Hadronization, Formation Times and CT in quantum-kinetic Transport Theory

Ulrich Mosel with Kai Gallmeister

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Time Course of a (γ,ν) *A* Reaction

- First, initial state (IS) interaction of incoming photon (*W*, *Z*) with Fermi-moving nucleon in a groundstate potential -> initially produced final state hadrons are affected by that potential
- Second, final state (FS) interaction of the produced hadrons in that same potential, move out through the nucleus to detector
  - → IS and FS do not factorize!
- Initial starting points for hadron FS transport are anywhere within the nuclear volume; photons illuminate the whole nucleus.

CT identification needs reliable FSI description

Simplicity

Correctness

- Kadanoff-Baym equation (1960s)
  - full equation not (yet) feasible for real world problems
- Boltzmann-Uehling-Uhlenbeck (BUU) models: GiBUU
  - Boltzmann equation as gradient expansion of Kadanoff-Baym equations, in Botermans-Malfliet representation (1990s) with off-shell transport
- Cascade models (typical event generators, GENIE, NEUT, NuWro, …)
  - Nuclei not bound, no mean-fields, primary interactions and FSI not consistent, frozen nuclear configuration, ….
- Purely absorptive Cascade: Glauber

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU** : **Quantum-Kinetic Theory and Event Generator** based on a BM solution of Kadanoff-Baym equations
- GiBUU propagates phase-space distributions, not particles
- Physics content and details of implementation in:
  Buss et al, Phys. Rept. 512 (2012) 1- 124
- Code from gibuu.hepforge.org, new version GiBUU 2021
- GiBUU works with a semiclassical bound target groundstate

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Quantum-kinetic Transport Theory

$$\overbrace{\mathcal{D}F(x,p)}^{\text{On-shell drift term}} - \overbrace{\mathrm{tr}\left\{\Gamma f, \mathrm{Re}S^{\mathrm{ret}}(x,p)\right\}_{\mathrm{PB}}}^{\text{Off-shell transport term}} = \overbrace{C(x,p)}^{\text{Collision term}} \; .$$

$$\mathcal{D}F(x,p) = \{p_0 - H, F\}_{\mathrm{PB}} = \frac{\partial(p_0 - H)}{\partial x}\frac{\partial F}{\partial p} - \frac{\partial(p_0 - H)}{\partial p}\frac{\partial F}{\partial x}$$

H contains mean-field potentials

Describes time-evolution of *F(x,p)*

$$F(x,p) = 2\pi g f(x,p)\, \mathcal{P}(x,p)$$

Spectral function

Phase space distribution

KB equations with BM offshell term

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU** describes: (within the same unified theory and code)
  - heavy ion reactions, particle production and flow
  - pion and proton induced reactions on nuclei
  - photon and electron induced reactions on nuclei
  - neutrino induced reactions on nuclei

