# Hadron production in nuclei

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## CFNS Adhoc Meeting: Target Fragmentation Physics with EIC

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# Outline

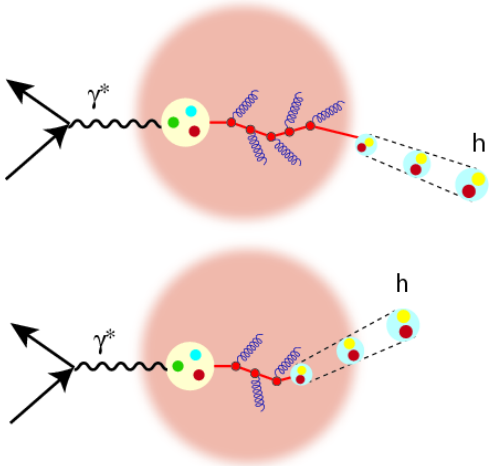
- Why hadron production in nuclei?
- In-vacuum hadronization and the production length.
- Final state interactions and in-medium hadronization.
- Considerations on the target region.

# General idea

Comparison of hadron spectra in SIDIS on P/D and A targets allow to obtain information on hadronization.

A central quantity is the production length $Lp$.

$Lp =$ length/time necessary for the parton to turn into a color singlet prehadron.



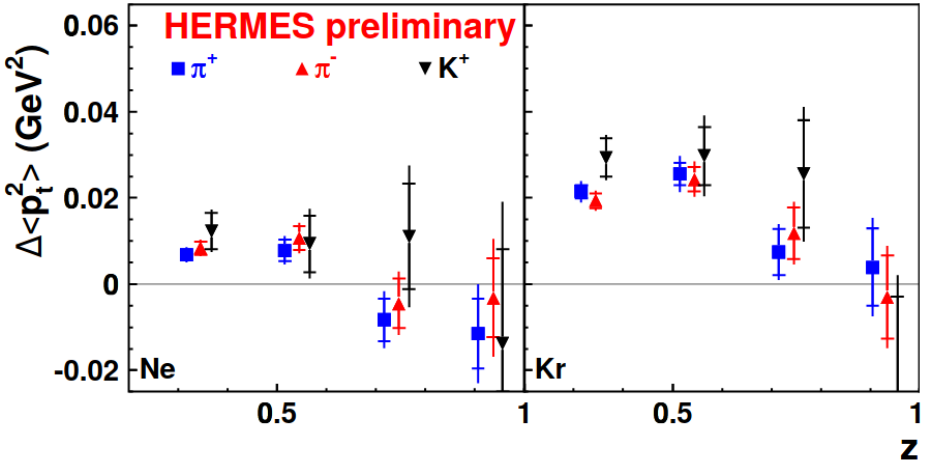

- Several new mechanisms appear with the presence of the nuclear medium, e.g., induced energy loss and nuclear absorption.
- A precise comparison with data helps to determine $Lp$ and to disentangle the different contributions.

# The two main observables

$p_t$ **broadening:**

$$\Delta p_t^2 = \langle p_t^2 \rangle_A - \langle p_t^2 \rangle_D$$

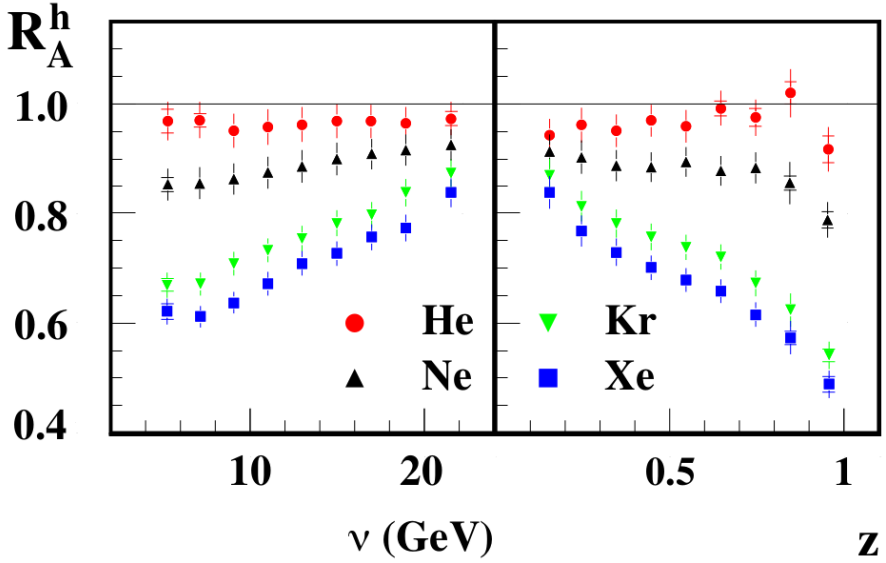
$$\langle p_t^2 \rangle_D \simeq 0.3 \text{ GeV}^2$$




**Multiplicity ratio**

$$R_A^h(z, Q^2, \nu) = \frac{\frac{1}{N_A^e} \frac{dN_A^h}{d\nu dz dQ^2}}{\frac{1}{N_D^e} \frac{dN_D^h}{d\nu dz dQ^2}}$$

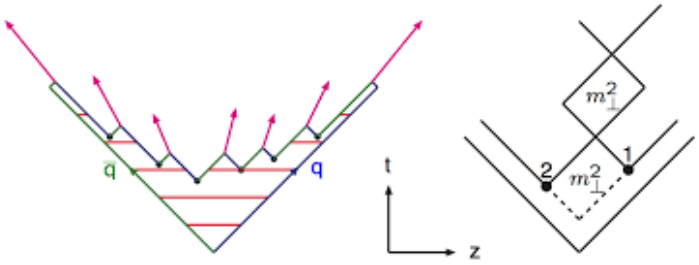
$$R_A^h(z, Q^2, \nu) \simeq \frac{D_A^h(z, Q^2, \nu)}{D^h(z, Q^2, \nu)}$$

