h(z) = \frac{\frac{1}{N_A^{DIS}} \frac{dN_A^h(z)}{dz}}{\frac{1}{N_D^{DIS}} \frac{dN_D^h(z)}{dz}}$$

- Simulation with PYTHIA 6.4.19
  - no nuclear effect yet
  - 10 weeks of beam at eRHIC
- <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)





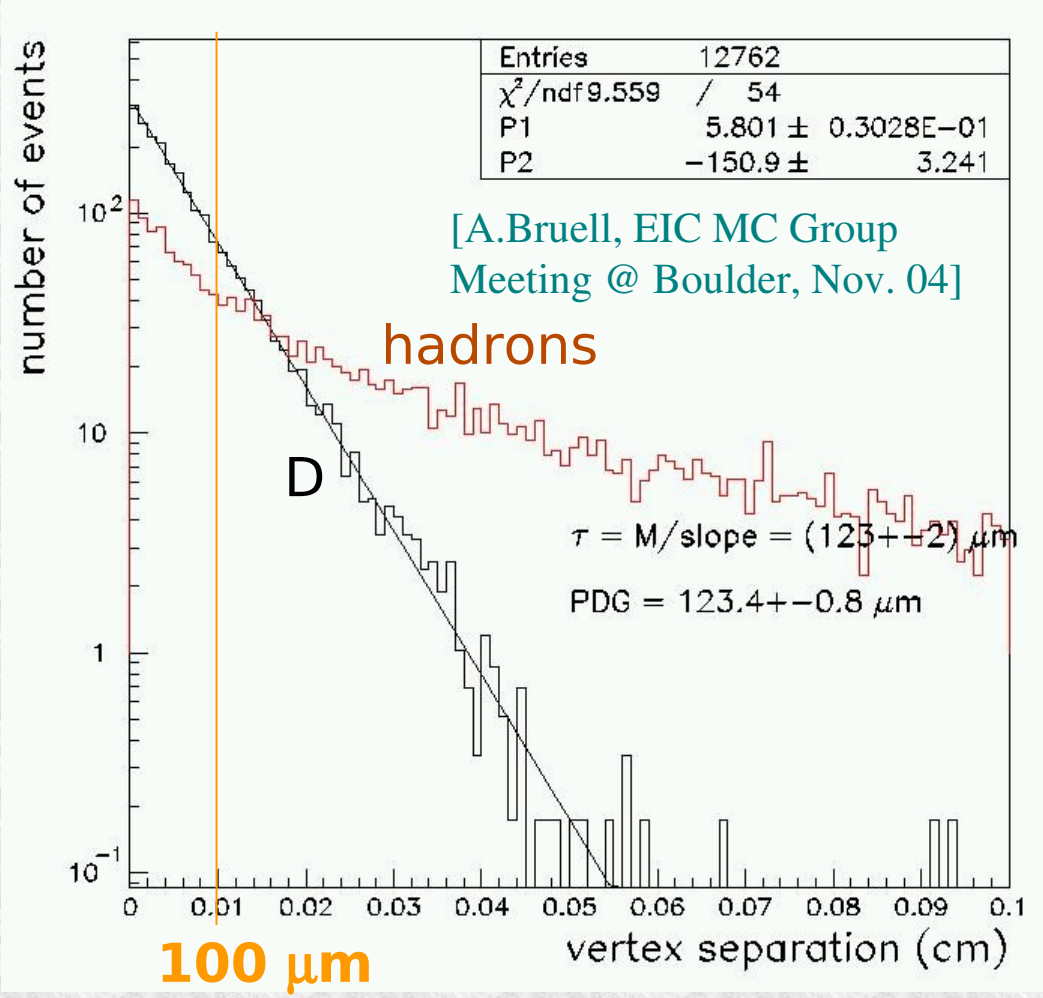


Heavy quarks identification

- 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
  - ...
- EIC needs vertex detector with spatial resolution

