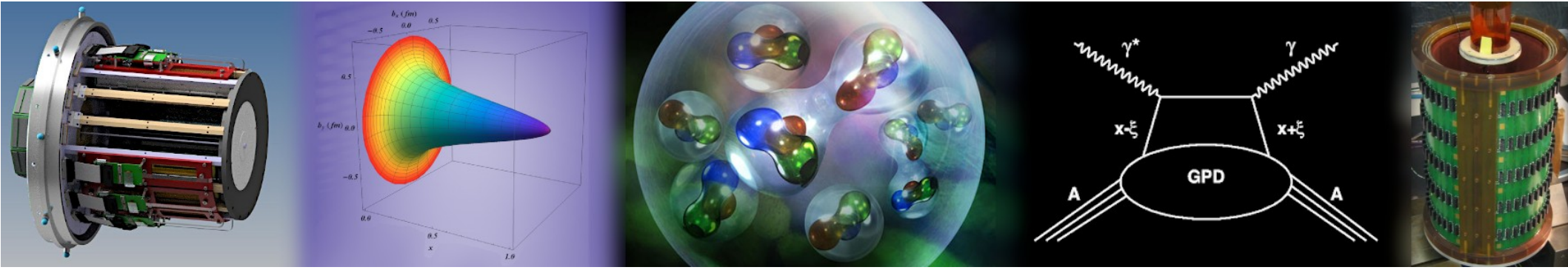
Nuclear TMD Phenomenology



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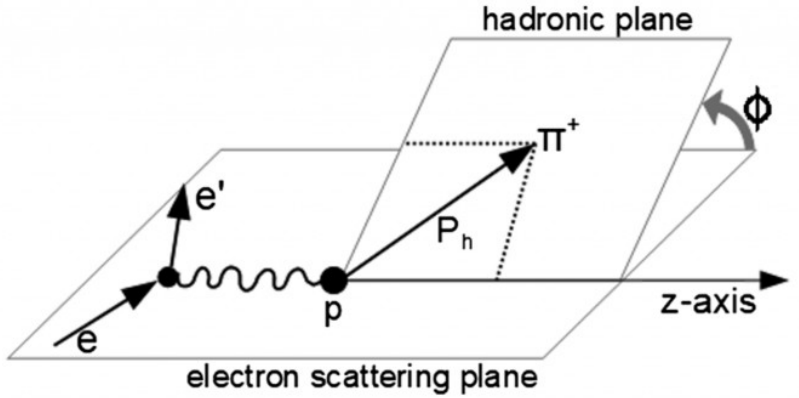
European Research Council
Established by the European Commission

SIDIS to study cold nuclear matter

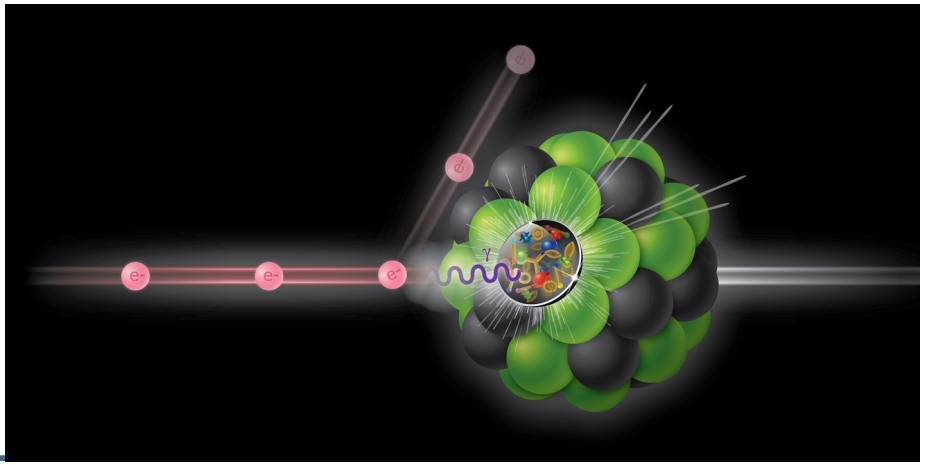
Semi-Inclusive Deeply Inelastic Scattering

- Ideal to study CNM
- Great control of the initial state
- Gives high sensitivity characterize the produced hadrons
  - **Giving the longitudinal direction !**



Not so used to study the CNM

- Experiments are not at high energy enough ?
- Communities not talking enough ?