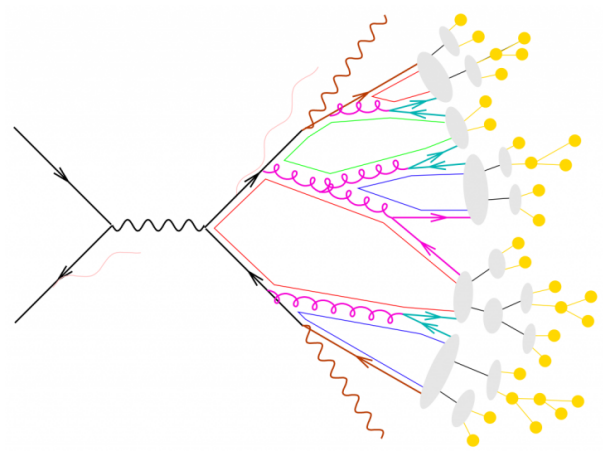



Data includes most probably hadrons coming from the two regions.

Theoretical description of these observables relies on the choice for $Lp(z)$.

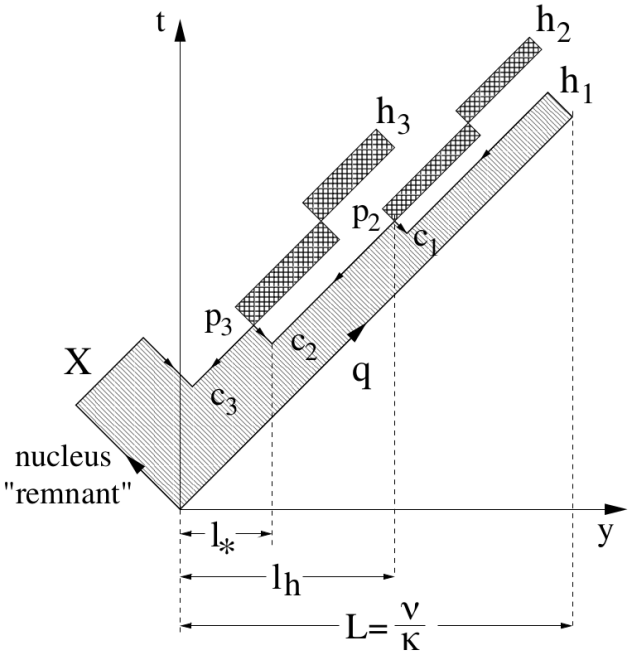
# $Lp$ and hadronization models

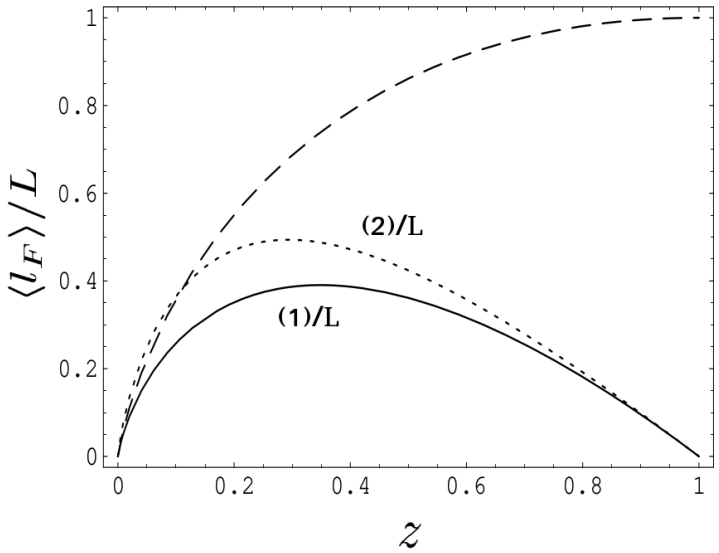


# The Lund model

**Advantage:** Can describe the target and current frag. regions.




*Pictures taken from Accardi, Muccifora, Pirner; Nucl.Phys.A 720 (2003) 131-156*

$$\langle l_* \rangle = \langle Lp \rangle = \left[ 1 + \frac{1+C}{2+C} \frac{1-z}{z^{2+C}} \, {}_2F_1 \left( 2+C, 2+C; 3+C; \frac{z-1}{z} \right) \right] (1-z) z L \qquad (1)$$

$$\langle Lp \rangle = \left[ \frac{\ln(1/z^2) - 1 + z^2}{1 - z^2} \right] zL \xrightarrow[z \to 1]{} (1-z) z L \qquad (2)$$

Both formulas obtained in the Lund model. Show a max at $z \sim 0.3$.