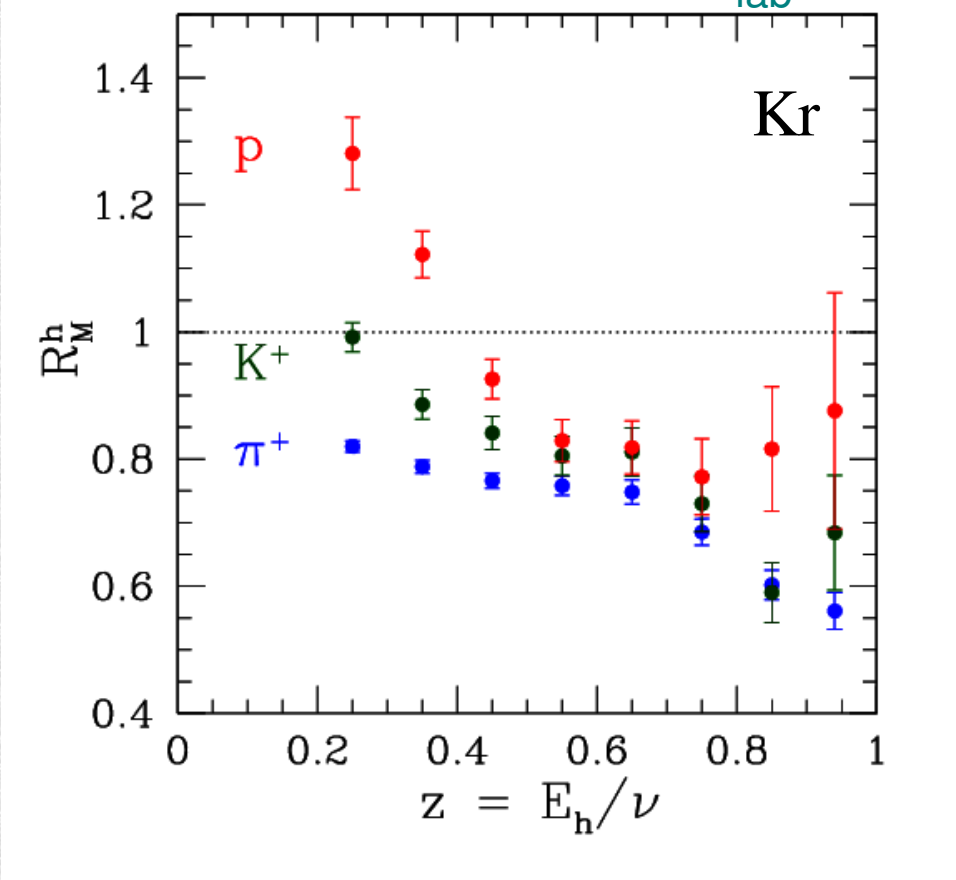
$$\Delta x \lesssim 100\ \mu m$$

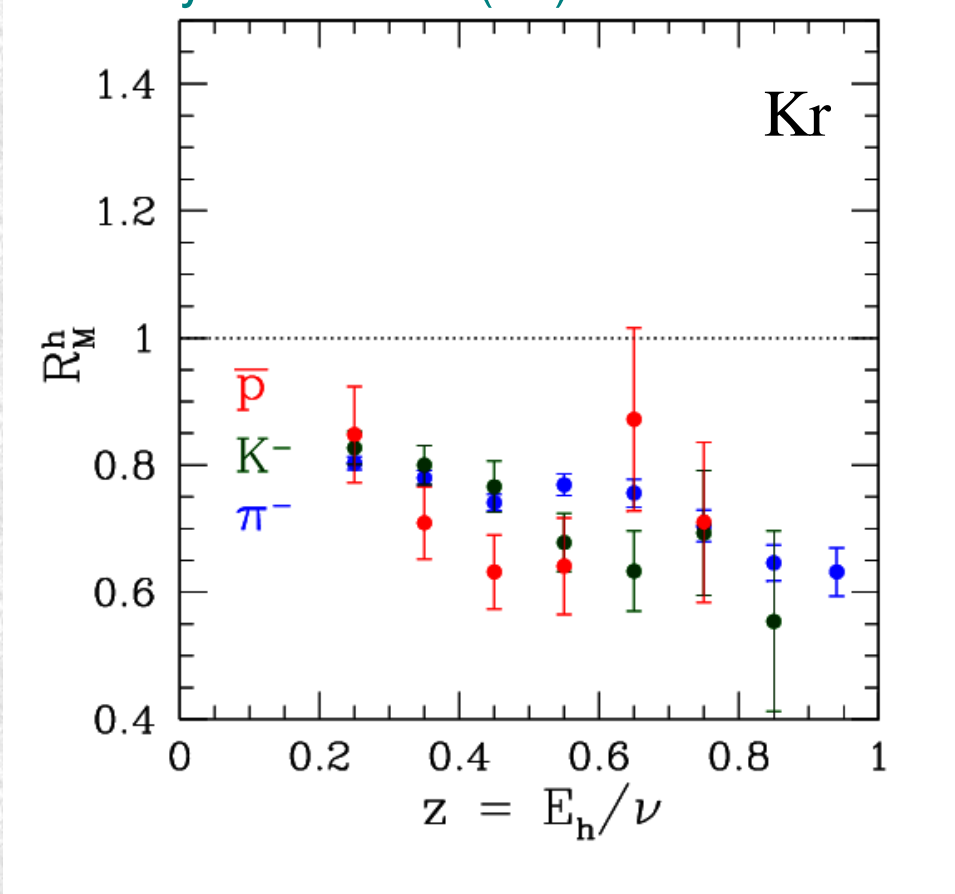
  - **more studies are needed**



