# Nuclear suppression of hadron yields: formation time and energy loss at HERMES

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**Part I - Nuclear absorption model** A.A, Muccifora, Pirner

**Part II - The model at work: understanding HERMES data**

- Flavour dependent formation length: $\pi$ and K
- The power of $Q^2$: absorption vs. energy-loss
- Effective $\kappa$ vs. reduced prehadron cross section

**Part III - How to learn more?**

- $K^-/K^+$ ratio
- A-dependence

**Conclusions**

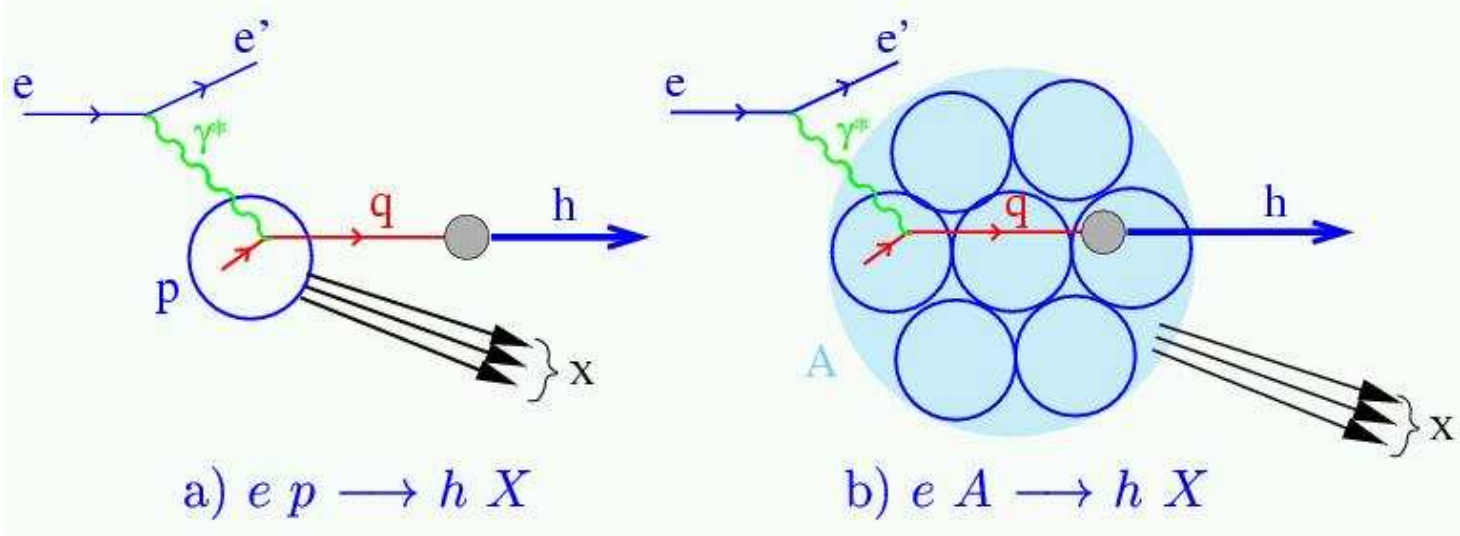
# Part I

# Nuclear absorption model

A.A, Muccifora, Pirner

NPA 720(2003)131 + work in progress

# pQCD description of DIS




$$\frac{1}{N_A^{DIS}}\frac{dN_A^h}{dz} = \frac{1}{\sigma^{\gamma^* A}}\int_{\text{exp. cuts}} dx\, d\nu \sum_f e_f^2\, q_f(x, \quad Q^2)\, \frac{d\sigma^{\gamma^* q}}{dx\, d\nu}\, D_f^h(z, \quad Q^2)$$

PDF pQCD x-sec FF

No nuclear effects, then:

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

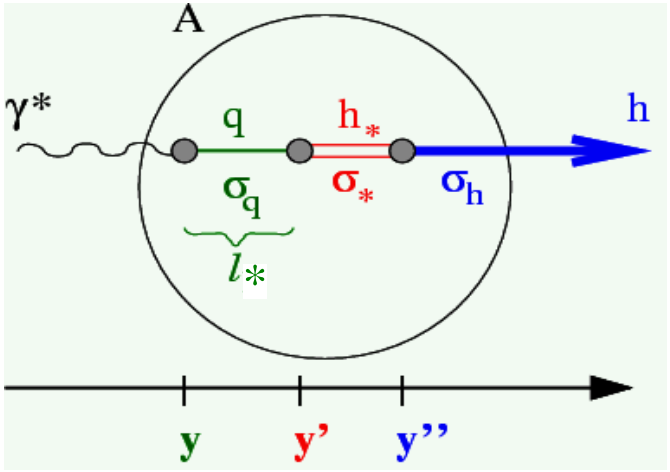
with $\boxed{R_M^h(z) = 1}$.

But experimentally:

$$R_M^h(z) \neq 1 \Longrightarrow \text{NUCLEAR EFFECTS}$$

- Hadron FSI (absorption, decay, ...)
- partial deconfinement in A
- struck quark energy loss

# Nuclear absorption & hadron formation length




Nucl. abs. factor = probability of exiting from the nucleus (Bialas-Chmaj '83)

$$\mathcal{N}_A = \int d^2b \int_{-\infty}^{\infty} dy\, \rho_A(b,y) \left[S_A(b,y)\right]^{A-1}$$

**(pre)hadron cross-section**

$$S_A(b,y) = 1 - \sigma_* \int_y^{\infty} dy'\, P_*(y'-y)\rho_A(b,y') - \sigma_h \int_y^{\infty} dy'\, P_h(y'-y)\rho_A(b,y')$$

prob. of formation at y'-y from interaction point:

$$P_*(y'-y) = \frac{\langle l_h \rangle}{\langle l_* \rangle - \langle l_h \rangle}\left(e^{-(y'-y)/\langle l_* \rangle} - e^{-(y'-y)/\langle l_h \rangle}\right)$$

$$P_h(y'-y) = 1 - e^{-(y'-y)/\langle l_* \rangle} - P_*(y'-y)$$

**average (pre)hadron form. length**

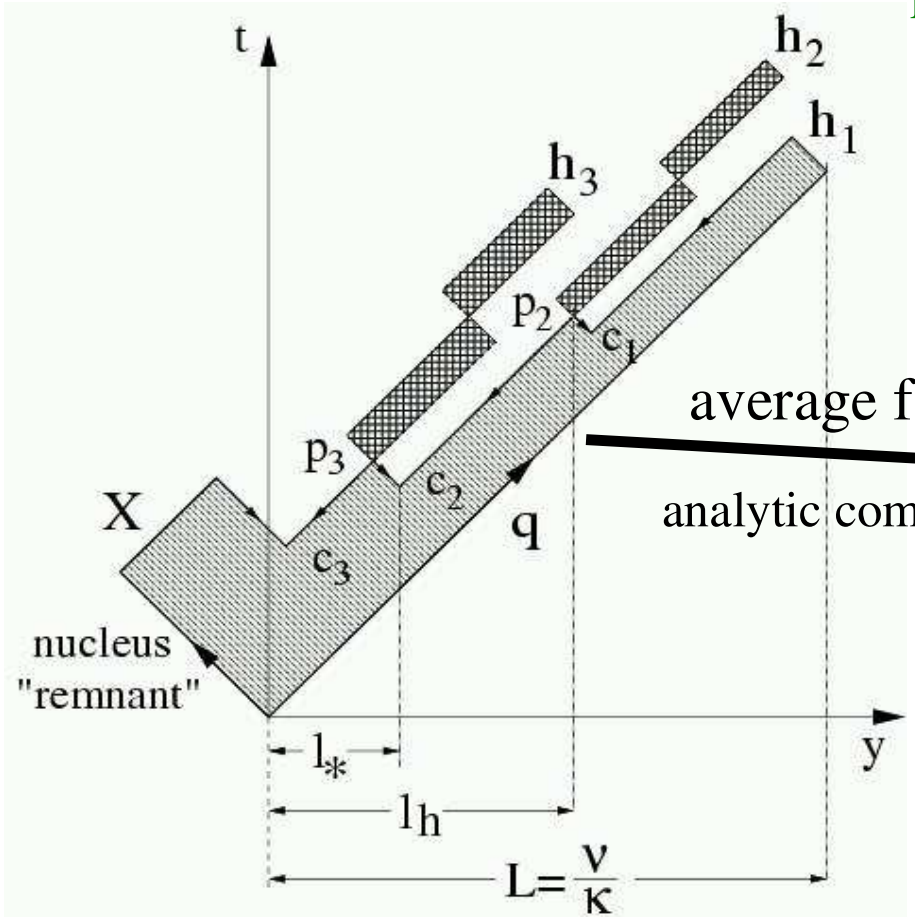
$$D_f^h(z,Q^2) \longrightarrow D_{f|A}^h(z,\nu,Q^2) = D_f^h(z,Q^2)\, \mathcal{N}_A^h(z,\nu)_{\kappa,\sigma_*,\sigma_h}$$

# LUND string model & formation lengths

Lorentz dilatation of rest-frame form. time:

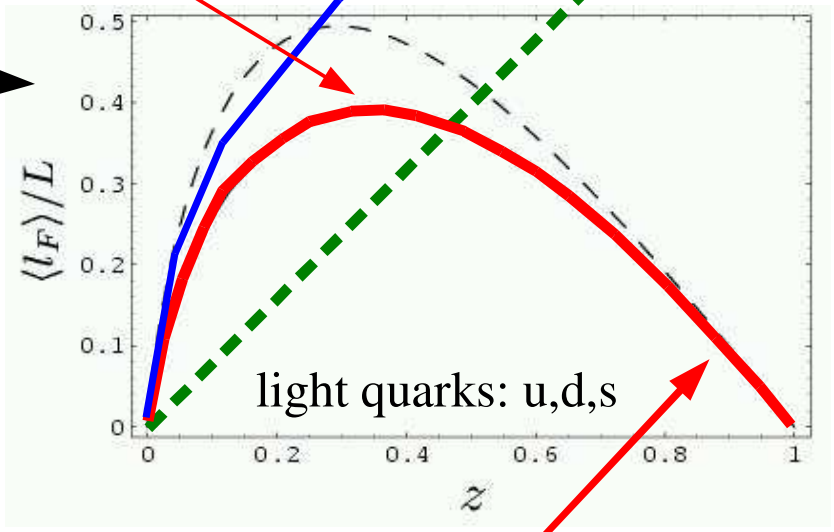
$$\tau_F = \frac{z_h \nu}{\underbrace{m_h}_{\gamma}} \tau_0 \propto z_h \nu$$

