The Concept of Hadron Formation Length

When/where does a hadron actually interact "hadronically"

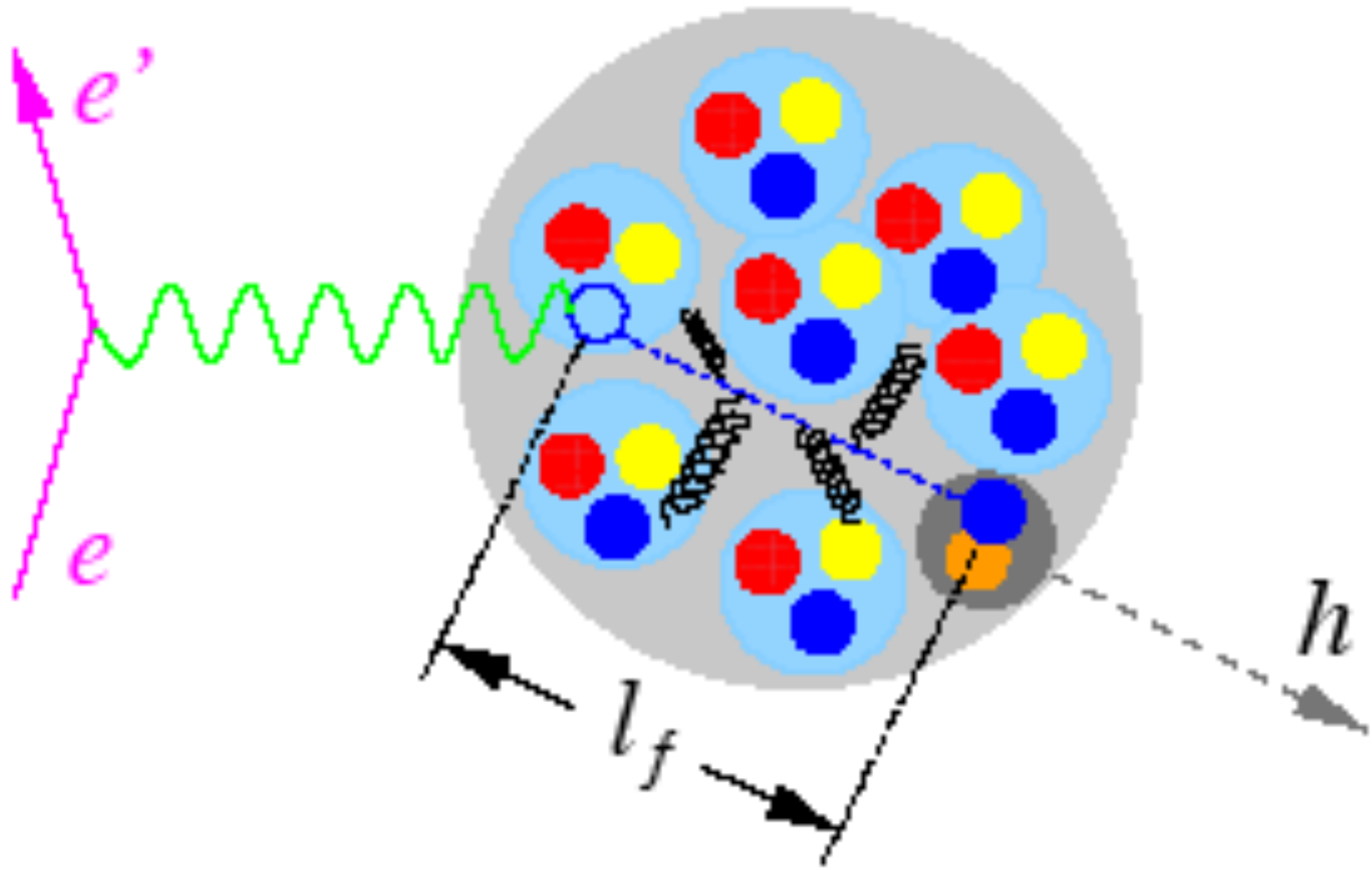
Jorge G. Morfín
Fermilab

Hadron (Pion) Formation Length - Hadronization