Proton anomaly also in cold matter!

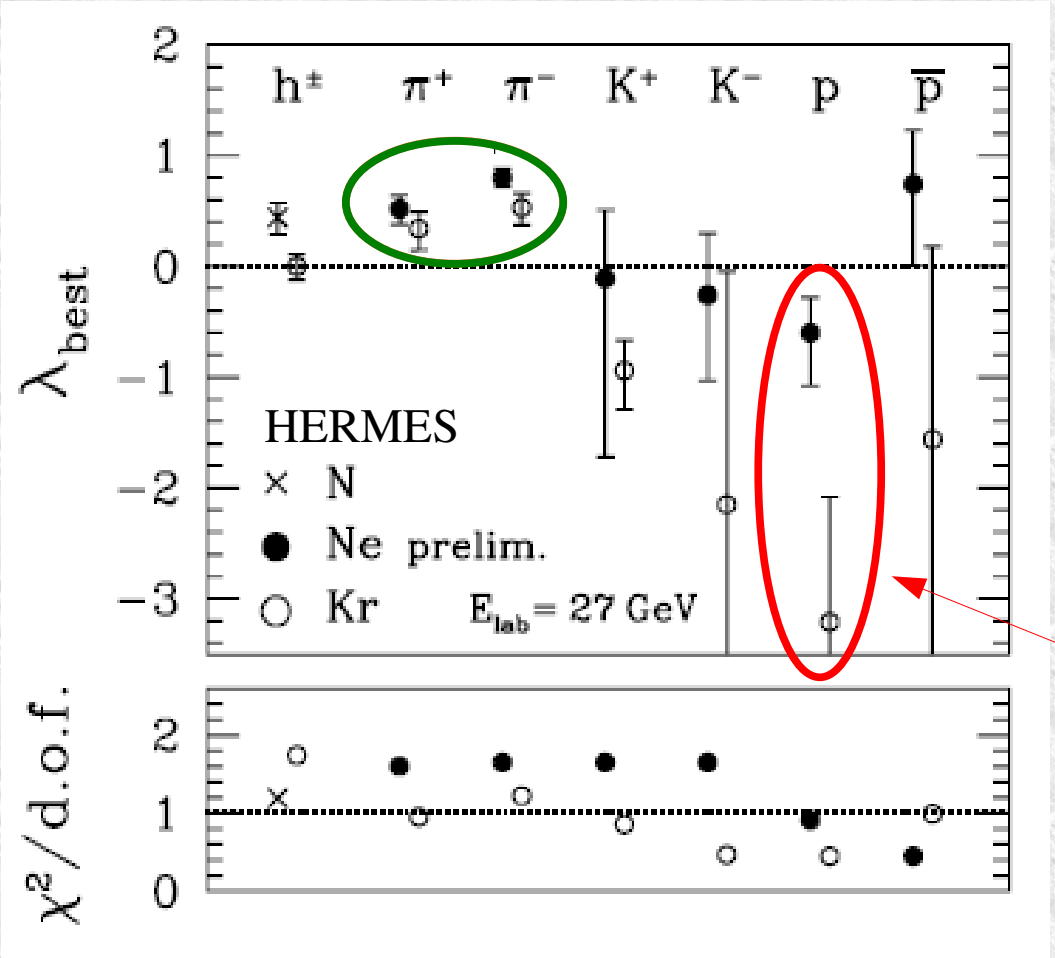
HERMES E_{lab}=27 GeV - Phys.Lett.B577(03)37