$\langle l_* \rangle = \langle l_h \rangle - z\,\nu/\kappa$




average for **n≥1**

analytic computation

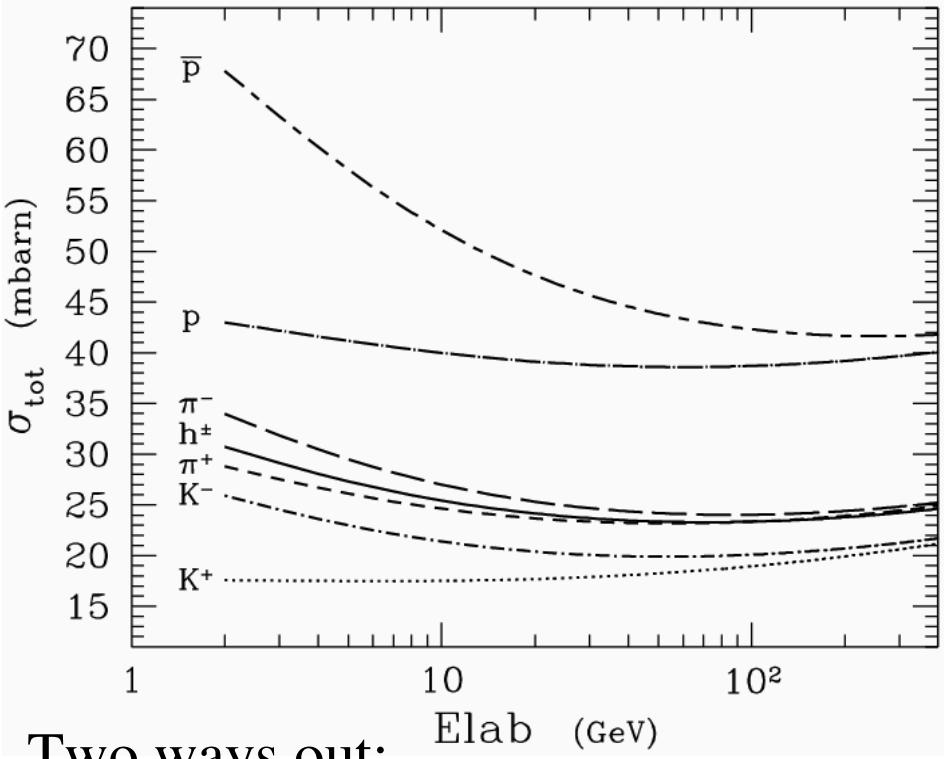



$$\propto (1 - z_h)\frac{\nu}{\kappa}$$

Note: In the HERMES kinematics prehadron absorption dominates (hadron absorption negligible)

see also
Kopeliovich et al. '96 + talk
HERMES coll. '01

# Hadron-nucleon cross-sections




- Hadron x-sec known,
  BUT prehadron x-sec unknown
- Most naive choice:

$$\begin{cases} \sigma_* = \sigma_h \\ \kappa = 1 \text{ GeV/fm} \end{cases}$$

$\Longrightarrow$ hadron suppression overestimated by far!

EMC, ZPC52(91)1; A.A.,Pirner '02;
N.Pavel Ph.D. thesis

Two ways out:

1) Use a phenomenologically reduced string tension, hence longer form. times
**(A.A. et al., NPA 720(2003)131)**

$$\begin{cases} \sigma_* = \sigma_h \\ \kappa_{\text{eff}} = 0.4 \text{ GeV/fm} < \kappa \end{cases}$$

2) The prehadron cross-section is smaller than the hadronic one

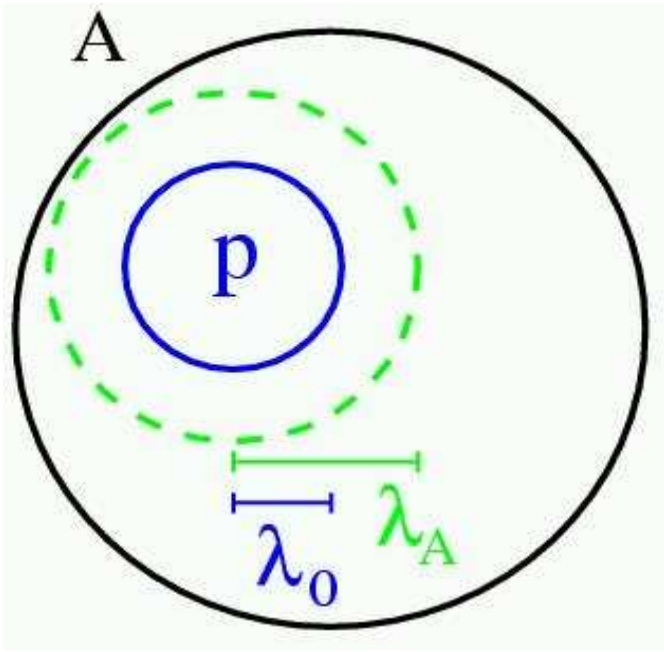
$$\begin{cases} \sigma_* \simeq 0.35\, \sigma_h \\ \kappa = 1 \text{ GeV/fm} \end{cases}$$

# Partial deconfinement & rescaling of FF's

Assume a change of confinement scale in A:

$$\lambda_A > \lambda_0$$

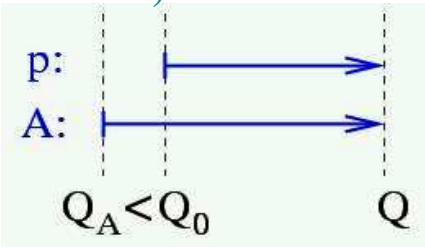
We have two consequences




**1)** Rescaling of PDF's and FF's:

(Jaffe et al. '84-'85, Dias de Deus '87)

$$Q_A \lambda_A = Q_0 \lambda_0$$




($Q_0$ = start of DGLAP evolution)

$$q_f^A(x,Q) = q_f(x, \xi_A(Q)Q)$$
$$D_f^{h|A}(z,Q) = D_f^h(x, \xi_A(Q)Q)$$

Longer DGLAP evolution
--> increased gluon shower

**2)** Rescaling of string tension:

$$\kappa_A \lambda_A^2 = \kappa \lambda_0^2$$

Partial deconfinement
--> looser colour flux tube
--> smaller string tension

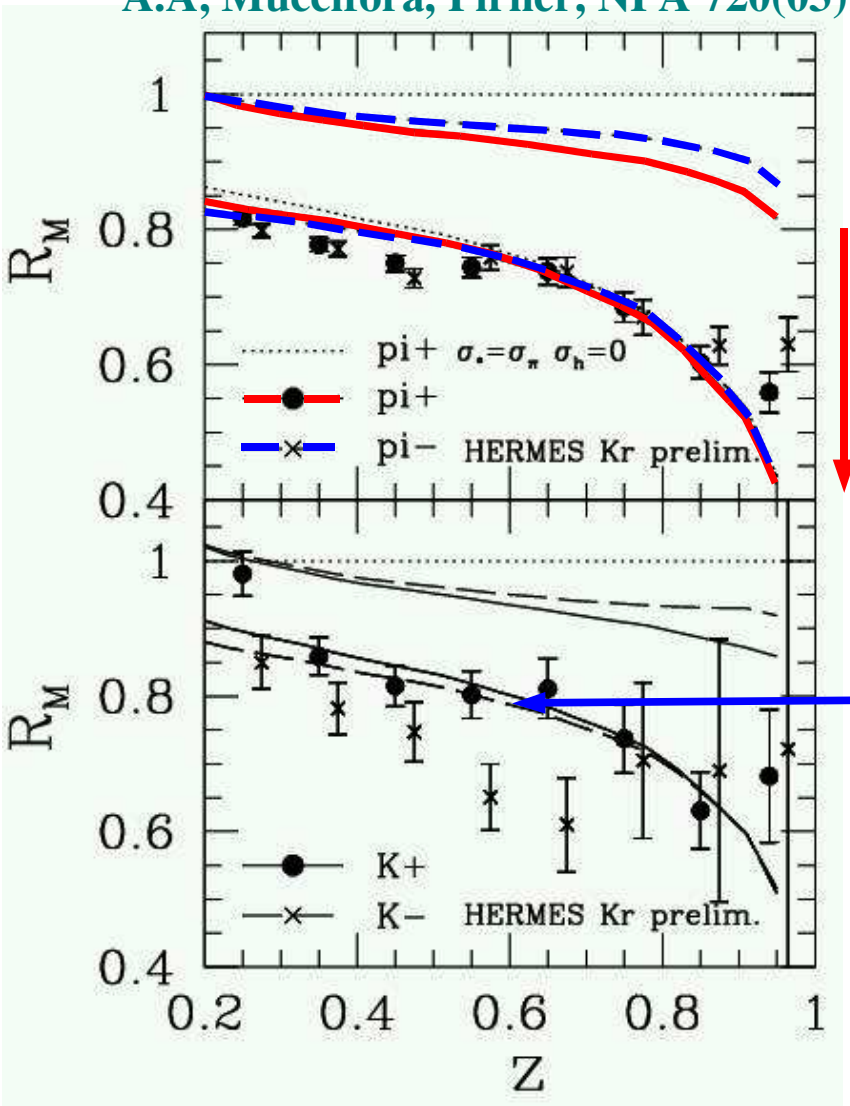
# Part II

# The model at work: understanding HERMES data

# $K^-$ vs. $K^+$: flavour-dependent formation length

In the absorption model so far:

A.A, Muccifora, Pirner, NPA 720(03)131




Ingredients

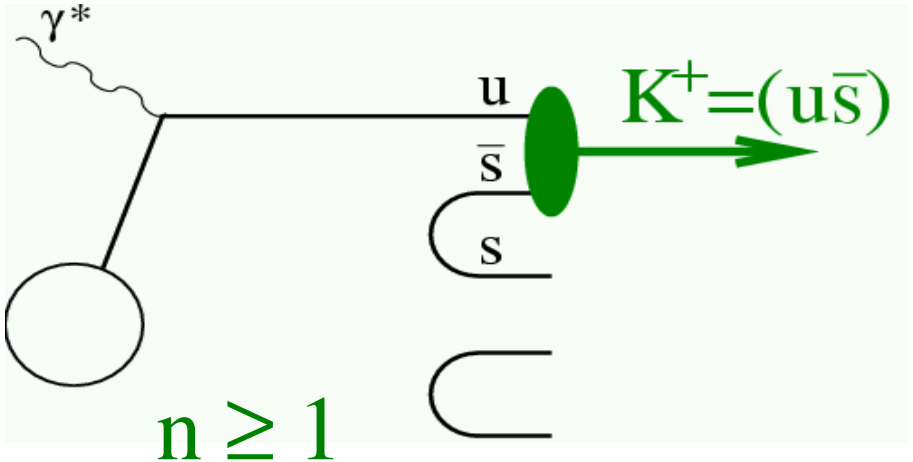
- two-step hadronization
- $\sigma_q = 0 \qquad \sigma_* = \sigma_h$
- $\kappa_{eff} = 0.4\ \kappa$ fitted to pions
- $\tau_F = f(z,\nu)(1-z_h)\,z\,\dfrac{\nu}{\kappa}$
- rescaling

**$K^-$ overestimated:**
**=> shorter form. time!**

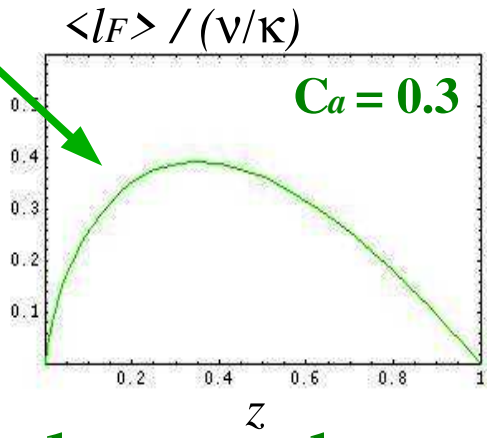
(or $\sigma_* > \sigma_h$ for $K^-$ only?
Unnatural...)