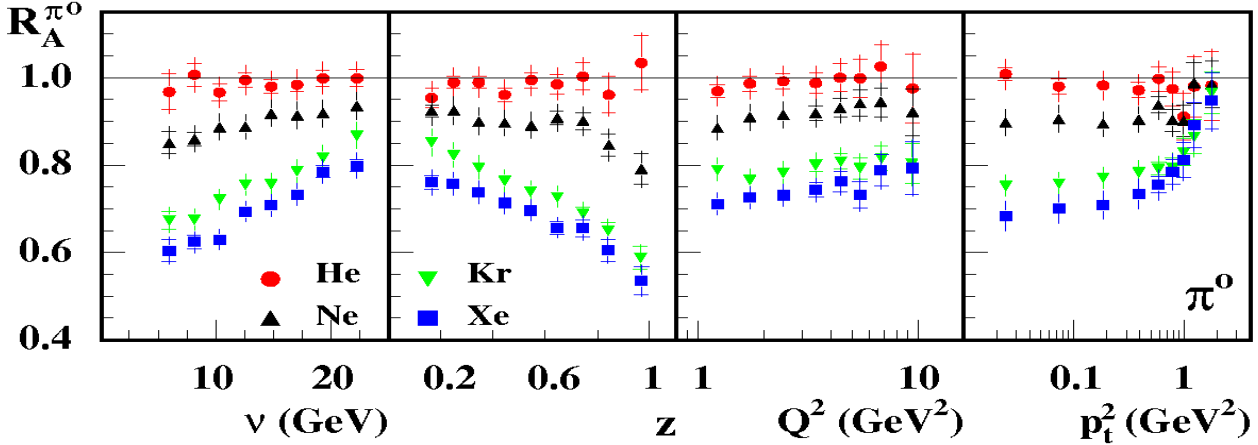
The HERMES data

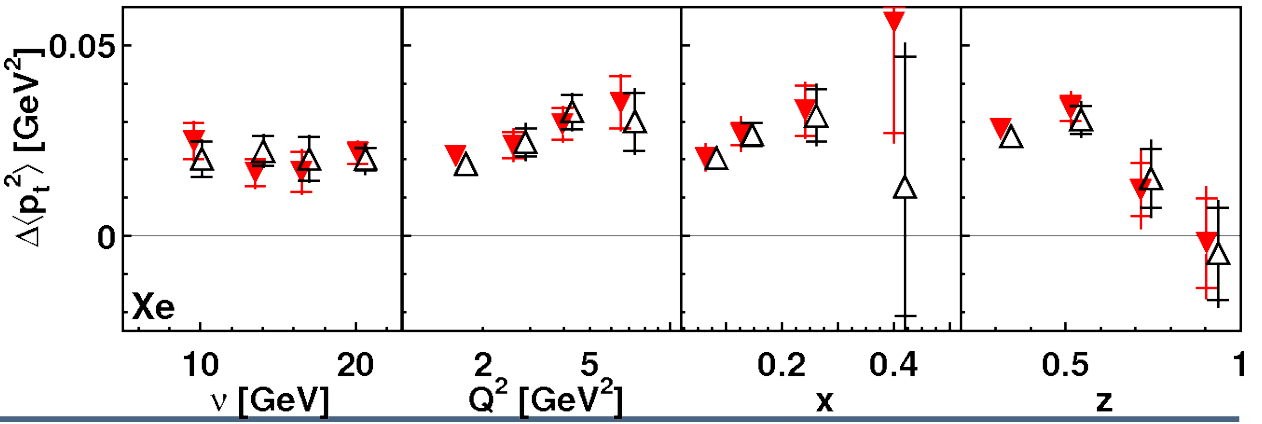
Great Dataset

- Several hadrons
- 6 to 22 GeV
- Both absorption and transverse momentum measured