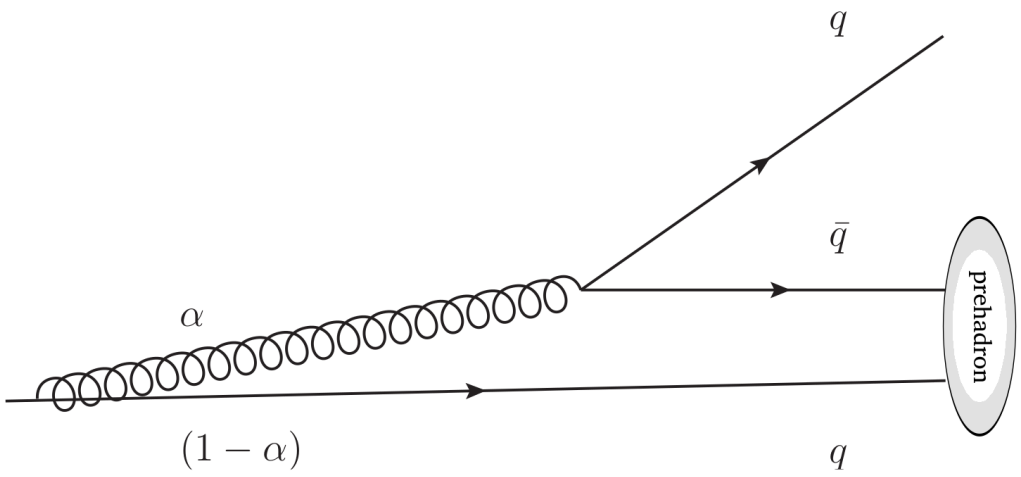
# The Berger Model

Only for the leading quarks!

**Berger**, *Phys. Lett. B 89 (1980) 241*

$$\frac{\partial D(z,p_t^2)}{\partial p_t^2} \propto \frac{(1-z_h)^2}{p_t^4} + \mathscr{O}(p_t^2/Q^2)$$

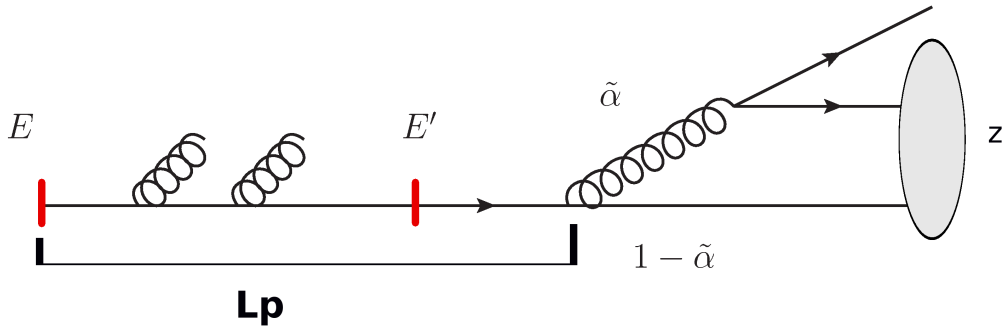
$$z_h = \frac{P_h.P}{q.P}$$




**Improved Berger model**
*(see i.e. Kopeliovich et. al., Physics Letters B 662 (2008) 117–122)*

$$\frac{\partial D(z,p_t^2)}{\partial p_t^2} \propto \frac{(1-\tilde{z}_h)^2}{p_t^4}$$

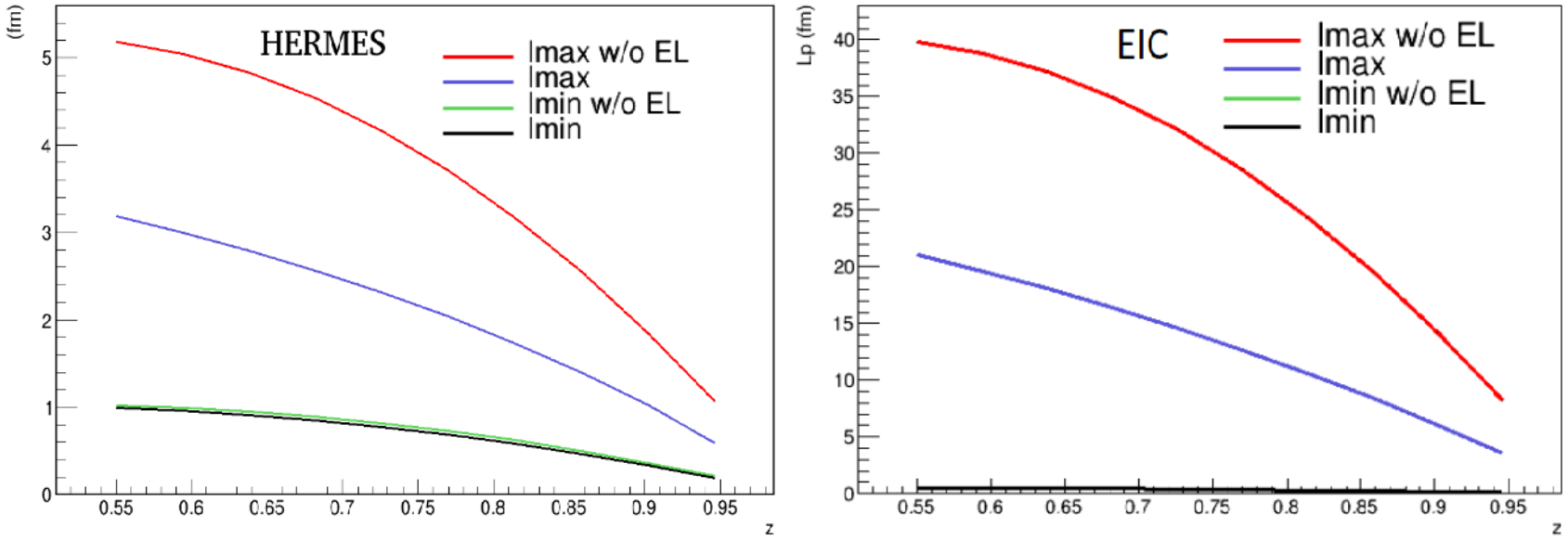
$$\tilde{z}_h = \frac{z_h}{1-\Delta E/E}, \quad \Delta E = E - E'$$




$Lp \equiv t_r \propto \frac{(1-\tilde{z}_h)z_h E}{p_t^2}$, where $t_r$ is the radiation time of the final gluon.