# Valence- and sea-channel hadronization

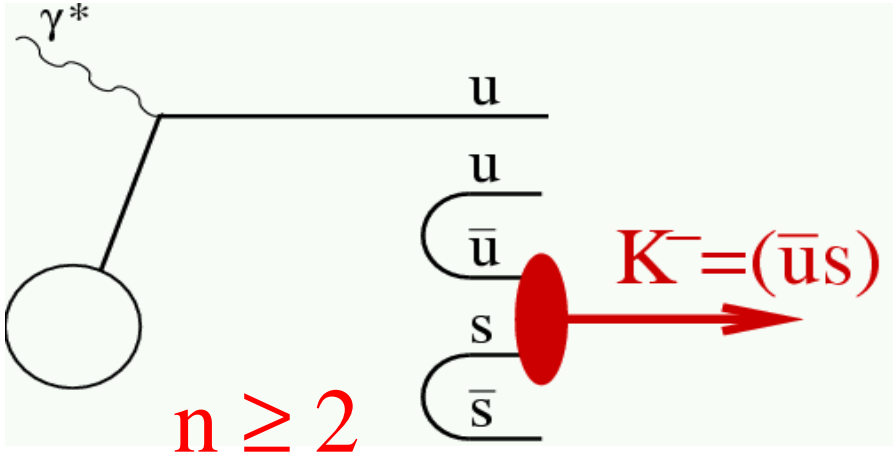
At HERMES, valence quarks give leading contribution to DIS and SIDIS.
Then, e.g., to produce a kaon from an up quark, we have:



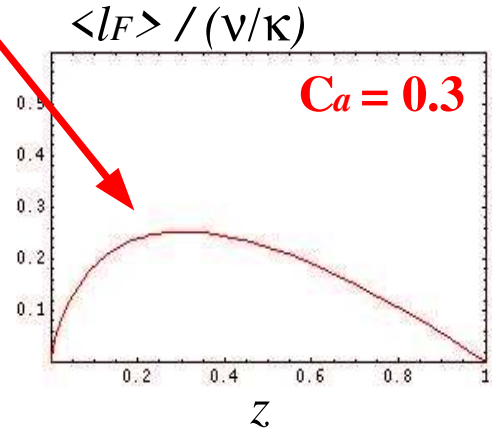

n ≥ 1




"valence-channel"



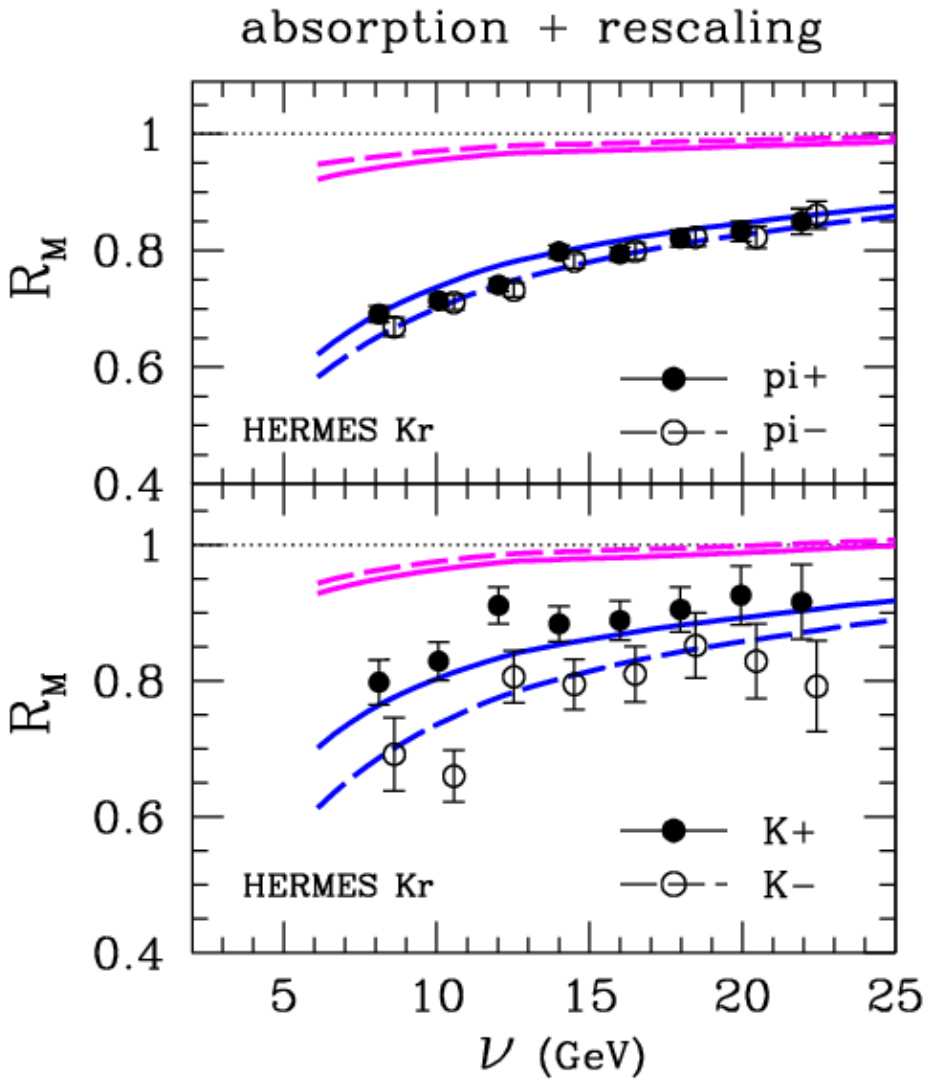

n ≥ 2

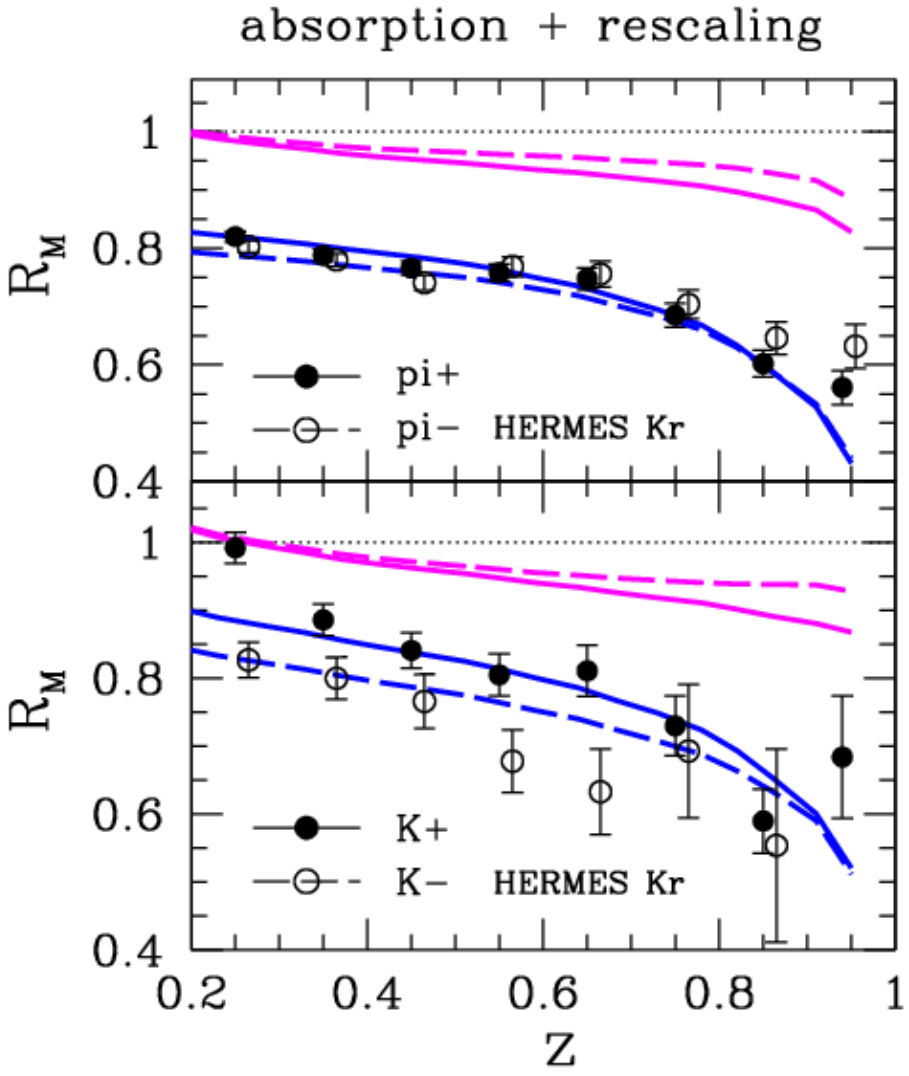



"sea-channel"

For down quarks (subdominant), both $K^+$ and $K^-$ produced at n ≥ 2

$$\begin{cases} \sigma_* = \sigma_h \\ \kappa_{\text{eff}} = 0.4\ \text{GeV/fm} < \kappa \end{cases}$$




Valence- and sea-channel hadronization in the Lund model can describe also the $K^-$

# The power of $Q^2$: energy loss vs. absorption

**NB:** experimental $\langle\nu\rangle$ ~ constant

**Absorption:**

- describes plateau at $Q^2 > 4$ GeV$^2$
- misses growth at $Q^2 < 4$ GeV$^2$
- Rescaling unfavoured by Ne data