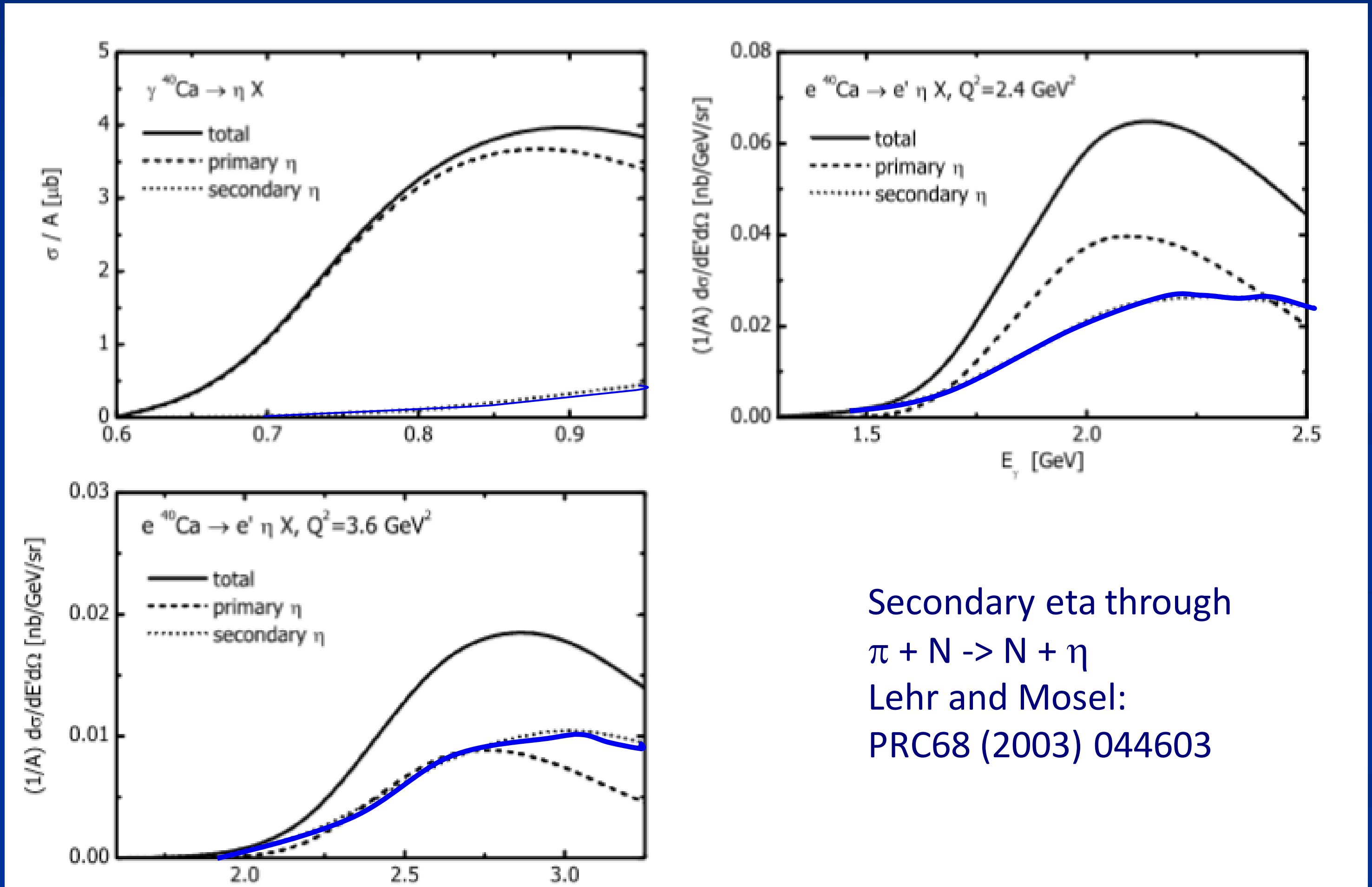
using the same physics input! And the same code!

NO TUNING! Independent checks for FSI

-> main strength in description of FSI

Transport vs Glauber

Final channel may be different from the initial one:



Secondary eta through
π + N -> N + η
Lehr and Mosel:
PRC68 (2003) 044603

Glauber gives absorption only, dcreases X-section, does not tell you where particles go

Transport allows for sidefeeding from secondary reactions, increases X-section

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GiBUU Ingredients: Lifetimes of prehadrons

- Baryon Resonances up to $W \sim 2$ GeV transported explicitly, with properties from PDG, *lifetime determined by widths*
- Baryon DIS Processes ($W > 2$ GeV) described by string fragmentation (PYTHIA), *lifetime determined by fragmentation time-scale*, no external \`formation times\`:

K. Gallmeister, U. Mosel
\`\`Time Dependent Hadronization via HERMES and EMC Data Consistency''
Nucl. Phys. A **801**(2008) 68

K. Gallmeister, T. Falter
\`\`Space-time picture of fragmentation in PYTHIA/JETSET for HERMES and RHIC''
Phys. Lett. B **630** (2005) 40

- Problem: Cross section development during these \`formation times\`, often taken to be *0* , e.g. GENIE: no interactions within *0.342* fm/c !