# HERMES and EIC production lengths

$Lp = \frac{4(1-\tilde{z})z}{p_t^2}\nu$ , *B.G., B. Kopeliovich, arxiv 2001.00974*



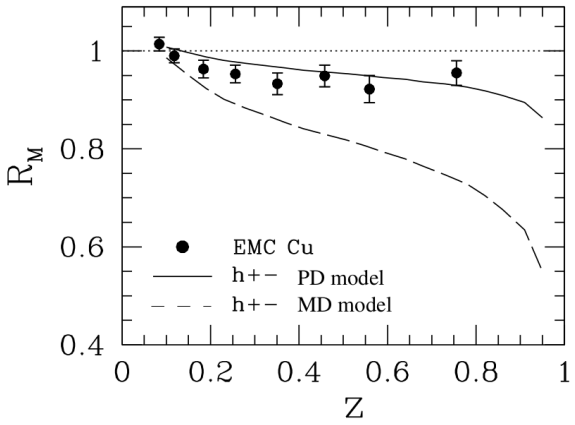

- $\langle l^* \rangle$ obtained in the Lund model is app. 2 times larger than above. But first rank hadrons have $Lp = 0$.

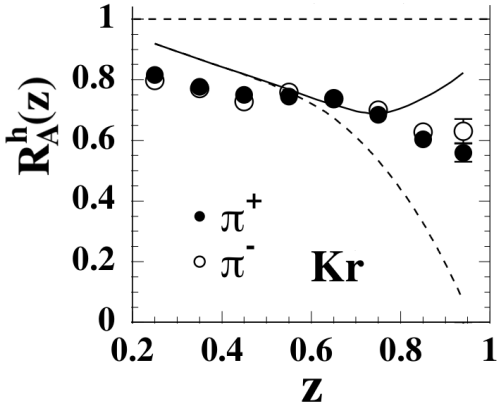
# Final state interactions

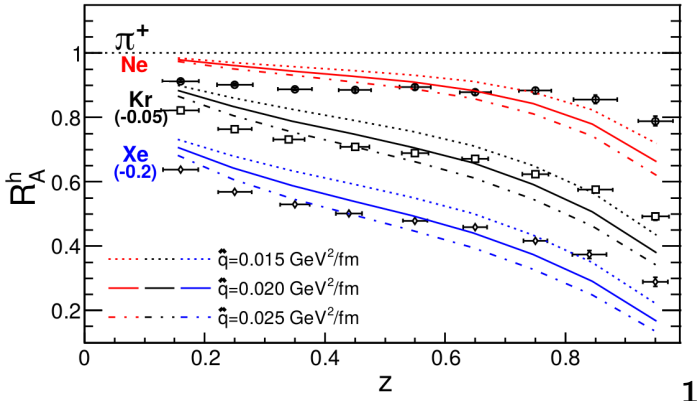
1. Modified in-vacuum fragmentation function.
2. (Pre)hadron absorption.
3. Final hadrons rescattering.

# Modified in-vacuum fragmentation function $D(z,Q^2)$

- **Shift in $Q^2$** *(Accardi, Muccifora, Pirner; Nucl.Phys.A 720 (2003) 131-156)*
  Rescaling models for structure func. extended to frag. func. (+ nuclear abs.).
  $D^A(z,Q^2) = D(z,\xi(Q^2)Q^2)$
  $Lp$ plays a minor role.
- **Shift in $z_h$** *(Arleo; Nucl.Phys.A 720 (2003) 131-156)*
  Induced energy loss.
  $zD_q(z,Q^2,A) = \int_0^{(1-z)\nu} d\varepsilon D(\varepsilon,\nu) z^* D_q(z^*,Q^2)$
  $z^* = z/(1-\varepsilon/\nu)$
  $Lp = \left[\frac{\ln(1/z^2)-1+z^2}{1-z^2}\right] z\frac{\nu}{\kappa}$
- **Modified DGLAP** *(Deng, Wang; Phys. Rev. C 81, 024902; Chang, Deng, Wang; Phys.Rev.C 89 (2014) 3)*
  Induced energy loss.
  $\tilde{\gamma}_{a\to bc}(z,Q^2) = \gamma_{a\to bc}(z) + \Delta\gamma_{a\to bc}(z,Q^2)$
  $\Delta\gamma_{q\to qg} = F(z)\int dy^- \hat{q}(y^-) 4\sin^2(x_L p^+ y^-/2)$
  $Lp$ "infinite".