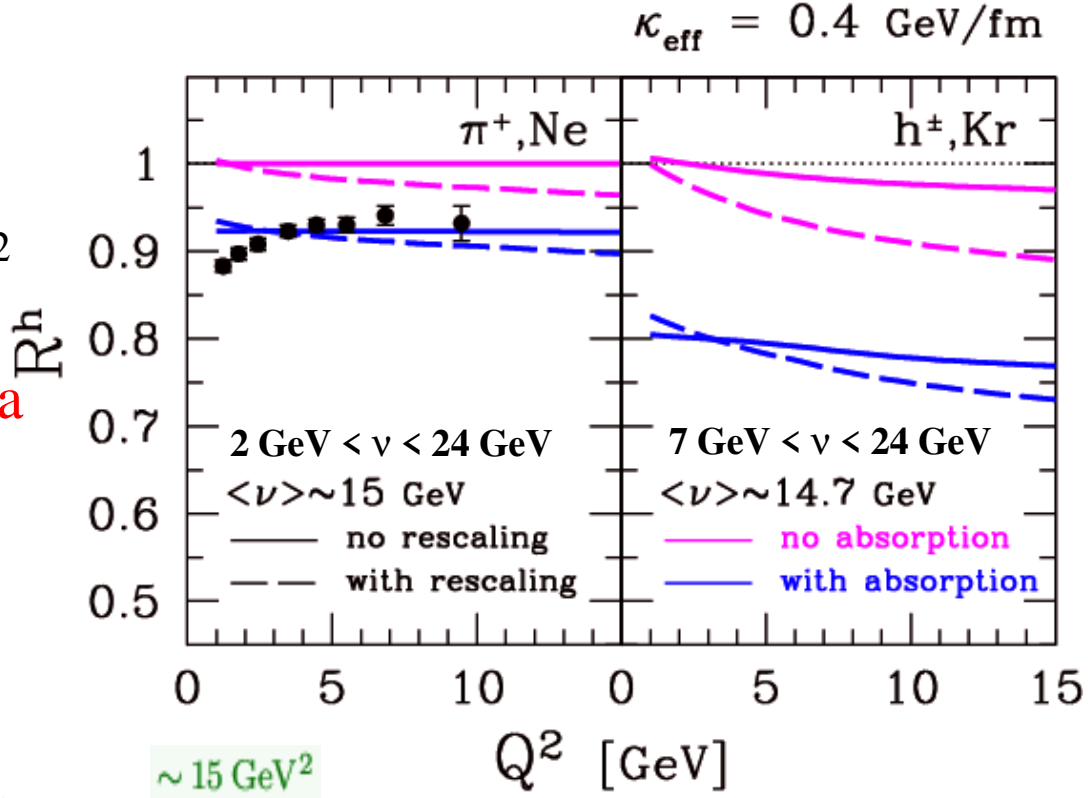
**Arleo's energy loss:**

- depends on $\langle\nu\rangle$ ~ const

  ⇒ mild dependence on $Q^2$

**Wang's energy loss:**

- depends on $1/Q^2$ ⇒ rising distrib.




$$\langle \Delta z \rangle_{|\,\text{Wang}} \propto \alpha_s^2(Q^2)\,\tilde{C}(Q^2)\;\underbrace{\frac{1}{\langle\nu\rangle}}_{\sim 15\,\text{GeV}}\;\ln\left(\frac{\overbrace{m_N\langle\nu\rangle}^{\sim 15\,\text{GeV}^2}}{Q^2}\right) \xrightarrow[Q^2 \to 15\,\text{GeV}^2]{} 0$$

However, this "mean field" argument fails at Q2~15 GeV2:

- fluctuations in $\langle\nu\rangle$ become important
- Higher-twist phase space not included

**$Q^2$-distribution has discriminatory power**

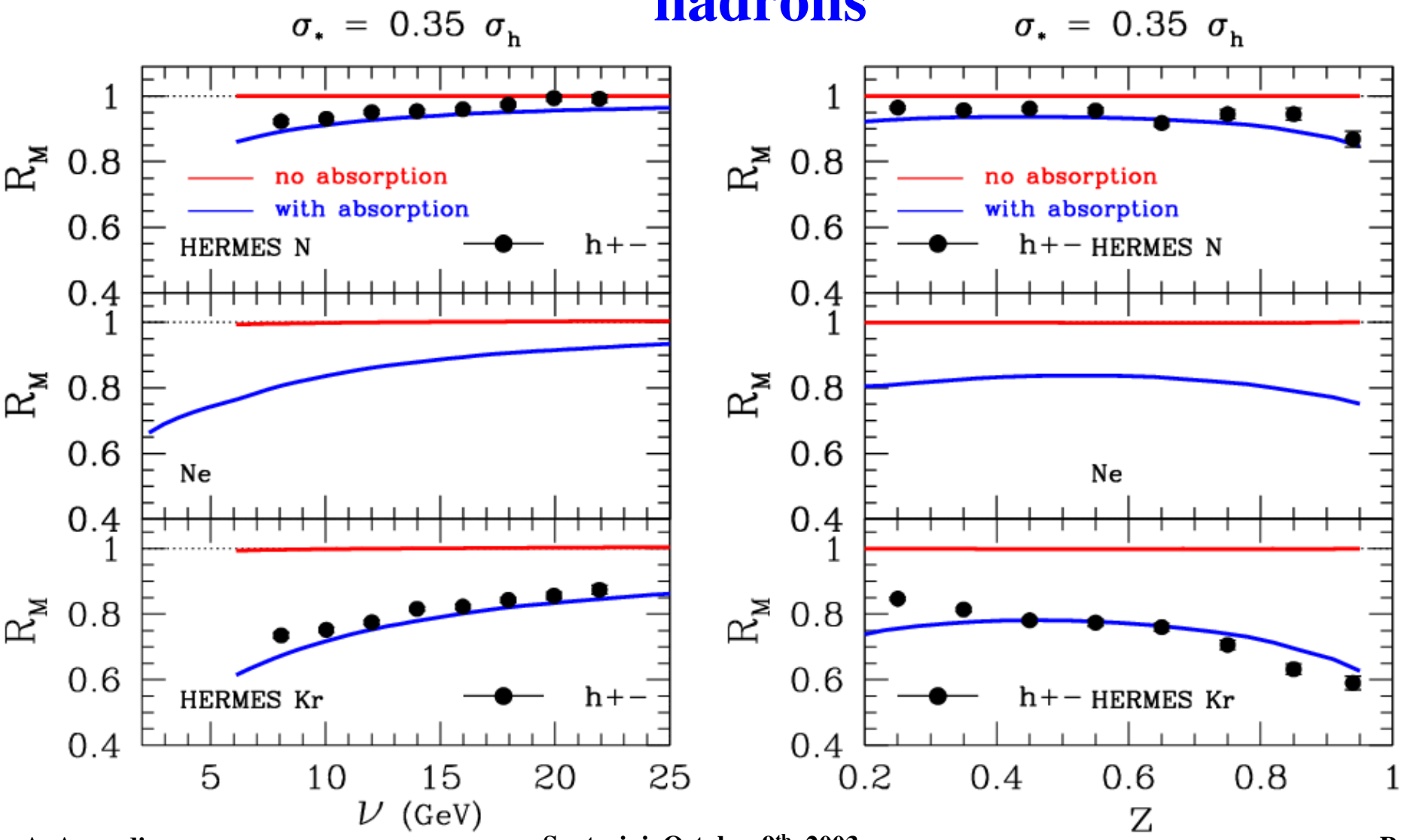
**Another effect needed at small $Q^2$: energy loss?**

# Effective κ vs. smaller prehadron cross-section

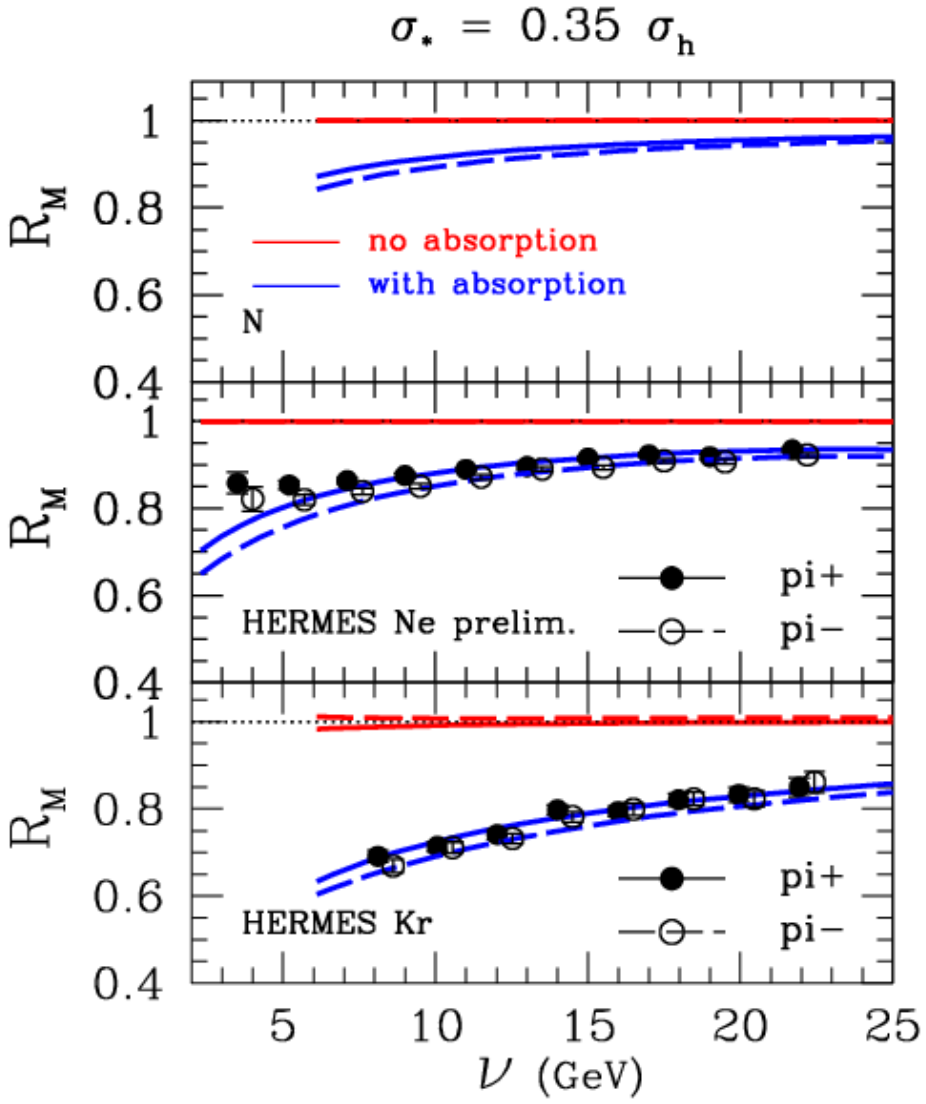
- Switch off rescaling, and
- assume a prehadronic $\sigma_* = 0.35\ \sigma_h$ (instead of $\kappa_{eff}$=0.4 κ: too big a nuclear effect)