Will Brooks – USM, Chile – Expert; source of many figures

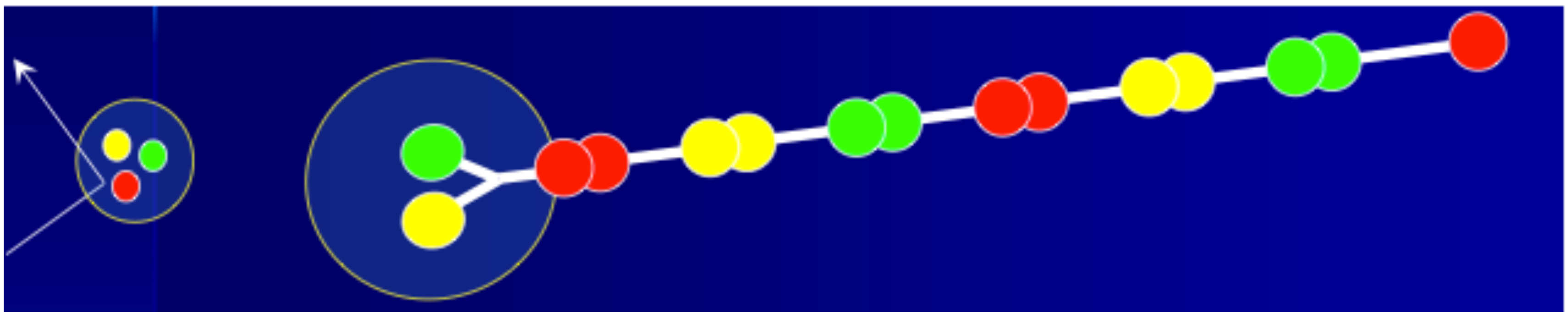
Jan Sobczyk et al. **Final State Interactions Effects in Neutrino-Nucleus Interactions**