There are others

- EMC and CLAS in particular



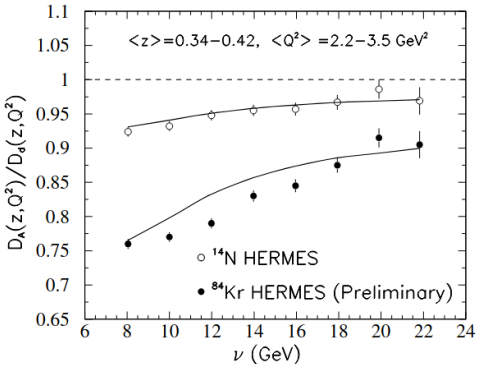


The Problem

The HERMES data was thorougly studied

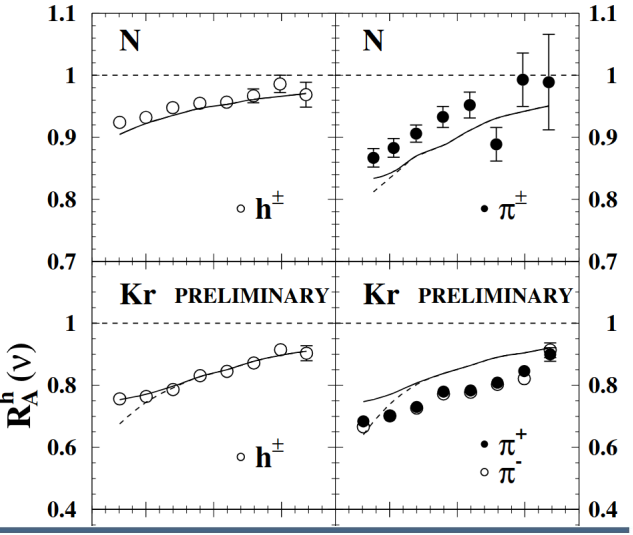
- Many models confronted to these data
  - **I show only a couple of examples**

Wang & Wang 2002, Arleo 2003 here



Matching the suppression and the transverse momentum

- That is the main issue !
- Quark energy loss calculation make a prediction on transverse momentum
  - **That happen to be very hard to match to measurement**
  - **Often discussed but not many figures**



Building of our phenomenological model

We built a TMD model

- Keeping the Gaussian assumption for simplicity
- Fitting HERMES data on proton

We added nuclear effects

- Nuclear PDF
- Fermi motion
- Quark energy loss
  - **Based on Arleo 2002**
- Nuclear absorption
  - **Ad hoc parametrization**

A TMD-based model for Hadronization off heavy nuclei
F. A. Ceccopieri and R. Dupré PRC 2024

$$f_{q/P}(x_B, Q^2, \boldsymbol{k}_\perp) = f_{q/P}(x_B, Q^2)\,\frac{1}{\pi\langle k_\perp^2\rangle}\,e^{-k_\perp^2/\langle k_\perp^2\rangle}$$

$$D_{h/q}(z, Q^2, \boldsymbol{p}_\perp) = D_{h/q}(z, Q^2)\,\frac{1}{\pi\langle p_\perp^2\rangle}\,e^{-p_\perp^2/\langle p_\perp^2\rangle}.$$

$$L_P(z,\nu) = N z^\lambda (1-z)^\beta \left(\frac{\nu}{\mathrm{GeV}}\right)^\gamma.$$

$$\overline{W}(\bar\epsilon,\bar\nu) = \frac{1}{\sqrt{2\,\pi}\,\sigma(\bar\nu)\,\bar\epsilon}\,\exp\left[-\frac{\left(\log\bar\epsilon - \mu(\bar\nu)\right)^2}{2\,\sigma(\bar\nu)^2}\right],$$