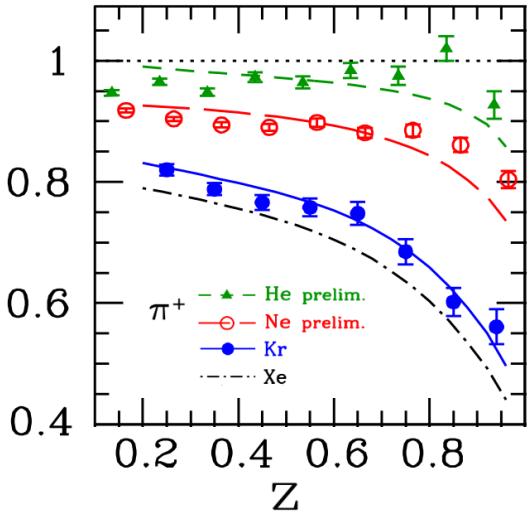


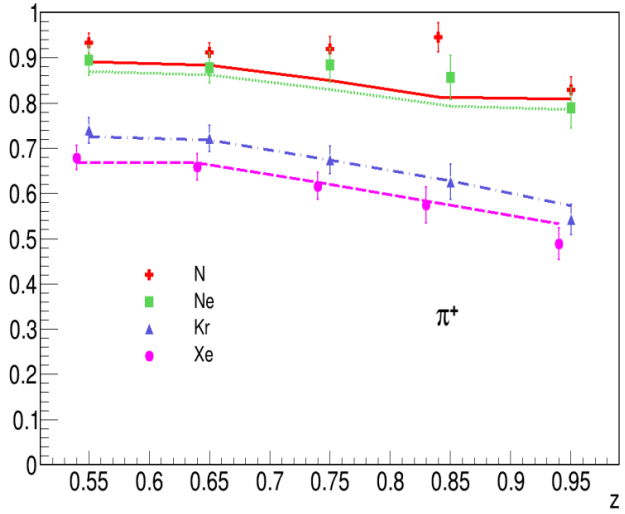



# (pre)hadron absorption

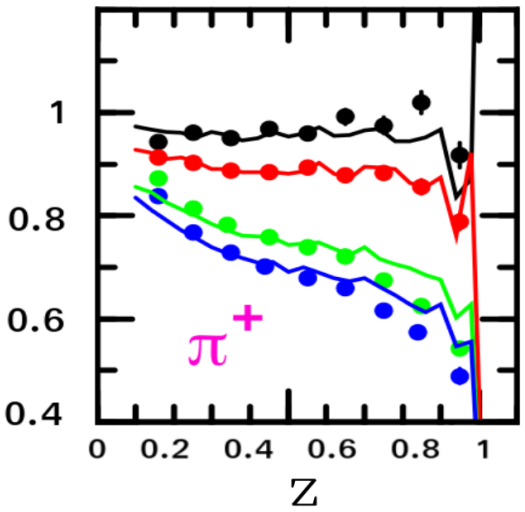
Published models agree qualitatively on the main features.




Accardi, Grunewald, Muccifora, Pirner
Nucl.Phys.A 761 (2005) 67-91




Guiot, Kopeliovich
arxiv 2001.00974




Gallmeister, Mosel
Nucl.Phys.A 801 (2008) 68-79

1. Prehadron absorption does matter (in particular at HERMES energies).
2. $\sigma_{h^*N} < \sigma_{hN}$. Increases linearly in *Nucl. Phys. A 801 (2008)* and *2001.00974*. Color transparency.
3. $Lp \to 0$ when $z \to 1$. Effect of nuclear abs. maximum at $z = 1$.

**Remark:** "absorbed" hadrons will be found at small $z$, i.e., in the target/central regions.

# More final state interactions

GiBUU code (Mosel, Gaitanos, Gallmeister, van Hees, Larionov):

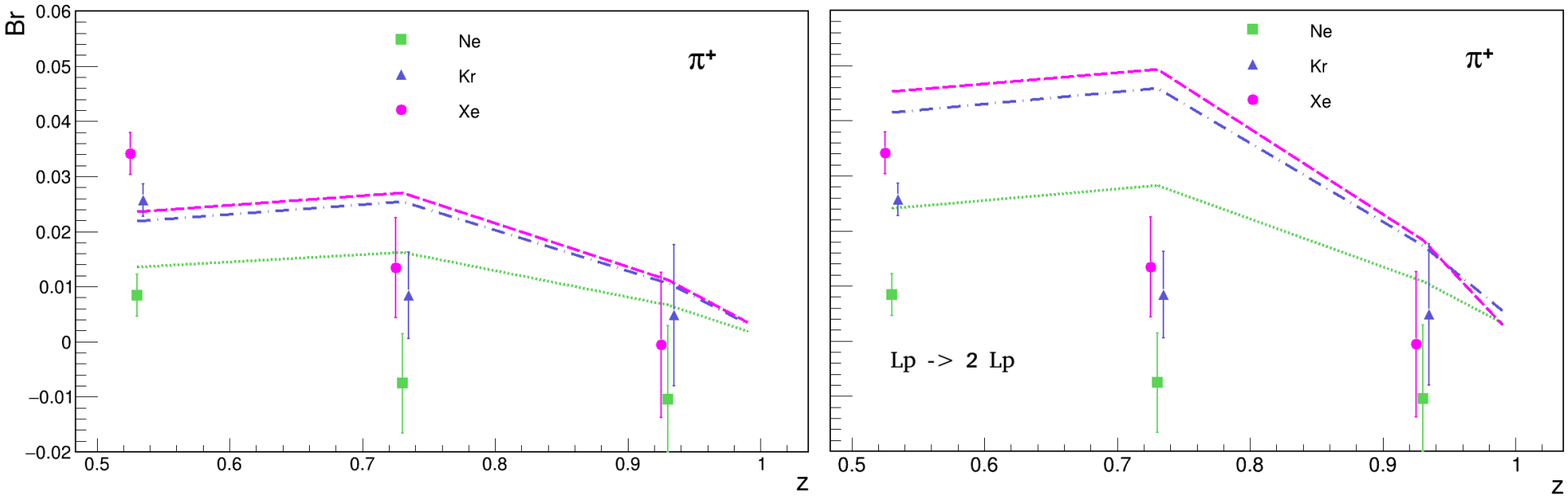
- Inelastic **and** eleastic rescattering of the produced prehadrons, based on the Boltzmann–Uehling–Uhlenbeck (BUU) transport description.
- Gives a complete description. In particular, it cares about secondary hadrons, generally ignored in the other studies.
- More information in Ulrich's talk.

# Comparisons with data

- The one-dimensional $R_M$ is not enough constraining.
- However, the multi-dimensional $R_M$ along with the $p_t$ broadening give important constraints.
- Consensus on $Lp$?