arXiv:1202.4197



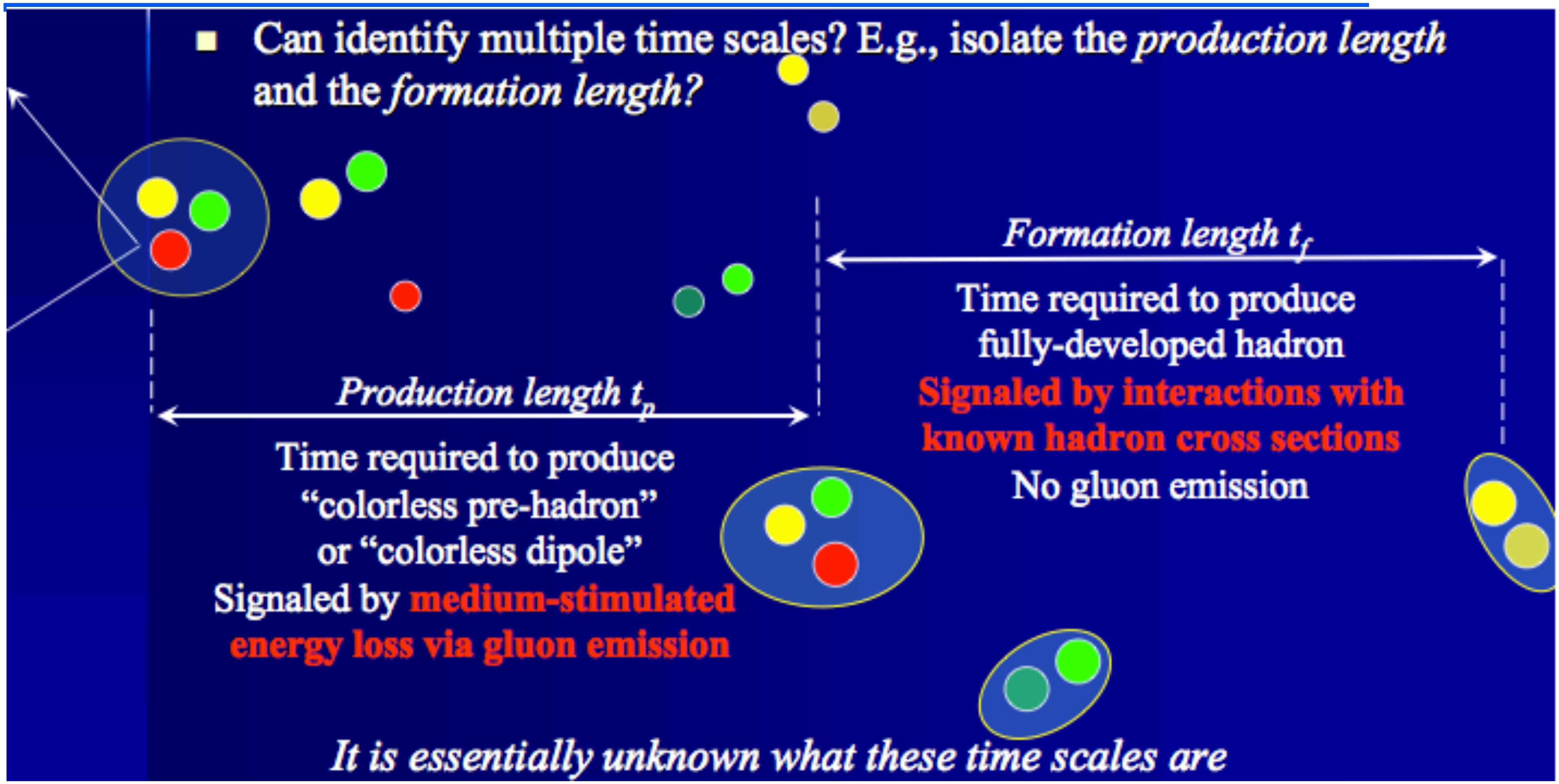
The Concept

- Hadronization via a two-step process: first production time/ length



- "Confinement" is still involved and we – have a "production" time before a "formation" time. During this production time the quark(s) can lose energy by emitting gluons or quark-N interactions …