$$-\frac{dE}{dx} = \frac{\alpha_s N_C}{4}\langle q_\perp^2\rangle,$$

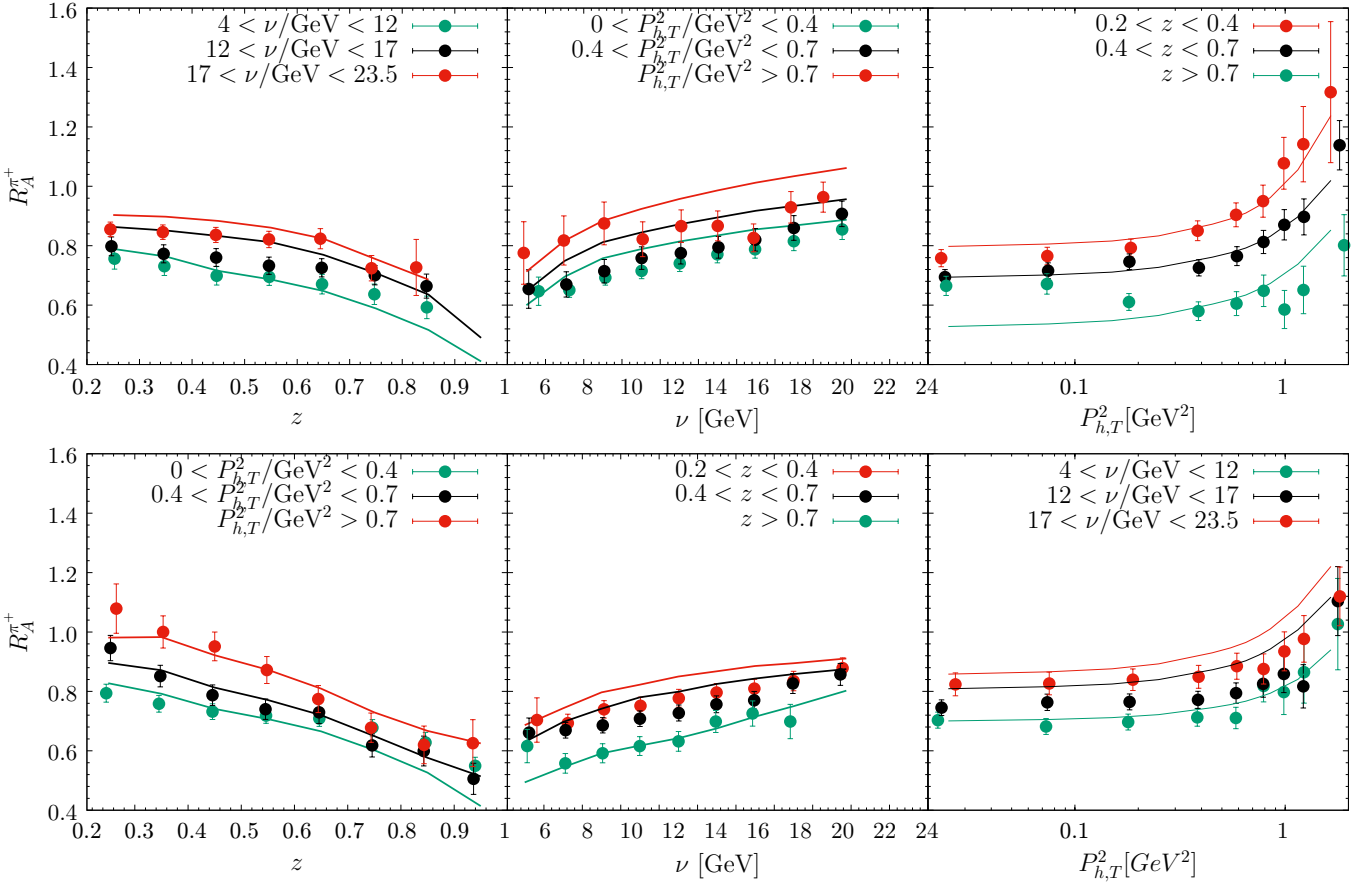
$$n_{att}(z,\nu;x_i,b_i) = 1 - \left[\frac{L_T^* - L_P^*}{L_{typical}}\right]^d,$$

Result of the model for absorption

We get a pretty reasonable description of the HERMES data

- Looks different for different binning
  - **Some correlations are missing in the base (non nuclear) model**

The transverse aspect looks fine from here



The Transverse momentum and parameters

The transverse mom. broadening

- Fine as well but the shape is off
  - **We will come back to this**

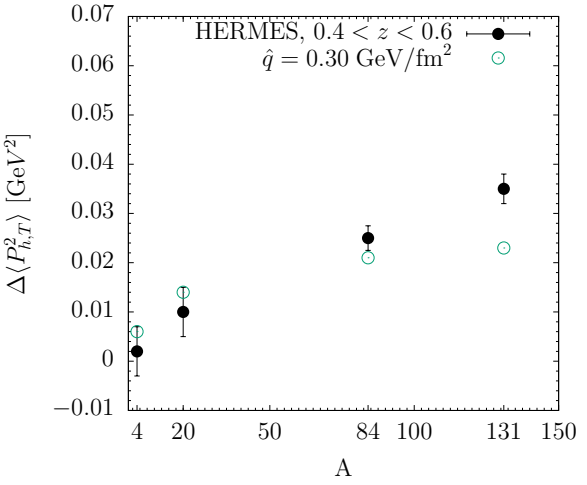
The parameters look fine

- q hat is reasonnable
- Absorption is large

The production length is strange

- Does not look like past assumptions
  - **Nothing outrageous but that where the data led us**