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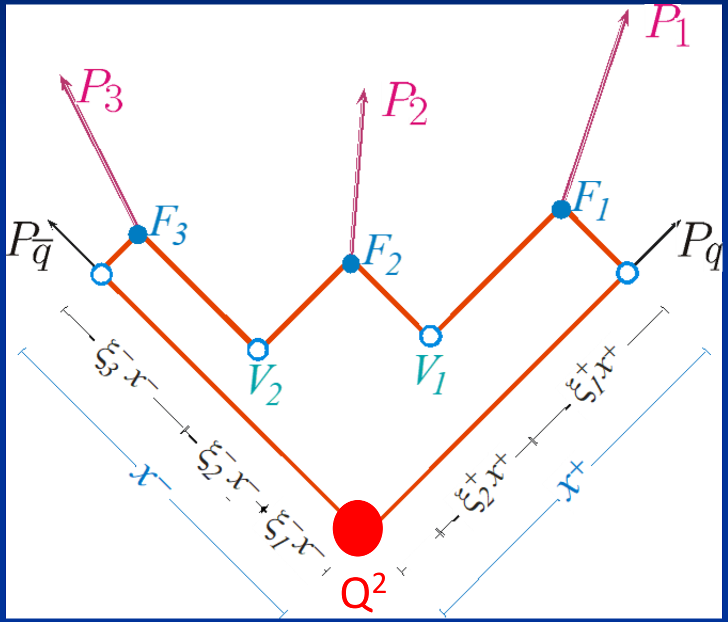
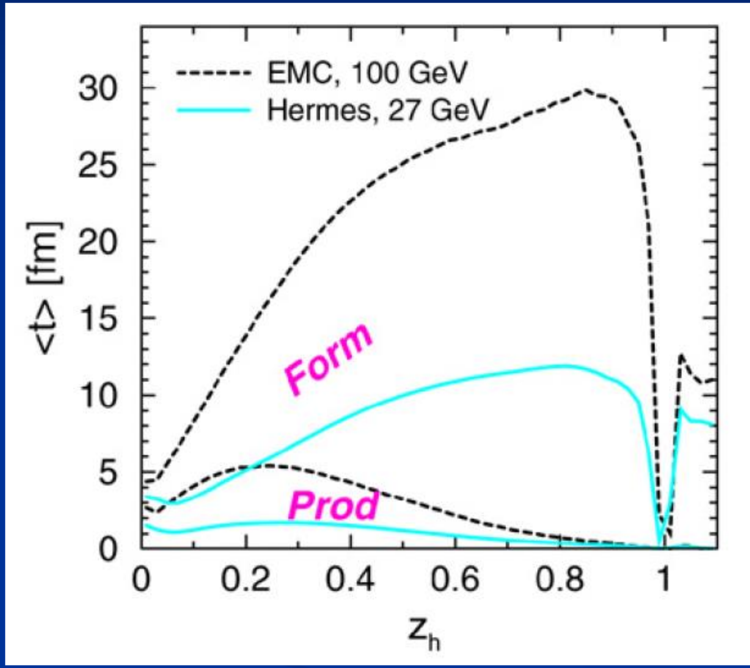
String model hadronization





Average times

1. Production V1: String breaking
2. Production V2: String breaking
3. Formation: F1, F2, F3

   P1 and P3 contain *leading partons*,

   P2 does not ! Only leading partons are directly influenced by Q^2

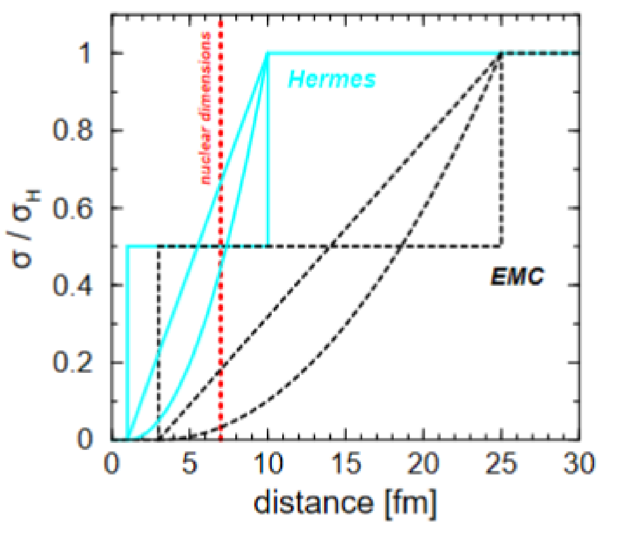
$z_h = E_h/\nu$

K. Gallmeister, U. Mosel
Nucl. Phys. A801 (2008) 68

Time-dependence of X-sections

- Dokshitzer in „Basícs of Perturbative QCD (1991)“ :
  - classical model: $\sigma^*(t) = \sigma_h\,(t/t_F)^2$, quantum model: $\sigma^*(t) = \sigma_h\,(t/t_F)$