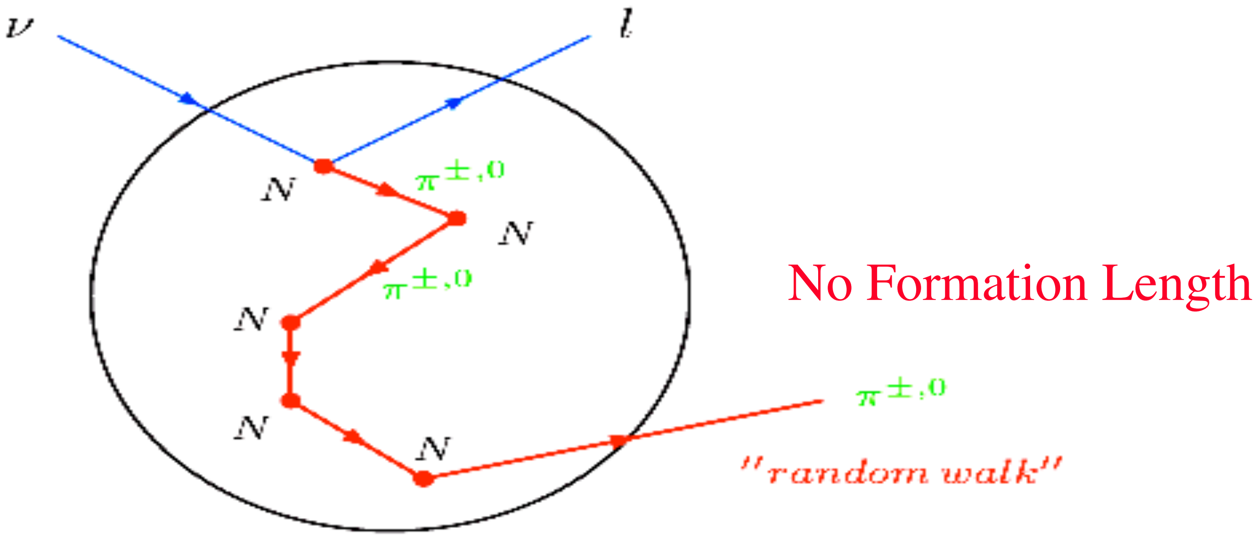
Two Time Scales for Hadron Formation



- Can actually estimate the different lengths via experiment.
- For us, let's consider only the sum of the two lengths.

Why do we care? Final State Interactions

- Two step process



1. single pion production in νN scattering
   $\rightarrow$ Pauli Principle, Fermi motion
2. multiple scattering of pions
   $\rightarrow$ Charge exchange, absorption, Pauli Principle

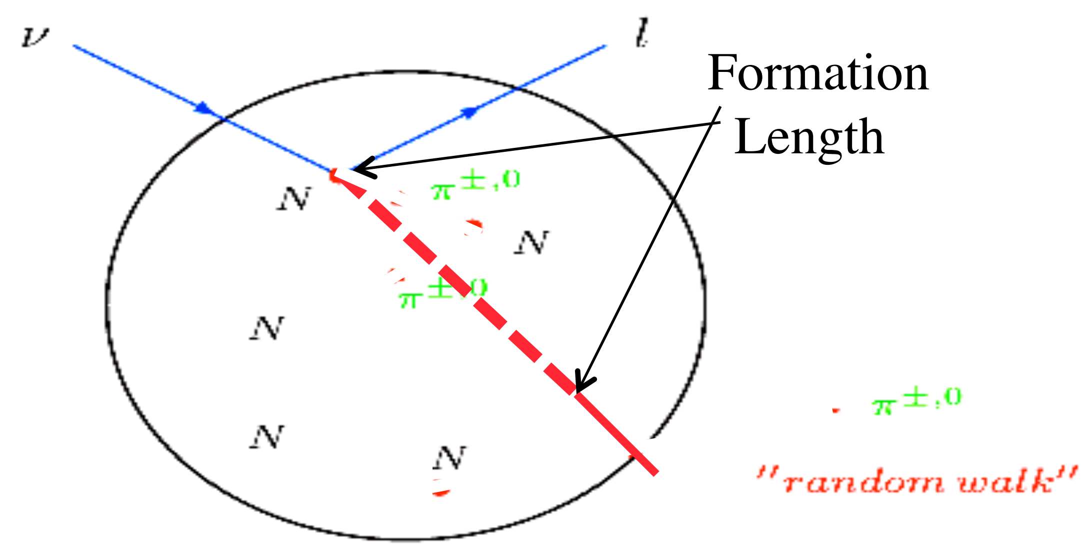
- step 2 is described by the charge exchange matrix M
  - only depends on properties of the target
    $\rightarrow$ charge density profile $\rho(r)$

Why do we care? Final State Interactions

Introduce Formation Length – no strong interactions until hadron is “formed”

Pion more probable to escape the nucleus without any FSI

- Two step process



1. single pion production in νN scattering
   → Pauli Principle, Fermi motion
2. multiple scattering of pions
   → Charge exchange, absorption, Pauli Principle

- step 2 is described by the charge exchange matrix M
  - only depends on properties of the target
    → charge density profile $\rho(r)$

◆ Without formation length:

- ▼ Lower average E of particles leaving the nucleus
- ▼ Broader p_T spectrum of particles leaving the nucleus

We can determine this “formation length” for a pion ($z = E_\pi / \nu$) via Hadron Multiplicity Ratios off various A

$$R_M(z,\nu,Q^2,p_t^2) = \frac{\left.\dfrac{N_h(z,\nu,Q^2,p_t^2)}{N_{DIS}}\right|_A}{\left.\dfrac{N_h(z,\nu,Q^2,p_t^2)}{N_{DIS}}\right|_D} \propto \frac{\left.\dfrac{\Sigma e_f^2 q_f(x,Q^2,p_T^2) D_f^h(z,Q^2,k_T^2)}{\Sigma e_f^2 q_f(x,Q^2,p_T^2)}\right|_A}{\left.\dfrac{\Sigma e_f^2 q_f(x,Q^2,p_T^2) D_f^h(z,Q^2,k_T^2)}{\Sigma e_f^2 q_f(x,Q^2,p_T^2)}\right|_D}$$

Leptonic variables : ν (or x) and Q^2

Hadronic variables : z and p_t^2

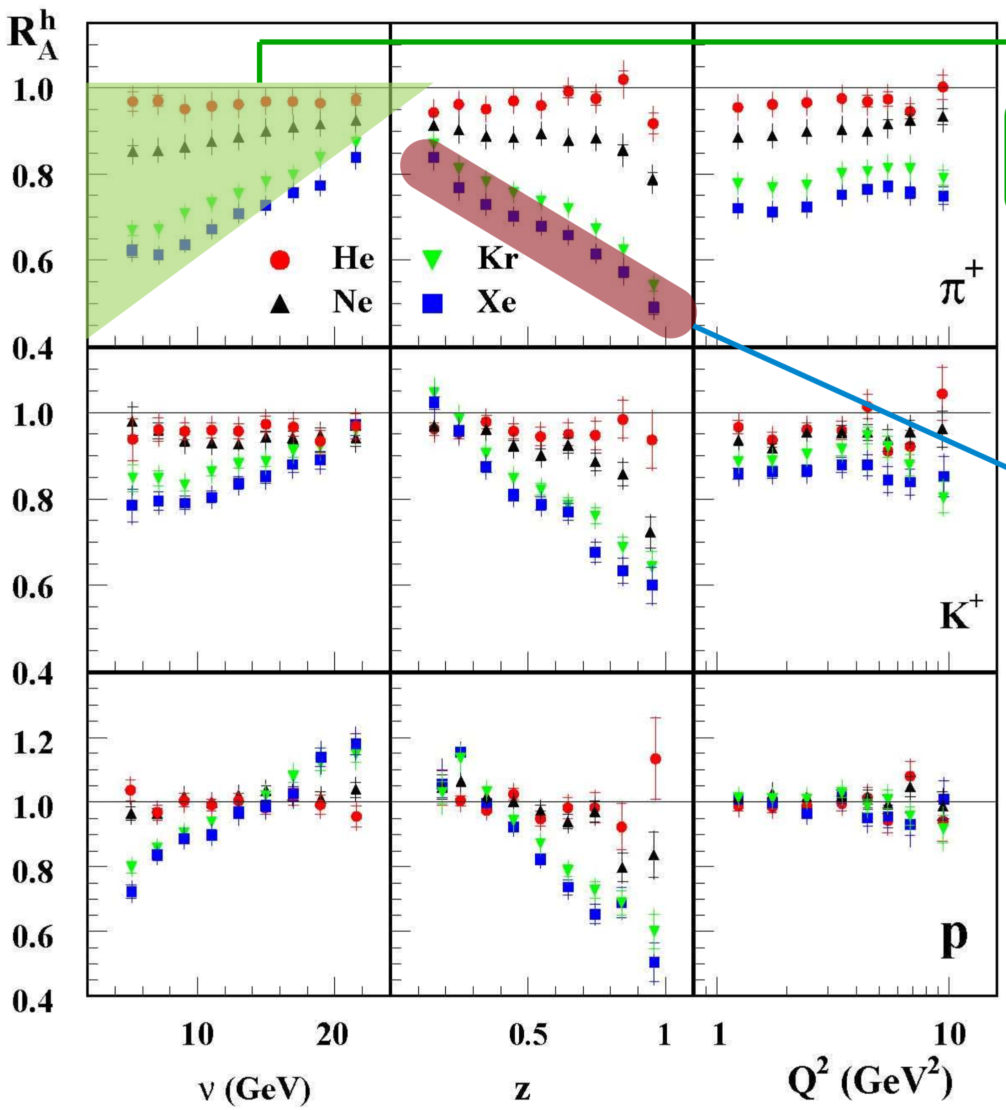
Different nuclei : size and density

Different hadrons : flavors and mixing of FFs

Double-ratio: no need for acceptance corrections

Systematic uncertainties are minimize in the double-ratio

Fit ratios to $\tau = f(A, z, \nu, Q^2, p_T^2)$
HERMES (SLAC, EMC, E665)