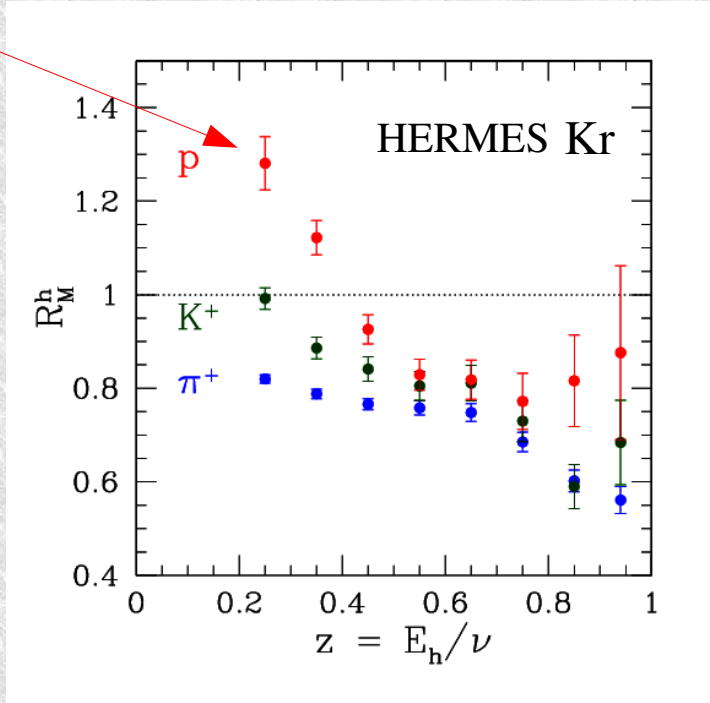




- **proton anomaly!** ...but anti-protons are normal...
- analogous to "baryon/meson anomaly" in p+p, p+A and A+A
  - what do they have in common, if anything?
  - What about "Higher-Twist" baryon production ?

Results – E_{lab} = 27 GeV





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

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:

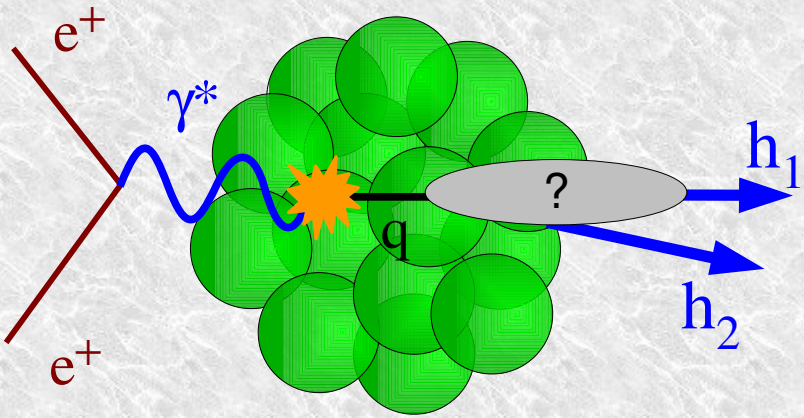
model		$Q^{-2}\Delta\langle p_T^2\rangle_{x_B}$ vs. Q^2	$x_B\Delta\langle p_T^2\rangle_{Q^2}$ vs. x_B
$t_p \propto \nu/\kappa$	LO	$\leftrightarrow$	$\leftrightarrow$
	mDGLAP (1)	$\uparrow$	$\leftrightarrow$
	NLO vs. LO (2)	$\leftrightarrow$	$\uparrow$
	colored h_c^* (3)	$\uparrow$	$\leftrightarrow$
$t_p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