$$L_P(z,\nu) = N z^{\lambda}(1-z)^{\beta}\left(\frac{\nu}{\mathrm{GeV}}\right)^{\gamma}.$$



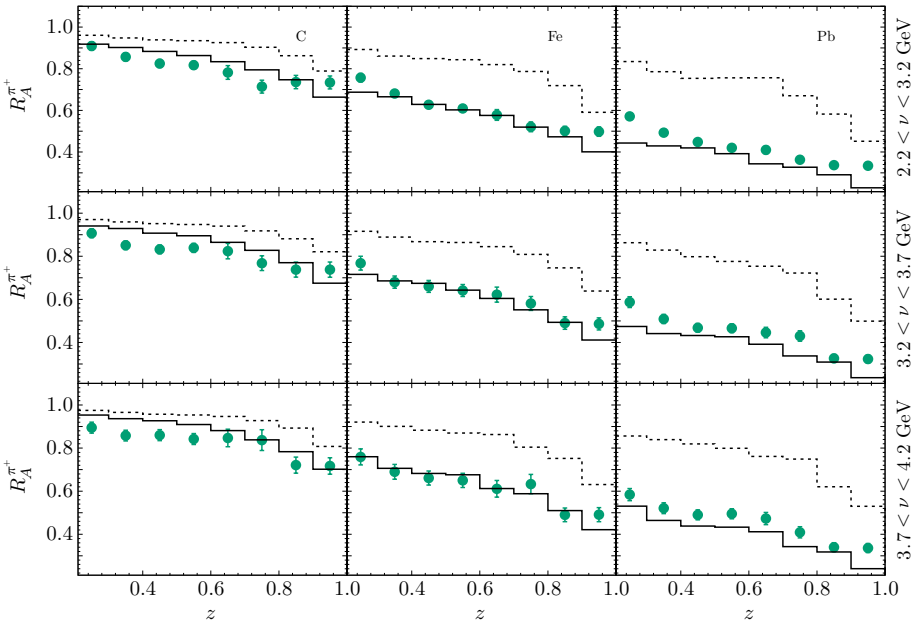
Production length			
N	λ	β	γ
4.0 fm	0.0	0.25	0.3

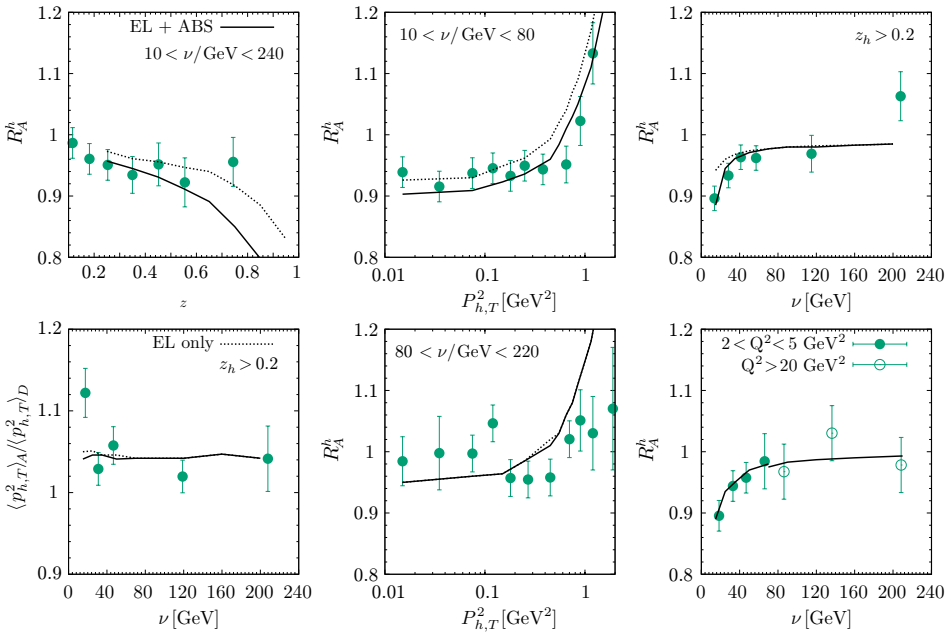
Transport coefficient		Nuclear absorption	
$\hat{q}$	α_s	$L_{typical}$	d
0.3 GeV/fm^2	0.5	2 fm	0.5