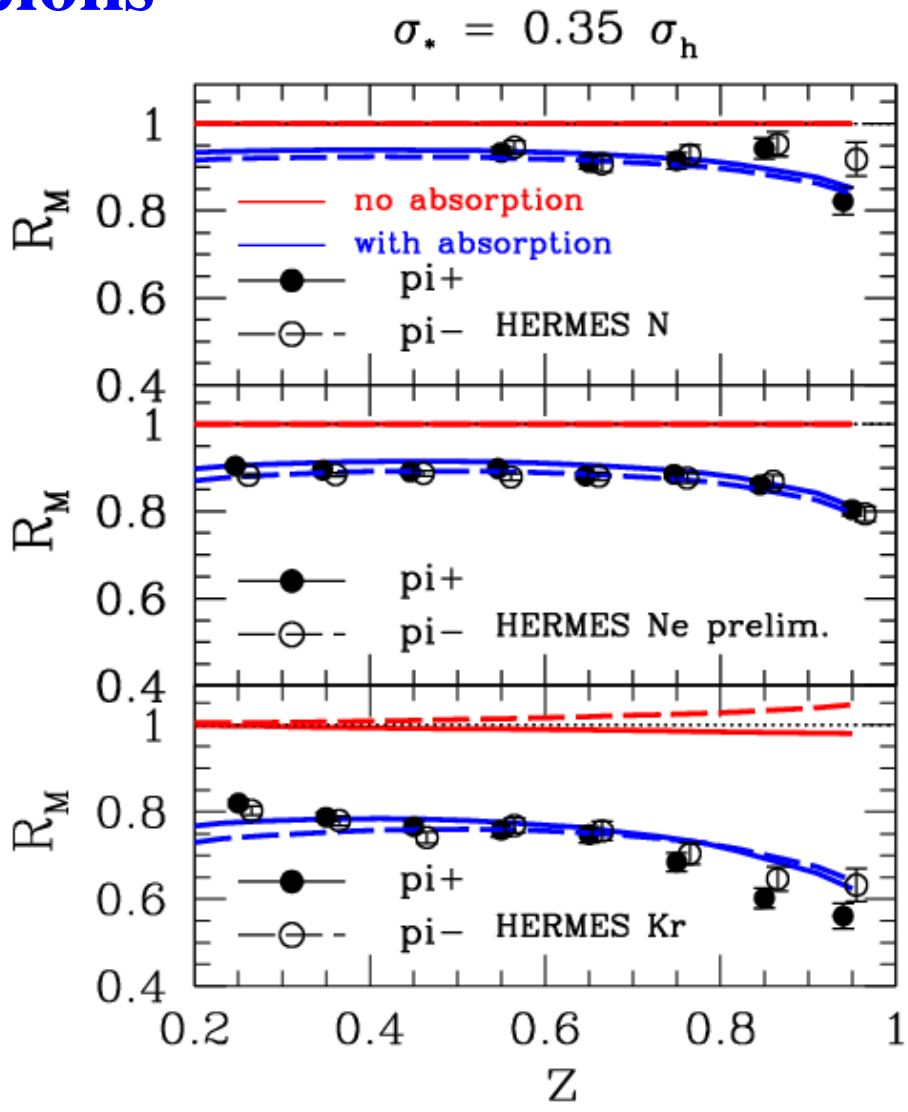
similar to Falter's $\sigma_*$

**hadrons**

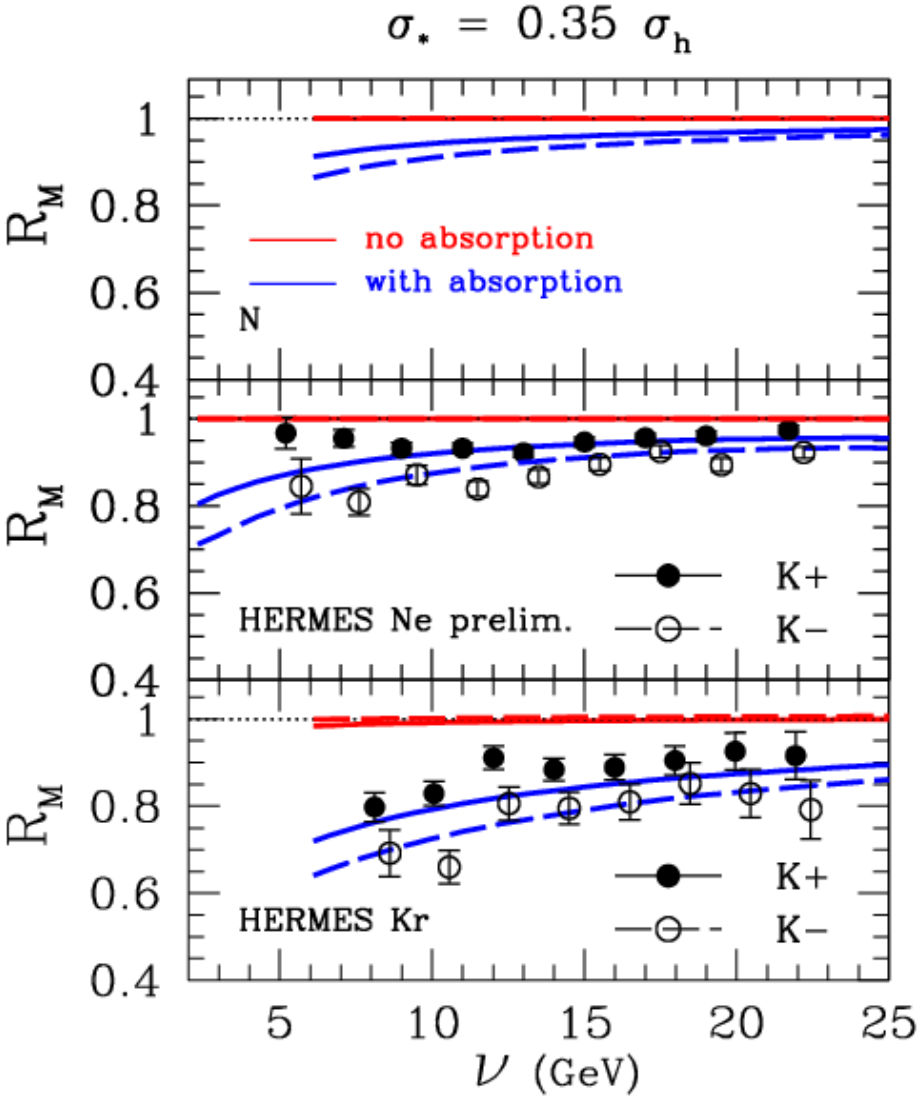


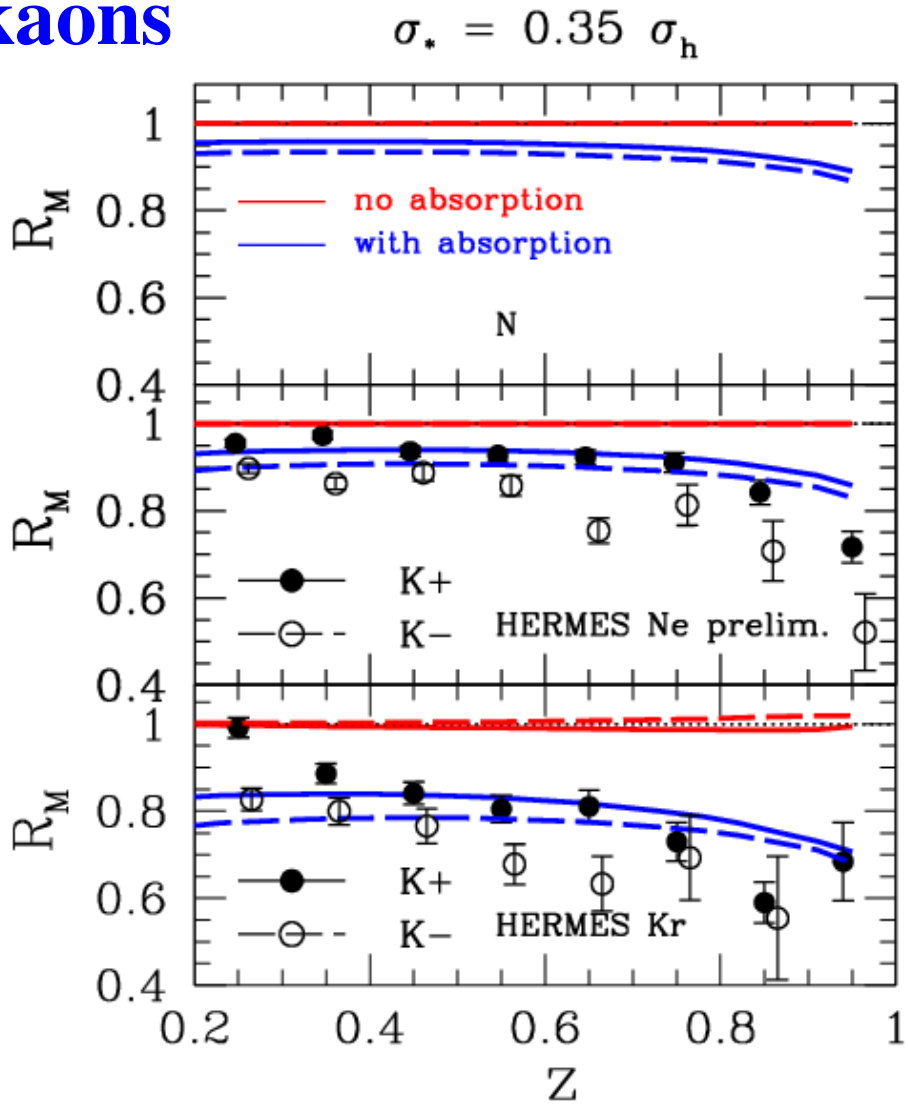
# pions


$\sigma_* = 0.35\ \sigma_h$
$R_M$
no absorption
with absorption
N
HERMES Ne prelim.
HERMES Kr
pi+
pi−
$\nu$ (GeV)


$\sigma_* = 0.35\ \sigma_h$
$R_M$
no absorption
with absorption
pi+
pi−
HERMES N
HERMES Ne prelim.
HERMES Kr
Z

# kaons




A smaller $\sigma_* = 0.35\ \sigma_h$ is as good as $\kappa_{eff} = 0.4\ \kappa$,
($\sigma_*=0.35\sigma_h$ compatible with $0.33\sigma_h$ by Falter et al.)

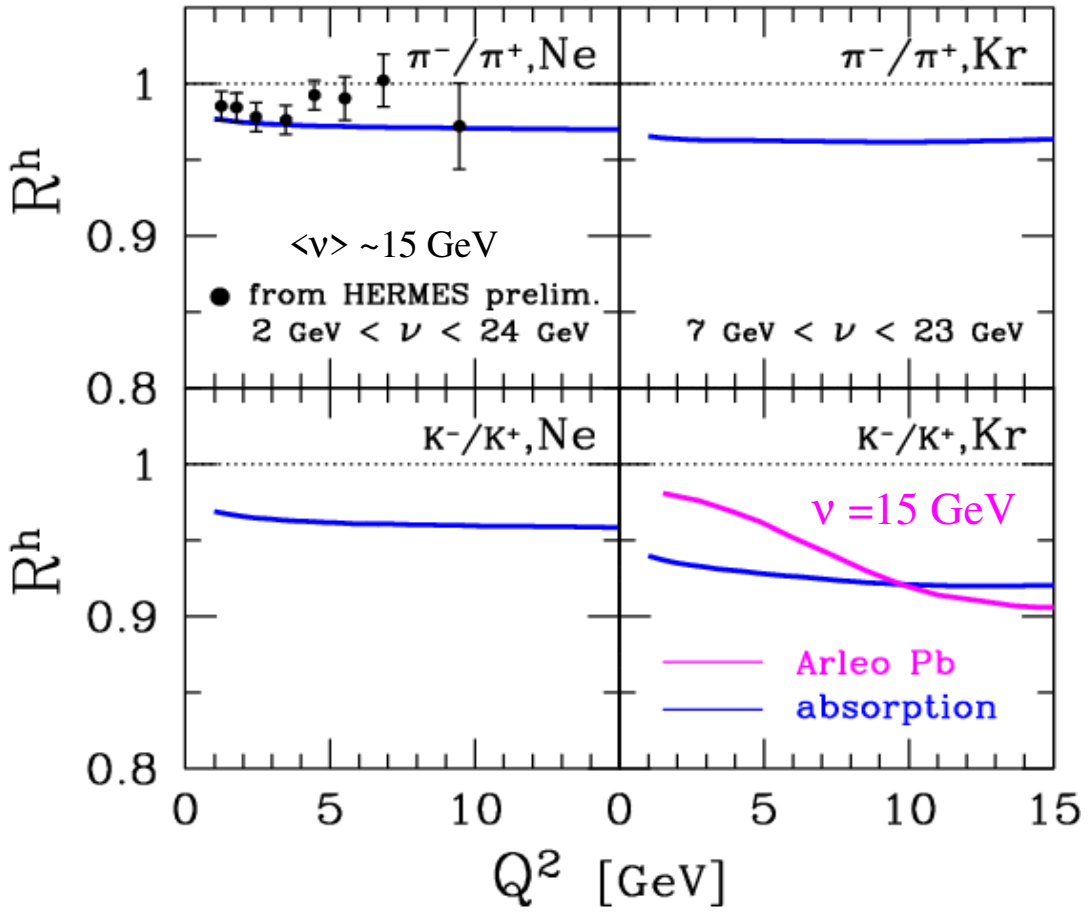
Good agreement on N, Ne, Kr also without rescaling