# Production length and $p_t$ broadening

- The $p_t$ braodening depends directly on $Lp$.
- HERMES data give a strong indication that $Lp(z=1)=0$, in agreement with hadronization models.

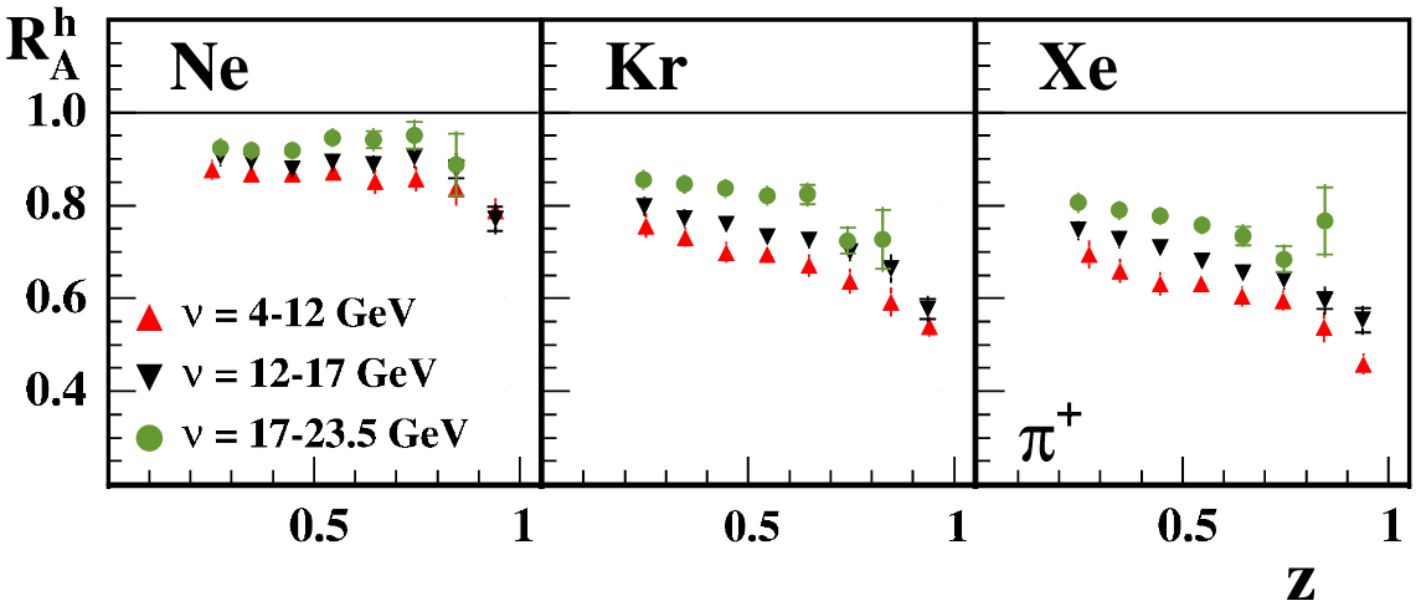



Here *(Guiot, Kopeliovich; 2001.00974)*, $Lp(\nu=13, Q^2=2.5, z=0.5) \simeq 2$ fm.

Schematically $\Delta\langle p_t^2\rangle(s,Lp) = 2C(s)\rho Lp$, with $\sigma_{q\bar{q}} = C(s)r^2$.

Elastic collisions of the prehadron neglected (large-$z$).