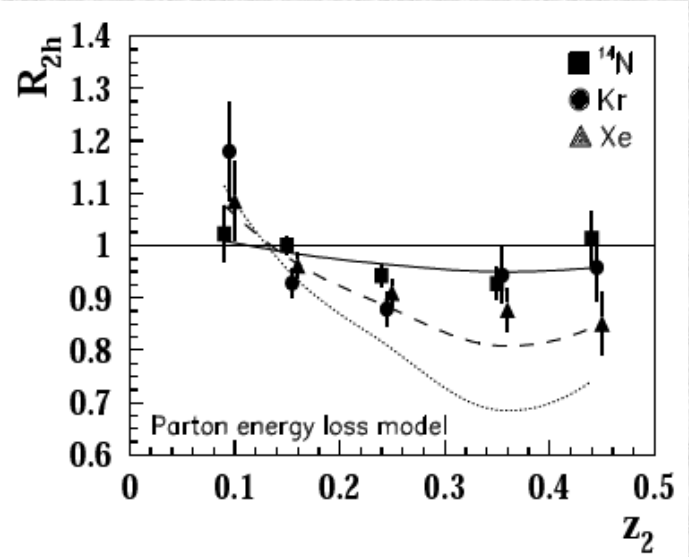
Two-particle correlations at HERMES

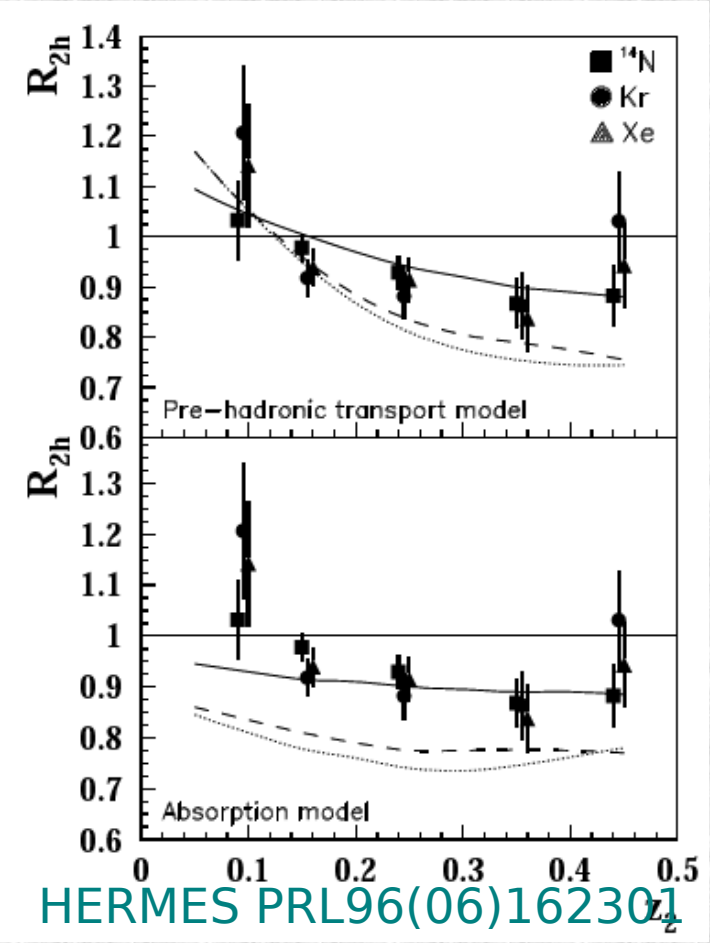
- **Double hadron attenuation** R_2
- in A+A = "same-side correlations", (akin to jet yield on top of ridge)