# Part III

# How to learn more?

# $K^-/K^+$ ratio & the isospin effect

(from an idea by F.Arleo - hep-ph/0309108 )




- **$\pi^-/\pi^+$ on Ne**:
  - absorption in the ballpark
  - little chance for abs vs. en.loss

  Note HERMES data accuracy!
  but... I'd like data at $Q^2$~15 $GeV^2$!
- **$K^-/K^+$ on Kr:**
  - effect is amplified
  - good chance for "model killing"
- Expect Wang's en.loss curve to grow with $Q^2$

**K-/K+ sensitive to dynamics underlying isospin effect**

**Kr has good chances to distinguish energy loss and nuclear absorption effects**

# A dependence

**Naive argument:**

$$\langle \Delta z \rangle_{|\,\text{en.loss}} \propto A^{2/3} \quad \text{(LPM effect)}$$

$$\text{absorption} \propto L \propto A^{1/3}$$

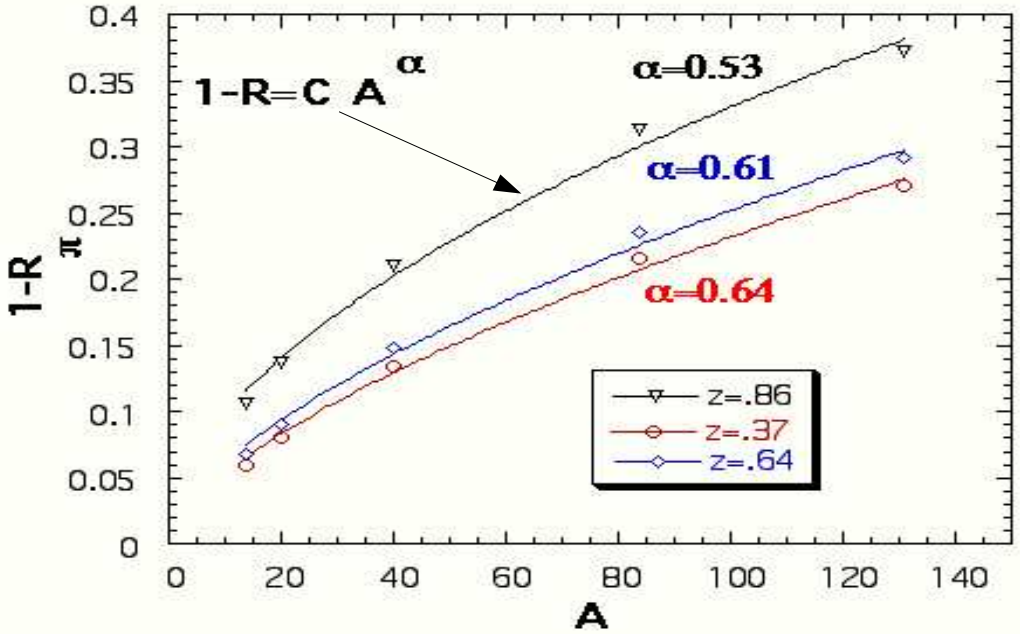
**But:**

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

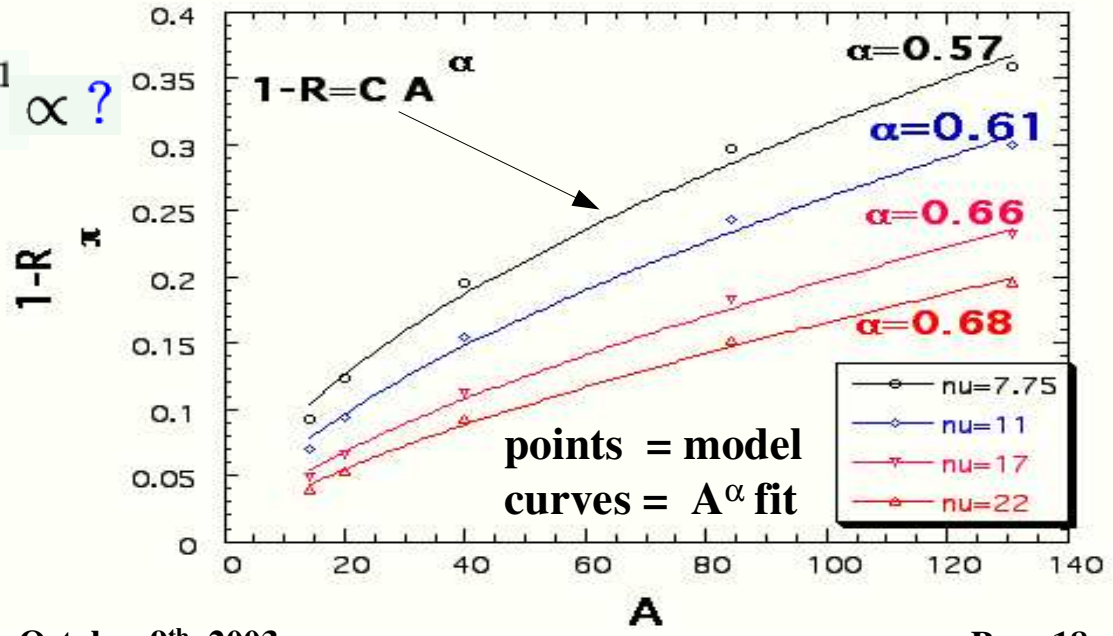
$$\mathcal{N}_A \sim 1 - \int d^2b\,dy\,\rho_A(b,y) \times \left[1-\sigma_*(1-e^{c A^{1/3}/\langle l_F\rangle - 1})\right]^{A-1} \propto ?$$

**absorption model's**
**$\alpha$ = 0.5-0.7**
**close to $\alpha$ = 2/3 !!**

**Absorption model** ($\pi^+$ at fixed $z$)




($\pi^+$ at fixed $\nu$)



# Conclusions

- HERMES data have good precision for detailed study
- Absorption model with flavour-dependent formation length
  + "weak" prehadron cross-section
  is rather good for N, Ne and Kr data
- Need of additional mechanism at small-$Q^2$
  (energy loss? it goes in the right direction)
- A-dependence of absorption model close to $A^{2/3}$

# How to learn more?

- **$Q^2$ distributions** - quite powerful! $Q^2<15$ GeV would be nice.
- **$K^-/K^+$ ratio** - promises good sensitivity on model assumptions
- **A systematics** - A = 4-131 (He, N, Ne, Kr data available
  Ar & **Xe** possible at HERMES)
  Needs numerical predictions in en. loss models
- Lessons from heavy-ions: Cronin effect?
  Two-particle azimuthal correlations?

# Extra slides

# Summary of part I: the ingredients of the model

**1)** lepton-nucleon cross-section as in pQCD

**2)** Nuclear effects:

- finite formation time from the Lund model
- two-step hadronization (quark->prehadron->hadron)
- nuclear absorption: (pre)hadron re-interactions
- Flavour dependent formation length ("sea- and valence-channels")
- partial deconfinement in nuclei --> rescaling of FF's

**3)** One free parameter:

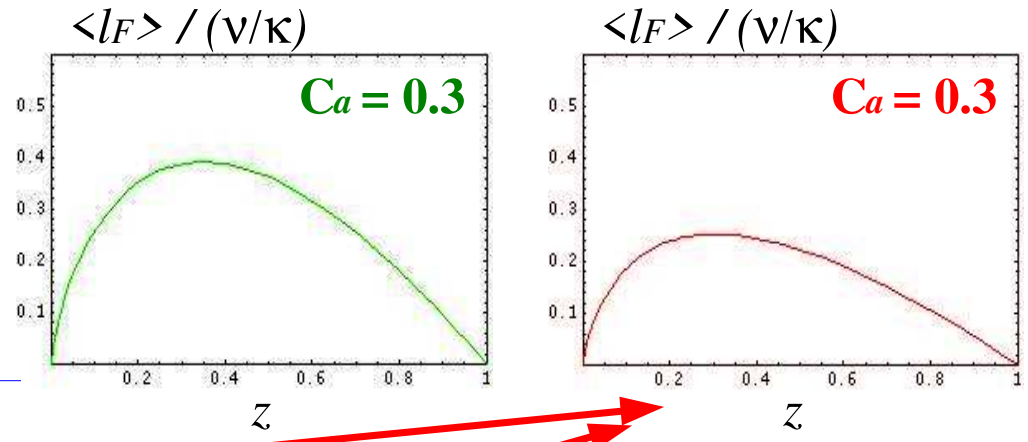
- either $\kappa_{eff} = 0.4\ \kappa$ and $\sigma_* = \sigma_h$
- or either $\kappa_{eff} = \kappa$ and $\sigma_* = 0.35\ \sigma_h$

**Missing:** quark reinteractions, → Wang&Wang, Arleo
feed-back from higher z and ν, resonance decays
target fragmentation → Falter et al.