# The $\nu$ dependence and the 2-dim. multiplicity ratio



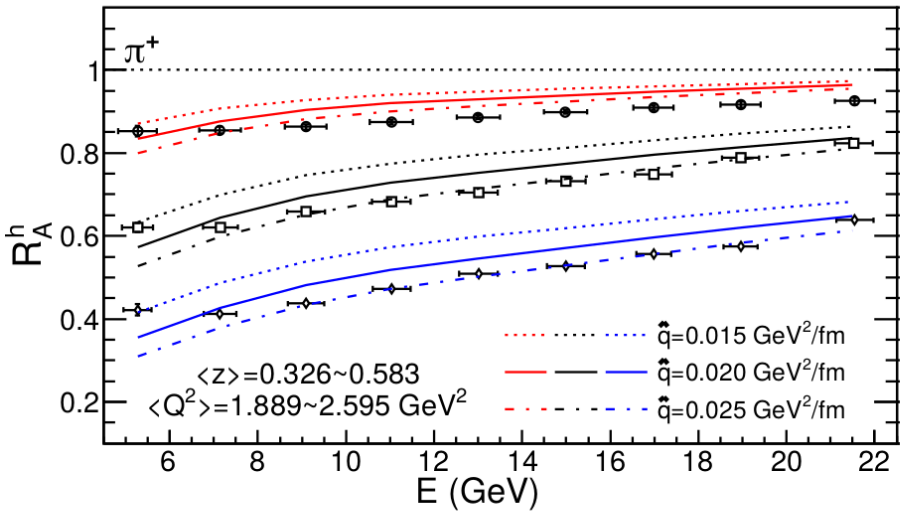

**Nuclear abs. point of vue:** Confirms that $Lp \propto z(1-z)\nu$ is smaller than the nuclear size.

**IEL point of view:** Confirms that $Lp$ is "infinite" (remember that $\Delta z = \frac{z\Delta E_{ind}(Lp)}{\nu}$).

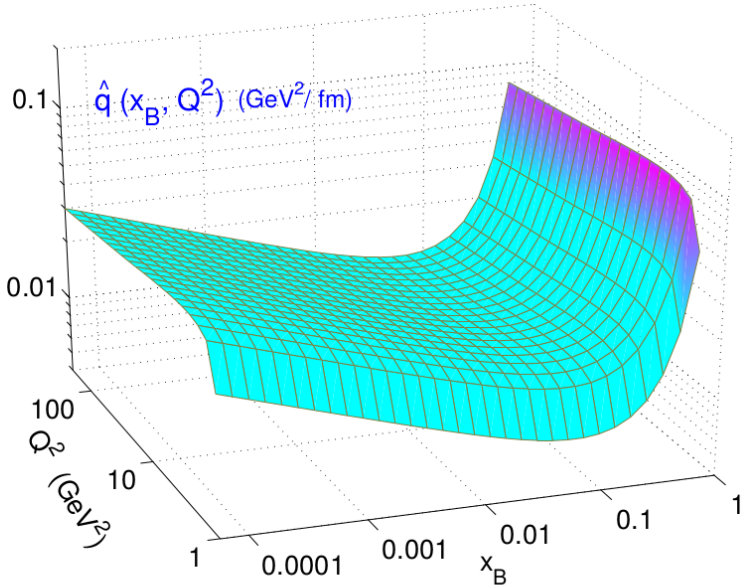
Models based only on IEL and using $Lp \propto z(1-z)\nu$ will fail to reproduce this observable $\Rightarrow$ need for nuclear abs.

# Determination of the transport coefficient

- However, can be used with $z$-averaged data to extract the transport coefficient $\hat{q}$ in cold nuclear matter.



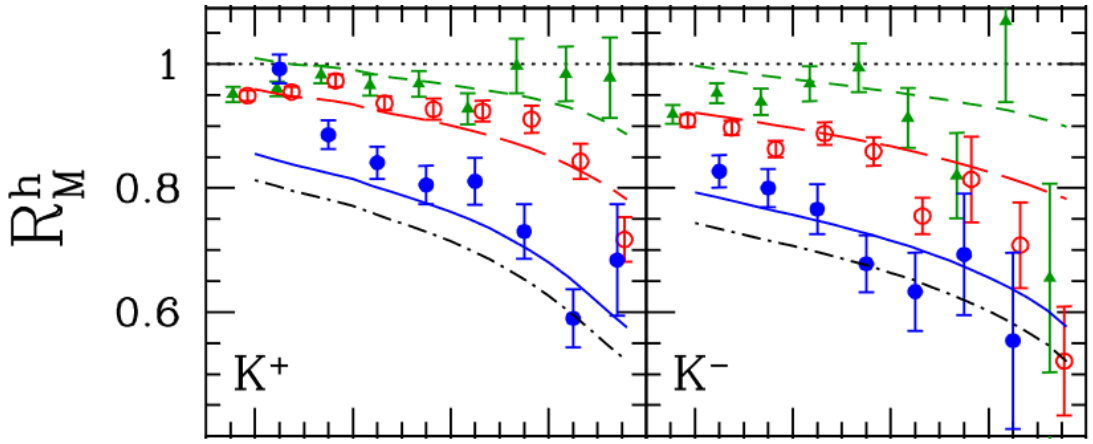

Chang, Deng, Wang
Phys. Rev. C 89, 034911 (2014)

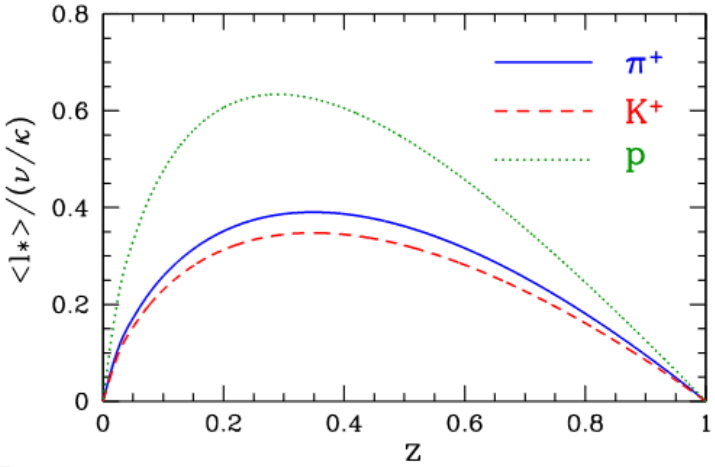


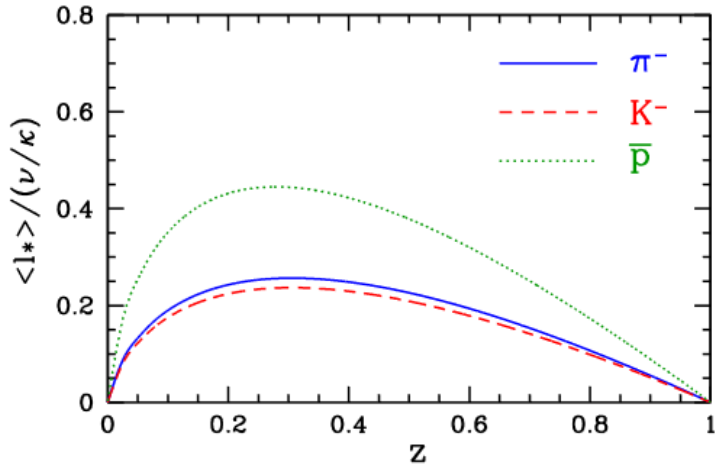

Kang, Wang, Xing, Zhang
arxiv 1907.11808

- For the quark-gluon plasma $\hat{q} \sim 2$ GeV$^2$/fm.