Describing more data with the model

We used the model to describe the EMC and CLAS data

- It works great (there is no transverse momentum broadening)
- Shows that at least the energy dependence of the parameters holds





Survivor Bias in Nuclear SIDIS

We found many biases

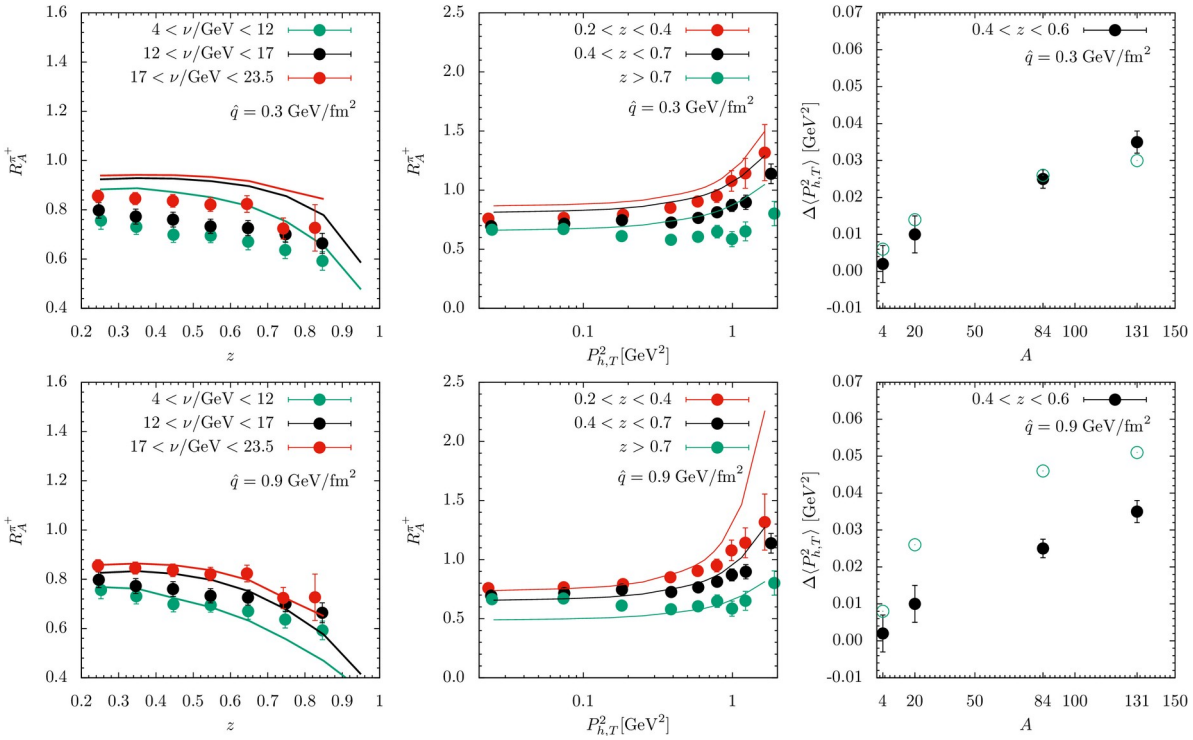
- Mostly ignored in the litterature
- But can be very large

We see an important survivor bias

- Affects significantly the transverse momentum broadening observed
- Might resolve some of the issues past studies had