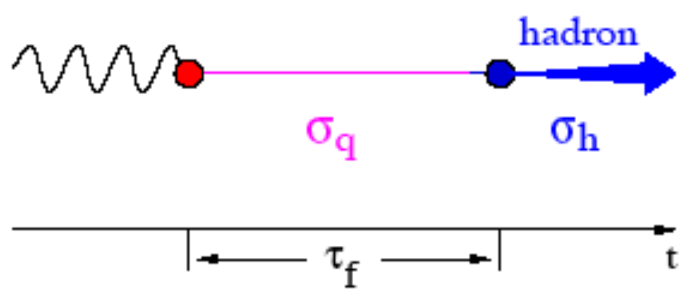


Strong A mass effect

z behavior
Partonic: energy loss +
FF modification
Hadronic: h formation length
+ absorption

Models of Hadron Attenuation: Sum Both Steps

- Hadron production from nuclei can be influenced by
  - Pre–hadronized quark interactions with other nucleons in nucleus
  - Produced hadron interactions with other nucleons
- $t_f = l_f / c$, the hadron formation time will affect which dominates



- One time–scale model - hadron produced "directly"

$\tau_f \approx E_h R_h / m_h$

For pion mass, $R_h = 0.66$ fm

For 0.5 GeV p, $\tau_f \approx 2.4$ fm

Two Expressions for Pion Formation Length

HERMES parameterization for pion formation length:

Valid for higher energy pions

$$\tau = 1.4 \cdot \nu \cdot (1 - z)\ fm$$

[1]

Example: $z = 0.5$ $\nu = 10$ Gev

$\tau = 7$ fm ≈ radius of Pb

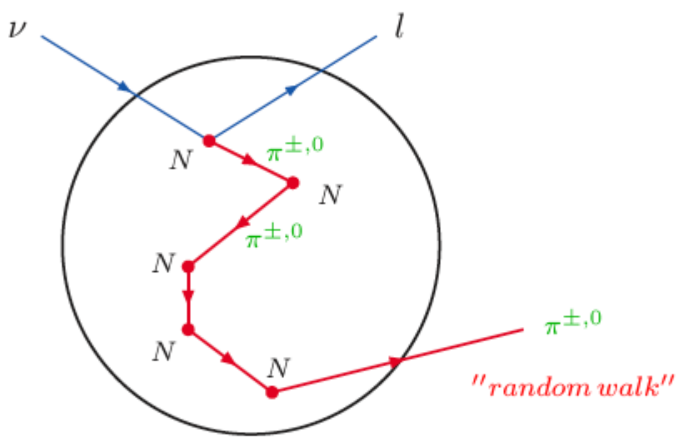
For lower E_π: $$\tau = \frac{.342\ p\ (GeV/c)\ m_\pi}{m_\pi^2 + a\ p_t^2}$$