# Flavor dependences



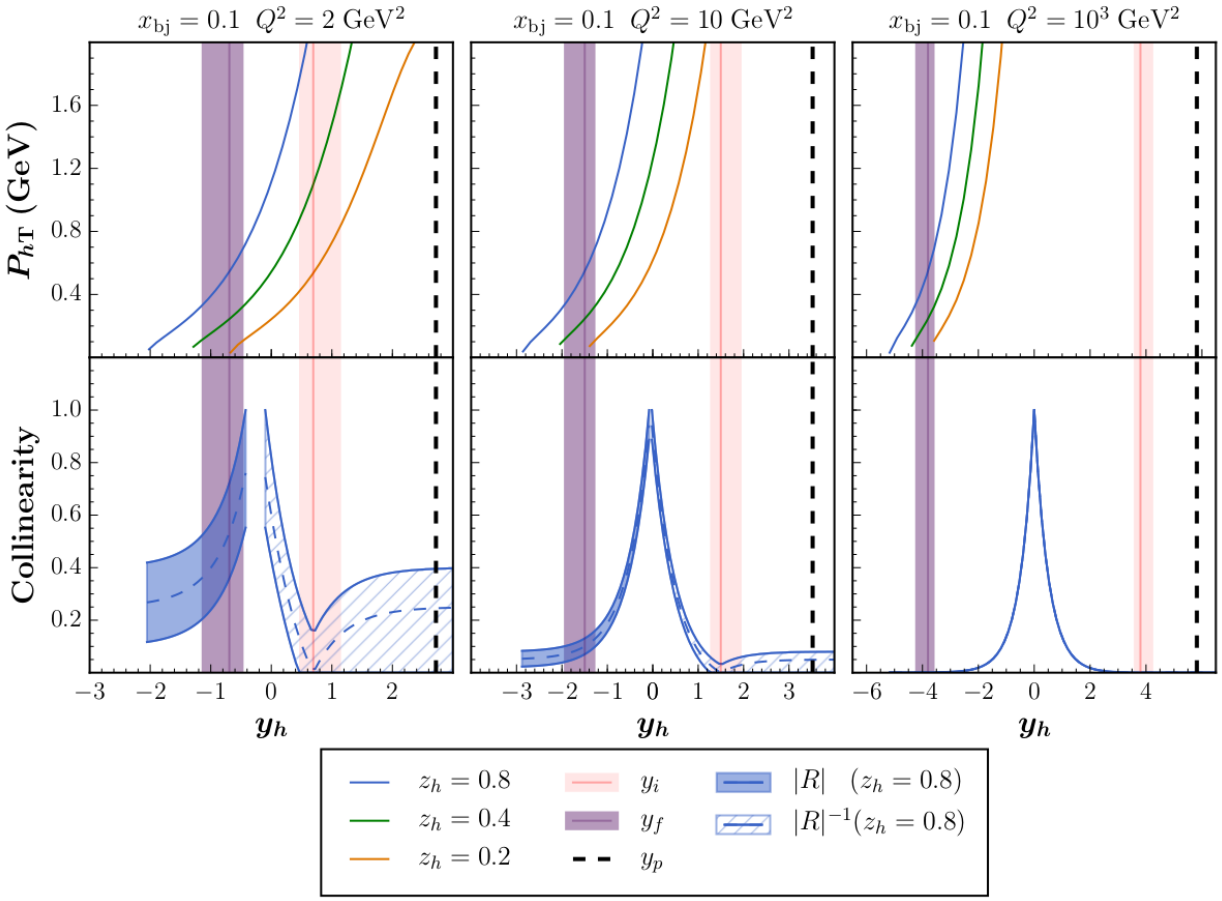

*Picture taken from Nucl.Phys.A 761 (2005) 67-91*

- Data also indicate that $Lp$ and/or $\sigma_{h^*}$ are flavor dependent
- Not a surprise since:
  1. $\sigma_{K^-N} > \sigma_{K^+N}$
  2. The Lund model predict a flavor dependent production length

Give another confirmation of the nuclear abs. picture!

# Considerations on the target region

Picture taken from *Boglione, Collins, Gamberg, Gonzalez-Hernandez, Rogers, Sato; Phys.Lett.B 766 (2017) 245-253.*




- EIC: target region corresponds to small $z$ (except if you choose a large $p_t$ hadron).
- JLAB/HERMES: from small to moderate value of $z$.

# Considerations on the target region

At small $z$, $Lp \to 0$. New mechanisms for the $p_t$ broadening? (hadrons rescattering)

The target region could easily receive contributions from the current region:

- Secondary hadrons (importance of event generators).
- Inelastic collisions of large-$z$ hadrons on nucleons (nuclear abs.).
- Is this one of the reasons why the $p_t$ broadening is not zero at small $z$?

Nucleus breakup and hadron-spectator interactions. "Fast hadron $E_h \sim \nu$ ignore the nucleus": not at moderate energies.
$E_h \sim \nu \Rightarrow z \sim 1 \Rightarrow Lp \sim 0$.

# Summary

- Hadronization models predict that $Lp \propto z(1-z)\nu$.
- Disagreement between IEL and nuclear abs. models on $Lp$. But $p_t$-broadening data indicate a small production length $Lp \sim 2$ fm at HERMES.
- $Lp$ and prehadron $\sigma_{h^*N}$ are flavor dependent.
- Prehadrons can be formed inside the nucleus (probably) even at the EIC.
- Color transparency $\Rightarrow \sigma_{h^*N} < \sigma_{hN}$. The prefered choice is a linear increase with time.
- $\hat{q}$ estimated to 0.02 GeV$^2$/fm in cold nuclear matter.
- Target region can receive contributions from the current region.