There are others

- Some are pretty convoluted
- All depend on the details of the model



The A Dependence is a Problem

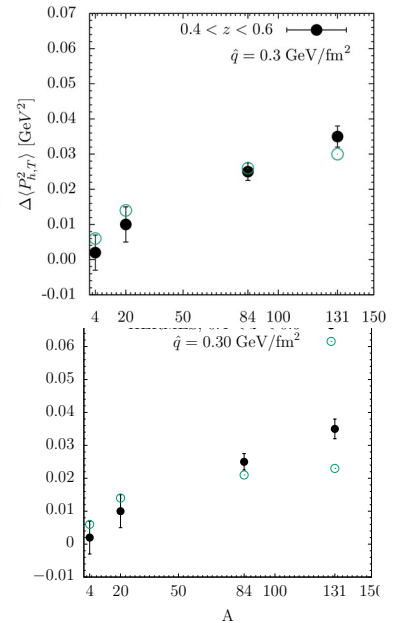
This A dependence shape is a general issue

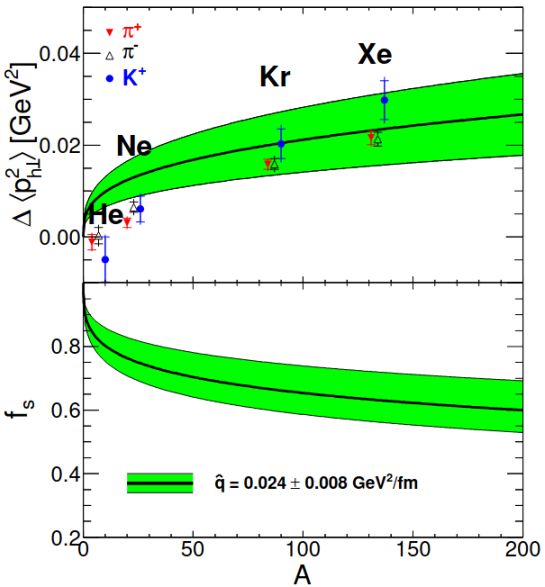
- Everybody looks similar in this regard
  - **This shape is mostly driven by simple geometry**
- Here I show a few exemples
  - **all overshoot light nuclei and undershoot heavy**

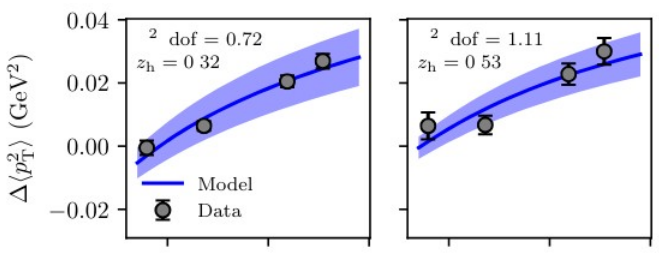
Song 2014, Ru 2021, Brooks 2021 (I kept the older ones out)

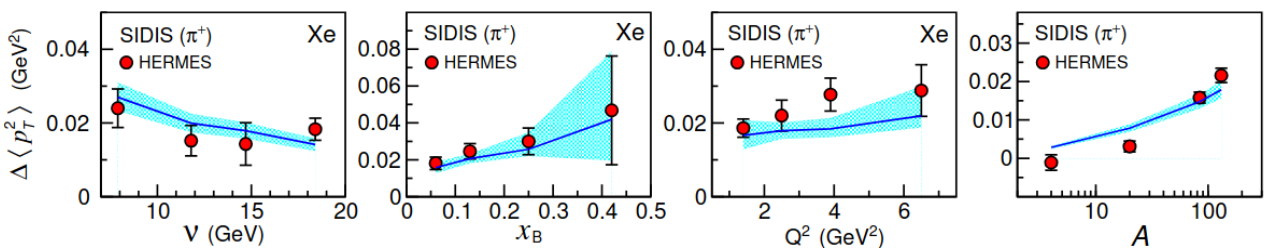
We notice that our model affects the shape

- We could not find a way to improve this
  - **Pure energy loss does not get it right**
  - **And absorption always deteriorates the description**









Summary and Conclusions

SIDIS data on nuclei offers a tough challenge to models

- Very constraining on parton energy loss calculations

We made a model to describe SIDIS data on nuclei

- We included the transverse momentum
- Most importantly we kept all correlations

We described the data well over a large energy range

- We found that survivor bias is very important
  - **This finding might resolve many issues past studies had**
  - **At the same time studies trying to extract information from the data should be careful**
- We found that the A dependence is not well described
  - **Pure energy loss offers the better description but needs improvement**