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

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



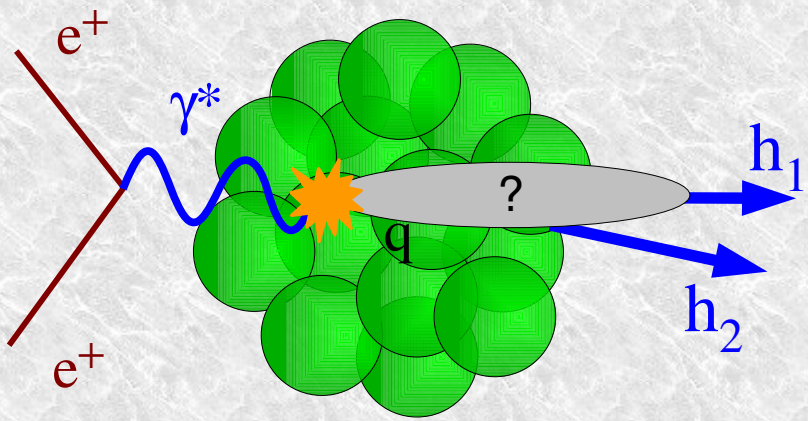




HERMES PRL96(06)162301

Two-particle correlations at HERMES

- Small A-depence: surface bias?

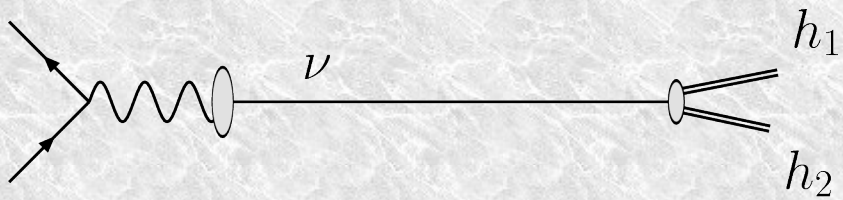


$$R_2(z_2) = \frac{\left.\frac{N_2(z_2)}{N_1}\right|_A}{\left.\frac{N_2(z_2)}{N_1}\right|_D}$$

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

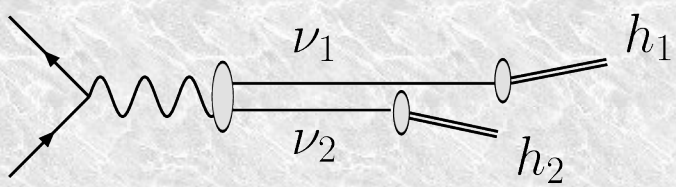
- E.g., NLO hard scattering

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"

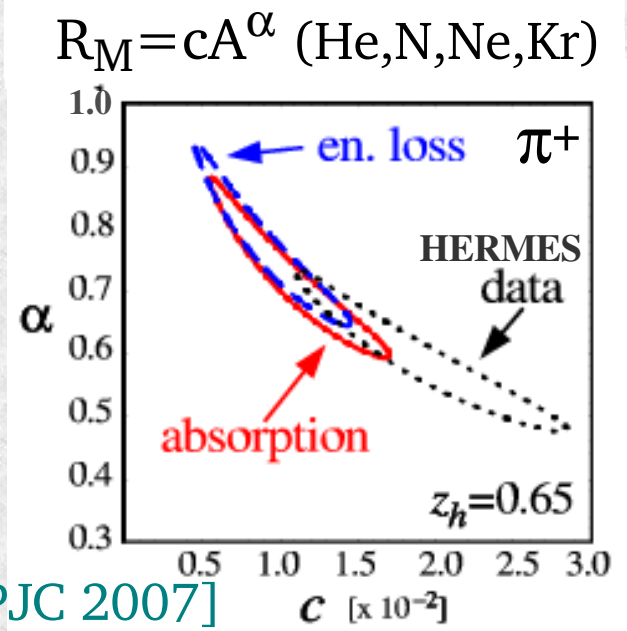
- Old thinking: the $A^{2/3}$ law
  - Energy loss (LPM effect in QCD): $1-R_M \sim \langle\Delta z\rangle \sim L^2 \sim A^{2/3}$
  - Hadron absorption: $1-R_M \sim \langle \text{no. of nucleons seen} \rangle \sim L \sim A^{1/3}$

WRONG!