In general, if the hadron has in its valence:

- an up or down quarks (dominant at HERMES)
- ==> it hadronizes domnantly at rank n ≥ 1 (valence-channel)
- otherwise, it hadronizes dominantly at rank n ≥ 2 (sea-channel)

| hadron | dominant channel |
|---|---|
| $\pi^+ = (u\bar{d})$ | valence |
| $\pi^- = (\bar{u}d)$ | valence |
| $\pi^0 = (u\bar{u} + d\bar{d})$ | valence |
| $K^+ = (u\bar{s})$ | valence |
| $K^- = (\bar{u}s)$ | sea |
| $K^0 = (d\bar{s})$ | valence |
| $\bar{K}^0 = (\bar{d}s)$ | sea |
| $p = (uud)$ | valence |
| $\bar{p} = (\bar{u}\bar{u}\bar{d})$ | sea |
| $n = (udd)$ | valence |




**Already observed experimentally:**

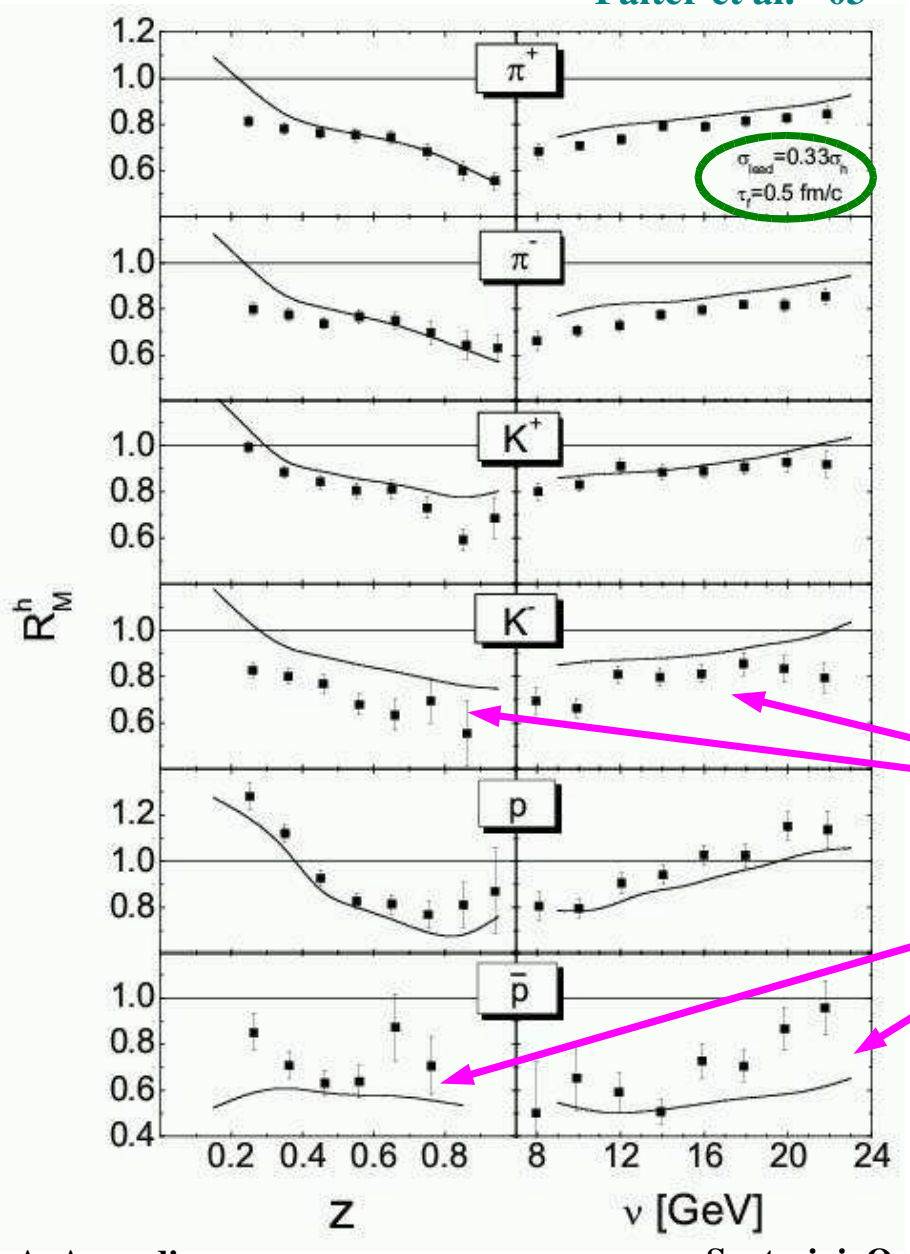
- $K^-$ more suppressed than $K^+$
- $\bar{p}$ more suppressed than p (but... target fragmentation at small-z)

Predictions:

- $\bar{K}^0$ similar to $K^0$ : shorter $< l_* >$ as $K^-$ vs. $K^+$, but compensated by larger cross section

# Other absorption models: formation times + FSI

Falter et al. '03




Falter et al., '03

- one-step hadronization + feed-back (reson. decay, elastic scatterings, ...)
- $\sigma_* < \sigma_h$
- $\tau_F$ from Lund for leading hadrons
- $\tau_F \propto \tau_0 z_h \nu$ for non-leading had's

free parameters

**pions & K+ rather good**

**K- overestimated**

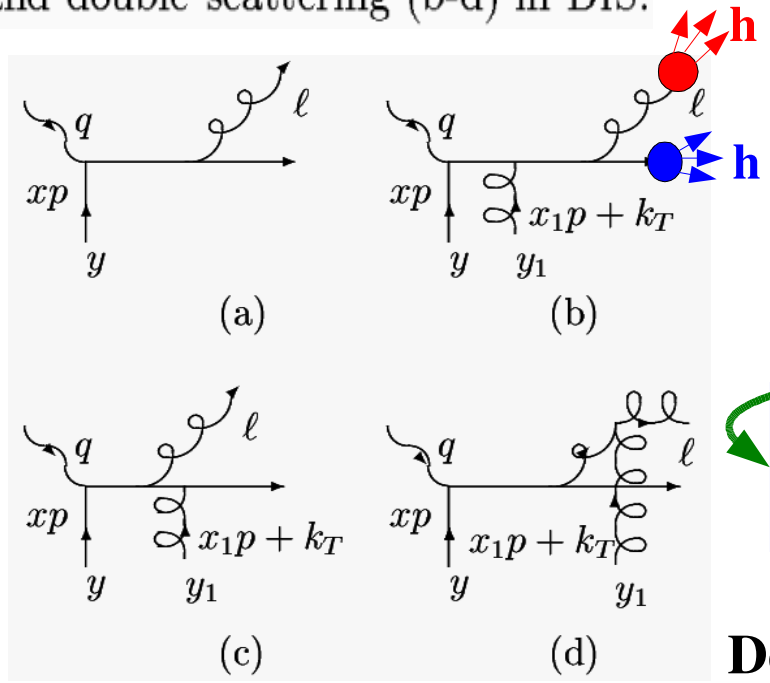
**anti-p underestimated**

**Hints of a flavour dependent formation time**

## 2) Twist-4 effects: quark rescattering and gluon bremsstrahlung

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

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




- Soft gluon emission
- quark rescattering + induced radiation

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

LO — NLO + twist-4

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

**Def:** quark fractional energy loss

$\langle z_g \rangle$ = average energy carried by radiated gluon

Result effectively approximated by:

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

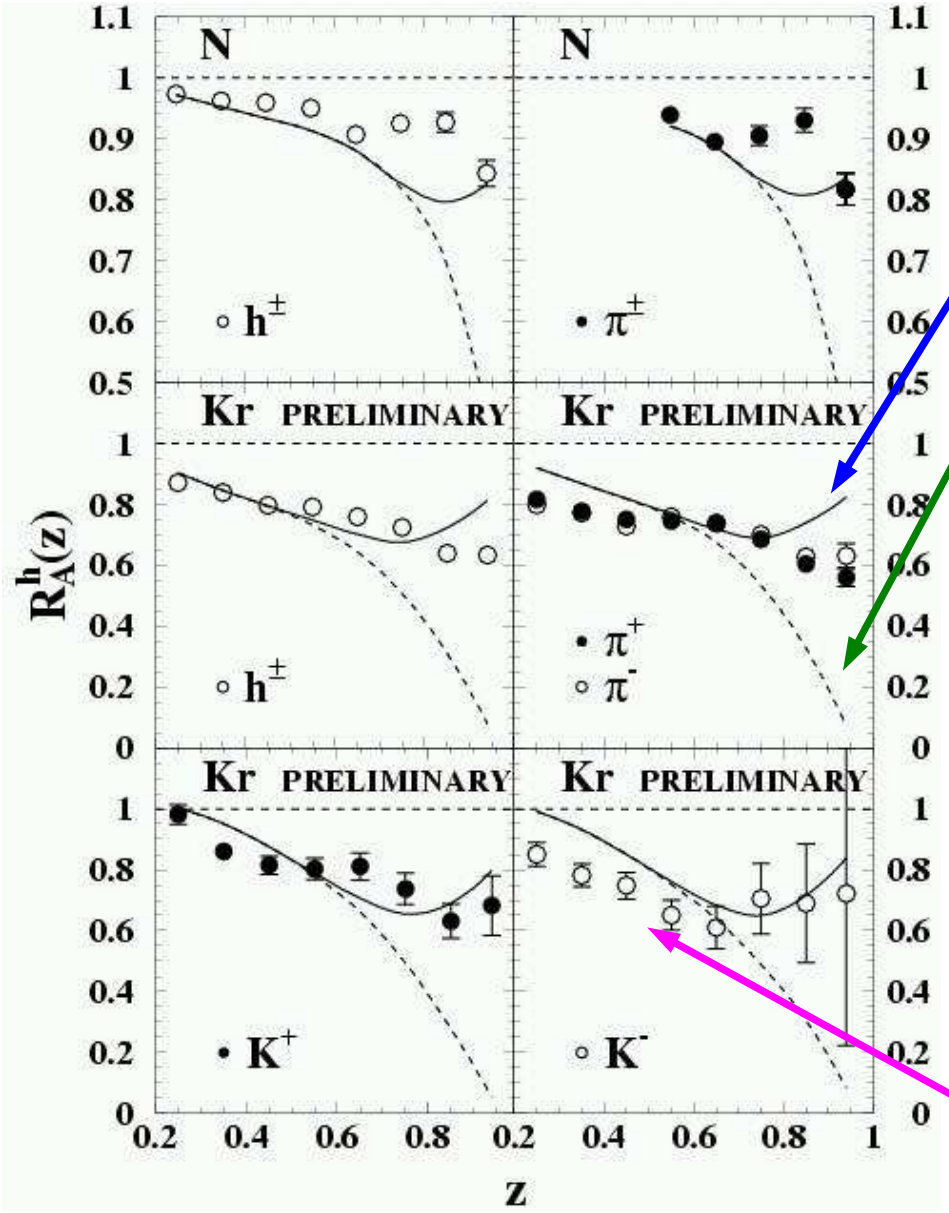
= 0.006 @ $Q^2$ =3 $GeV^2$ **fitted to HERMES**
0.013 @ $Q^2$ =40 $GeV^2$ fitted to DY

Where:

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

# Energy loss models vs. data

Arleo '03

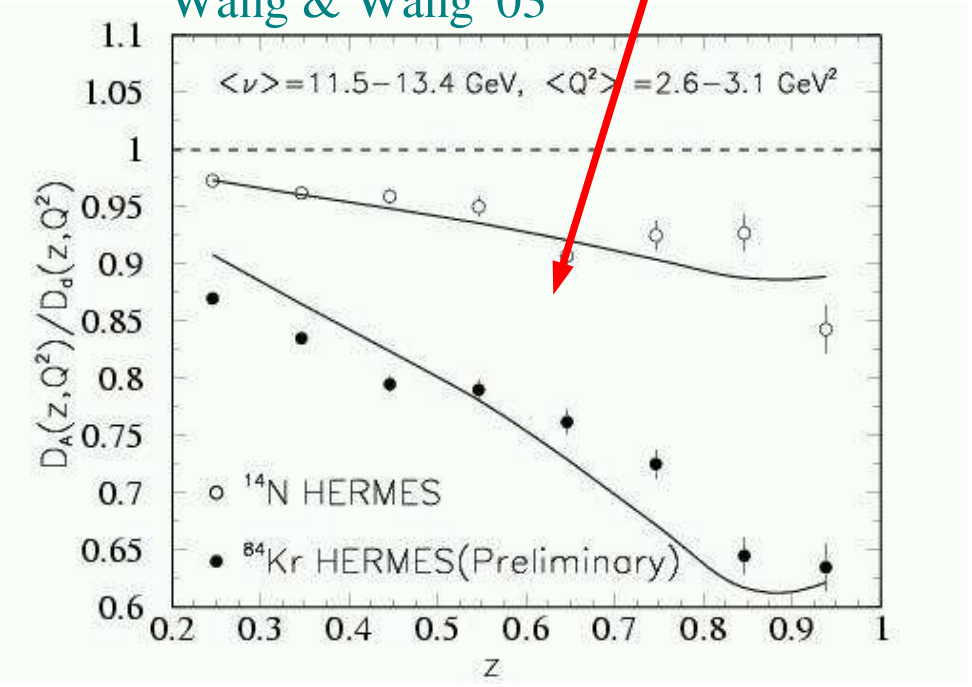



en. loss + LUND form. time

energy loss only

twist-4:
quark rescatt. and en. loss

Wang & Wang '03




**K- overestimated**

**(see also nu-dependence)**

# In detail...

$$\langle l_h \rangle(z,\nu) = \langle l_* \rangle(z,\nu) + z\,\frac{\nu}{\kappa}$$

$$\langle l_* \rangle(z,\nu) = f(z;C,C_a)\,(1-z)\,z\,\frac{\nu}{\kappa}$$

dynamical modulation

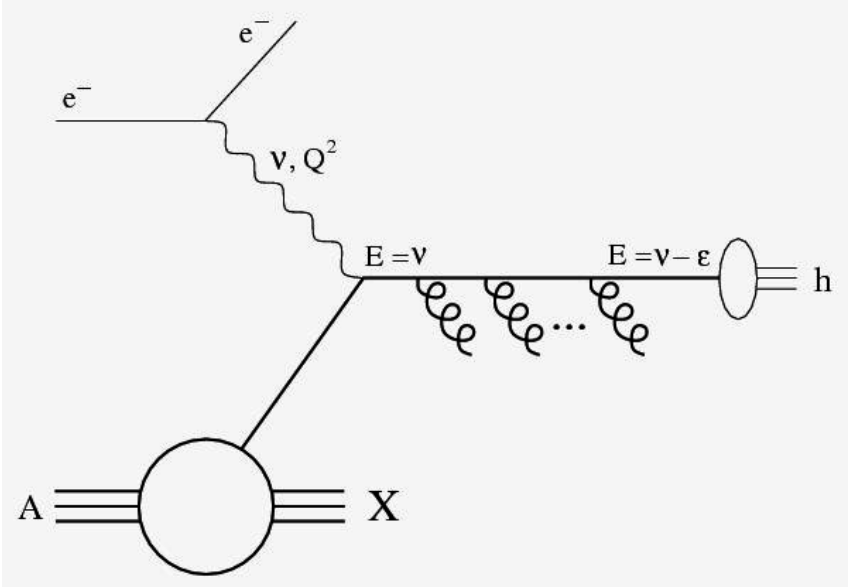
Lorentz boost + bremsstrahlung

$$f(z;C,C_a) = \frac{1+C_a}{1+C+(C_a-C)z} \times \left[1+\frac{1+C}{2+C_a}\,\frac{(1-z)}{z^{2+C_a}}\,{}_2F_1\left(2+C_a,2+C_a;3+C_a;\frac{z-1}{z}\right)\right]$$

$$C = 0.3 \qquad C_a = \begin{cases} 0.3 & a = u,d,s \iff \pi, K \\ 1.3 & a = q\bar{q} \iff p,\bar{p} \\ \cdots & a = \cdots \end{cases}$$

# The power of $Q^2$: energy loss vs. absorption

## 1) Medium-induced independent soft gluon emission - Arleo '02-'03




$$D^h_{q|A}(z,Q^2,\nu) = \int_0^{(1-z)\nu} d\epsilon\ \mathcal{P}(\epsilon,\nu;\hat{q},L)\ \frac{1}{1-\epsilon/\nu}\ D^h_q\left(\frac{z}{1-\epsilon/\nu},Q^2\right)$$

$\hat{q} = 0.72 \pm 0.54$ GeV/fm$^2$ from NA3 DY data

$\hat{q}$ = transport coefficient (medium density)

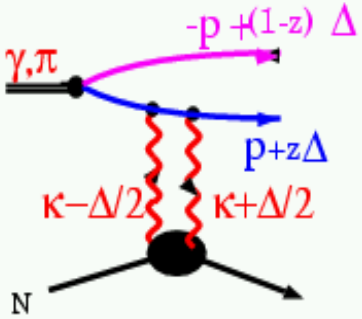
$\mathcal{P}(\epsilon,\nu;\hat{q},L)$ = prob. that a quark loses energy ε

Baier et al. '01 (BDMS); Arleo '02

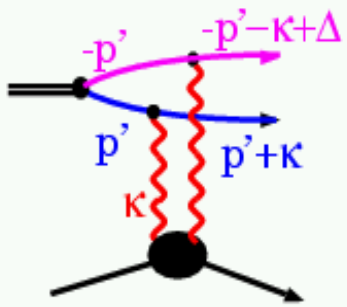
$$L = \min\left(\frac{3}{4}R_A, \langle l_F\rangle\right)$$

- Nuclear effects depend mainly on ν and z - soft dependence on $Q^2$
- After being formed, a hadron stops radiating (it's a colour singlet)
  Two possibilities:
  - a) large formation lengths => L = 3/4 $R_A$ always
  - b) Lund formation lengths => L ≤ 3/4 $R_A$ depending on ν and z

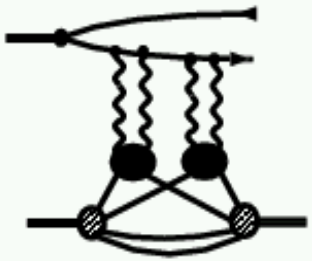
# Two-particle azimuthal correlations



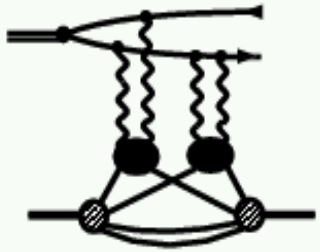

Landau-Pomeranchuk mechanism: jets carry soft intrinsic transverse momentum



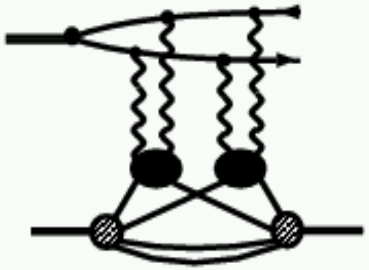

The pomeron splitting: jets acquire the perp. momentum from gluons. Dominates at large p-perp, probes the unintegrated gluon SF



Shadowing of the Landau-Pomeranchuk amplitude

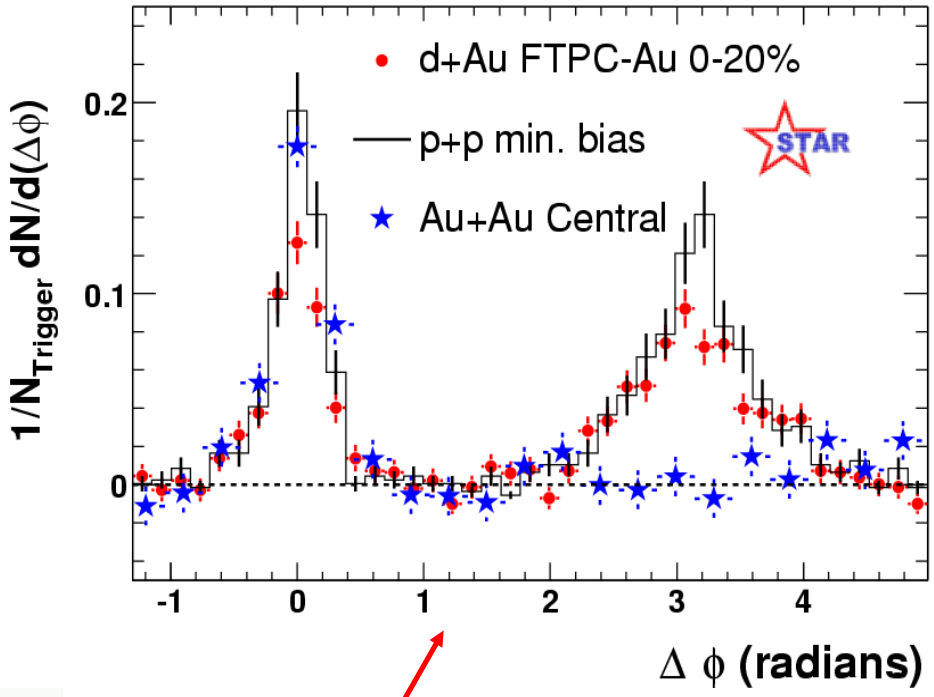


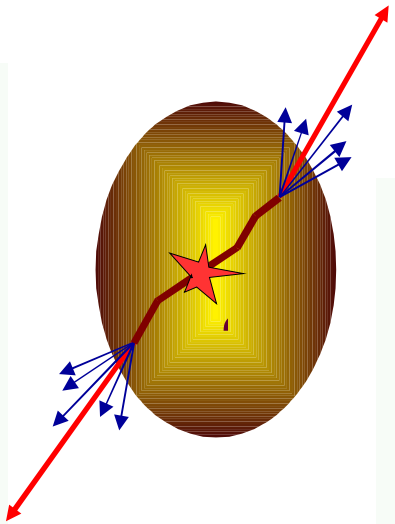
Shadowing of the pomeron splitting

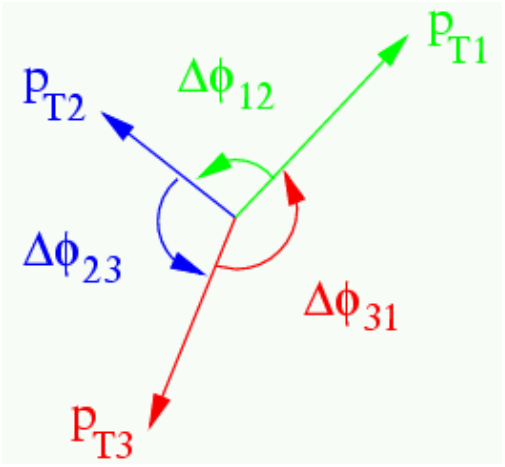


Multiple pomeron splitting: jets acquire the transverse momentum from gluons of several split pomerons

(N.N.N., W.Schäfer, G.Schwiete, *Phys. Rev.***D63** (2000) 014020; *JETP Lett.* **72** (2000)405.)





# The End