Nucleus	A	r_0 (=1.2 fm $A^{1/3}$)	p ($l_f > r_0$)
C	12	2.7 (fm)	1.1 (GeV/c)
Fe	56	4.6	1.8
Pb	207	7.1	2.9

Nuclear Effects - Formation length

Adler, Nusinov, Paschos model (1974)

1. single pion production in νN scattering
   $\rightarrow$ Pauli Principle, Fermi motion
2. multiple scattering of pions
   $\rightarrow$ Charge exchange, absorption, Pauli Principle

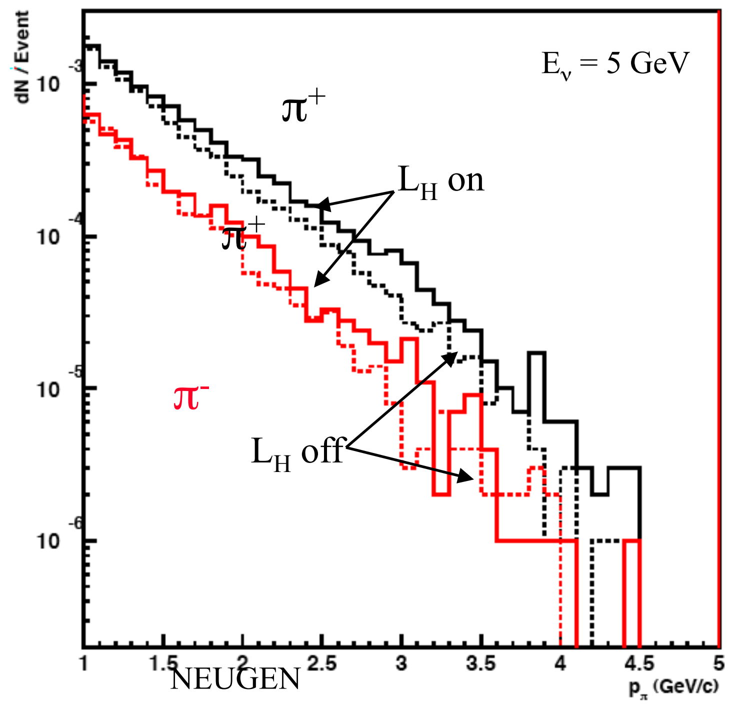


- charge exchange matrix M for isoscalar targets
  ($M = M^T$, $\sum_j M_{ij} = A_p$, $M_{+0} = M_{-0} \rightarrow$ 3 param. A_p, d, c)

$$M = A_p \begin{pmatrix} 1-c-d & d & c \\ d & 1-2d & d \\ c & d & 1-c-d \end{pmatrix}$$

- π^+ cross section is largely reduced (up to 40%) $\leftrightarrow$ charge exchange M
- π^0 cross sections is slightly increased by the nuclear corrections

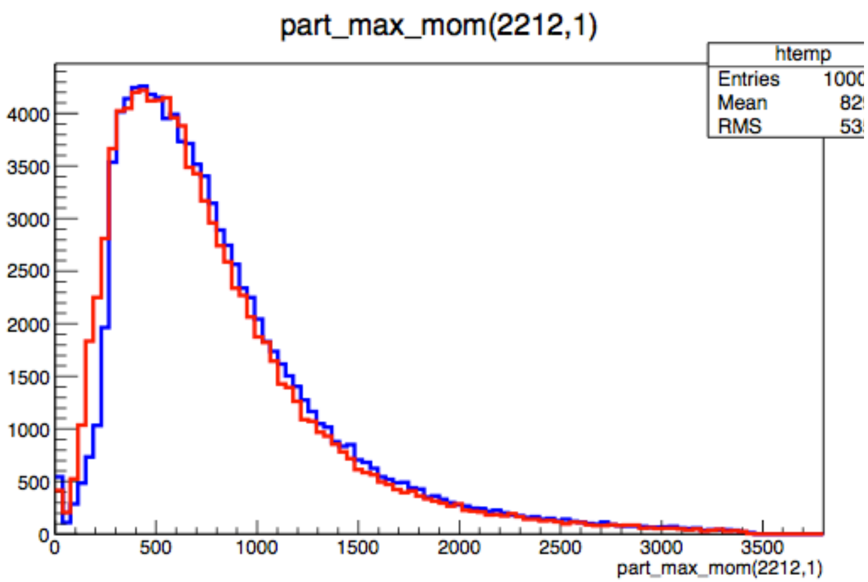
One obvious omission, this model does not include **hadron formation length corrections**