- $A^{2/3}$ also for absorption models!
  [A.A., et al., NPA 761(2005)67]
  - additional dimensionful scale: prehadron production length $\langle t_p \rangle$
  - neutralize it ⇒ additional power of A

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

  - typically $A^{2/3}$!!

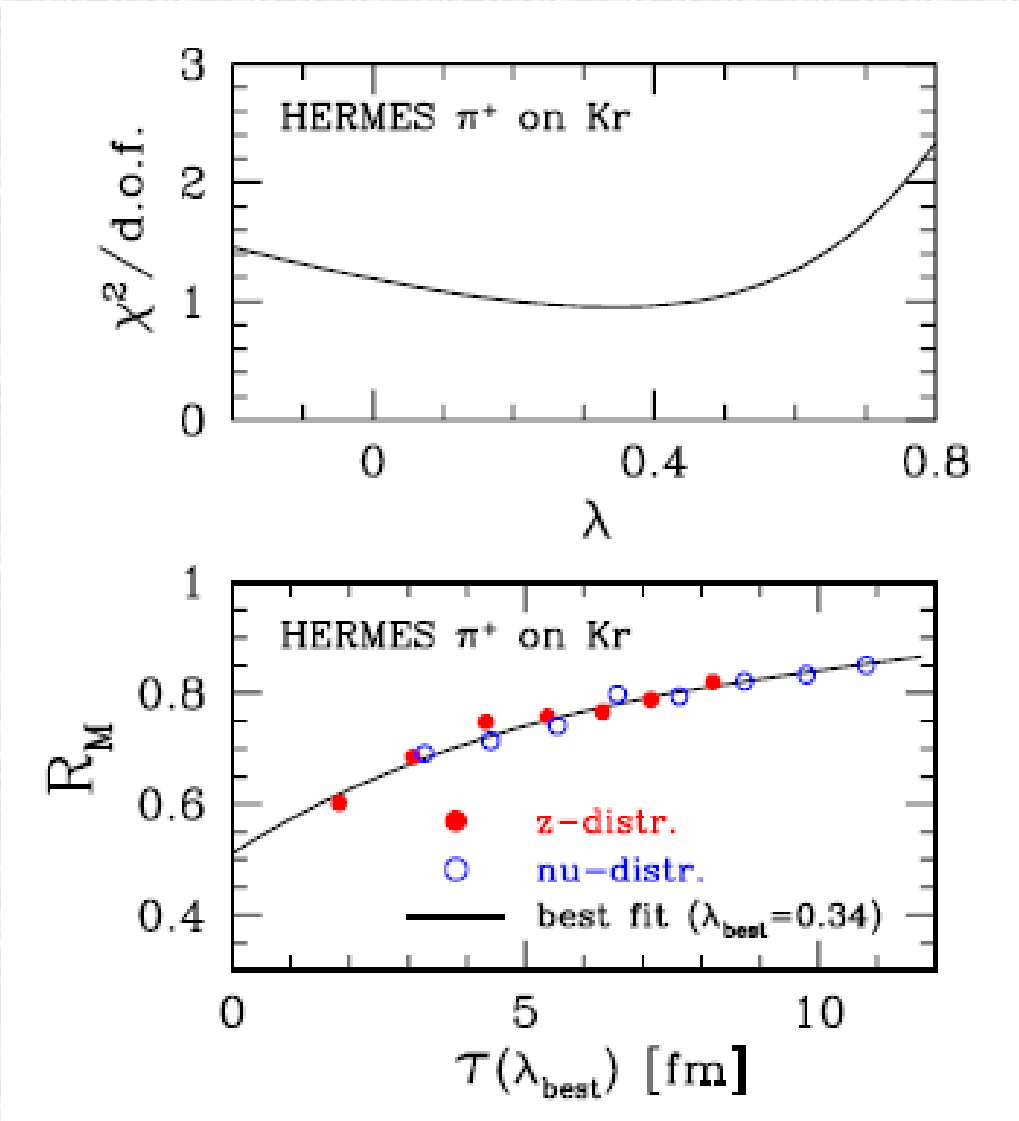


[A.A.,EPJC 2007]

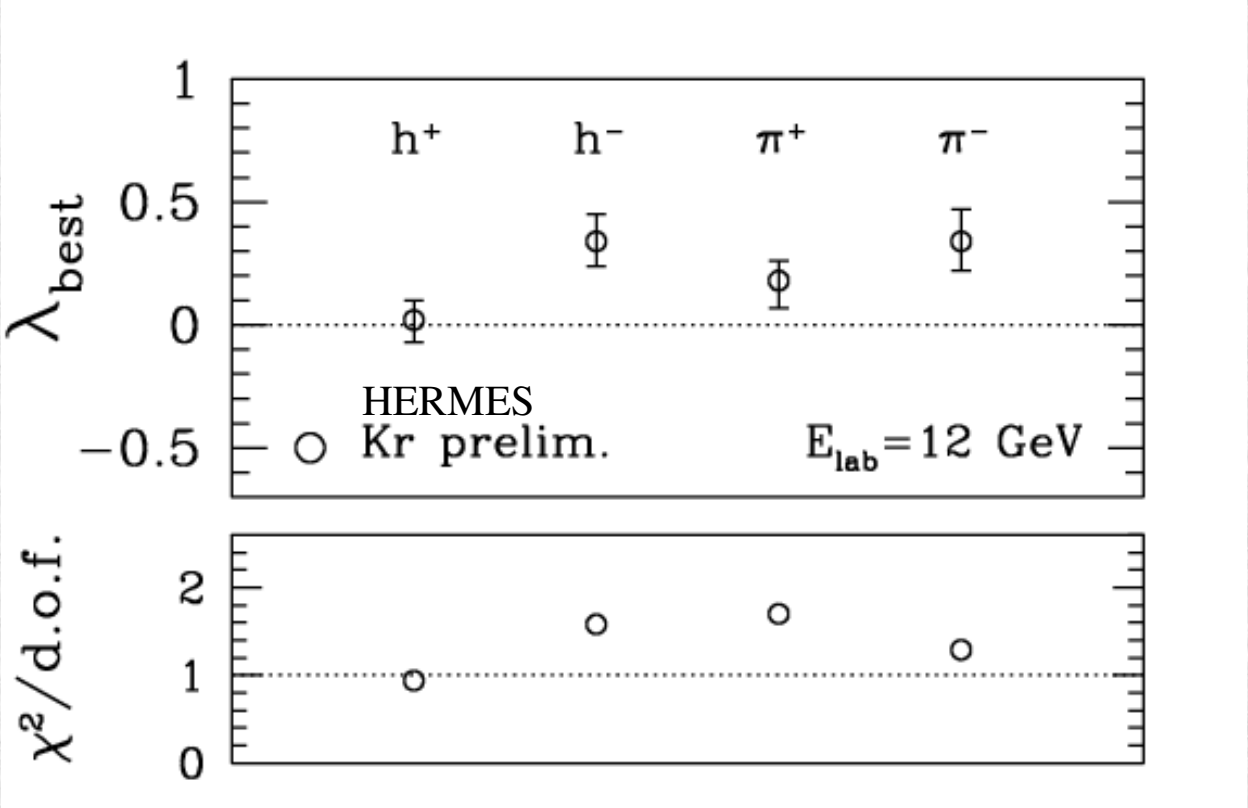
A-dependence of R_M does not test dominance of partonic or prehadronic physics: no info on parton lifetime

2) Scaling 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!