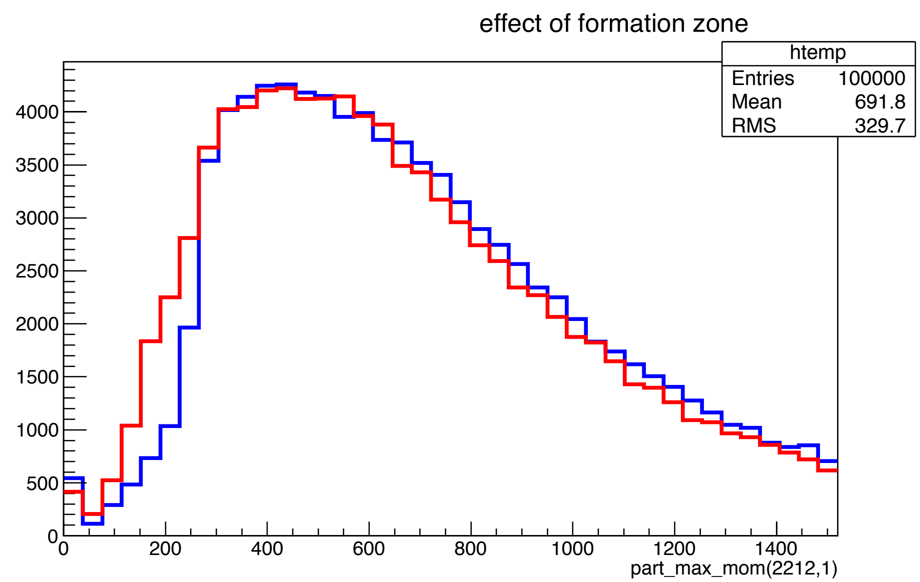


MINERνA can measure L_H off of C, Fe and Pb

What About Nucleons?

- Jan Sobczyk with T. Golan and C. Juszczak summarized the concept of using the "uncertainty principal" in terms of a "coherence length".
- It gives us a "reaction time" within which the proton cannot interact: $\tau = E / |p.\ q|$
  $\rightarrow$ $\tau_{SKAT} = E / \mu^2$ with $\mu^2 = 0.08 \pm 0.04\ GeV^2$
- With E_ν = 3 GeV, using NuWRO Jan gets the following. An average increase of momentum of protons out of the nucleus of 40 MeV/c.





Formation Length in MC Generators (Jan)

TABLE III. Formation Time models in various Monte Carlo event generators.

MC	QE	RES[a]	DIS
NEUT	–	SKAT	SKAT
FLUKA	Coh length	Rantf	Rantf
GENIE	–	–	Rantf-like
NUANCE	1 fm	1 fm	1 fm

[a]Note that every MC has its own definition of what the RES and DIS terms mean.

- NuWro uses a formation zone for both nucleons and pions.
- Jan currently looking at FZ effects for 1 and 2-track QE with complete LE spectrum on scintillator, Fe and Pb. For 2-track looking at fraction with p above 150 MeV while for 1 track checking the outgoing proton and neutron energy spectra with and without FZ.