    „A good, complete experimental program studying almost exclusive reactions in nuclei should be able to tell us which is the better formula at a given momentum transfer.”



$$\frac{\sigma^*(t)}{\sigma} = \left(\frac{t - t_P}{t_F - t_P}\right)^n, \quad n = 1, 2.$$

Hermes (28 GeV): ~ 0.5 of hadronization inside nucleus
EMC (100 GeV): nearly all hadronization outside nucleus

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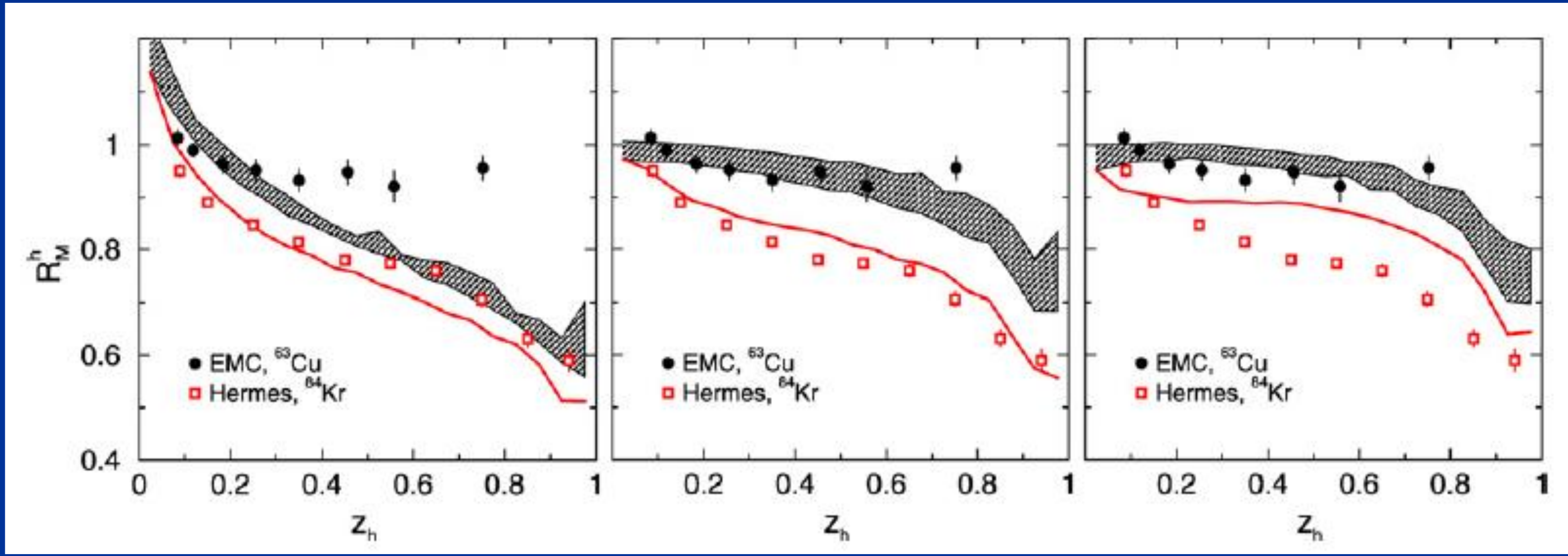
Dokshitzer's question answered:

Nuclear modification:

$$R_M^h(\nu, Q^2, z_h, p_T^2, \ldots) = \frac{[N_h(\nu, Q^2, z_h, p_T^2, \ldots)/N_e(\nu, Q^2)]_A}{[N_h(\nu, Q^2, z_h, p_T^2, \ldots)/N_e(\nu, Q^2)]_D}$$



constant linear quadratic

EMC: 100/280 GeV
HERMES: 27 GeV

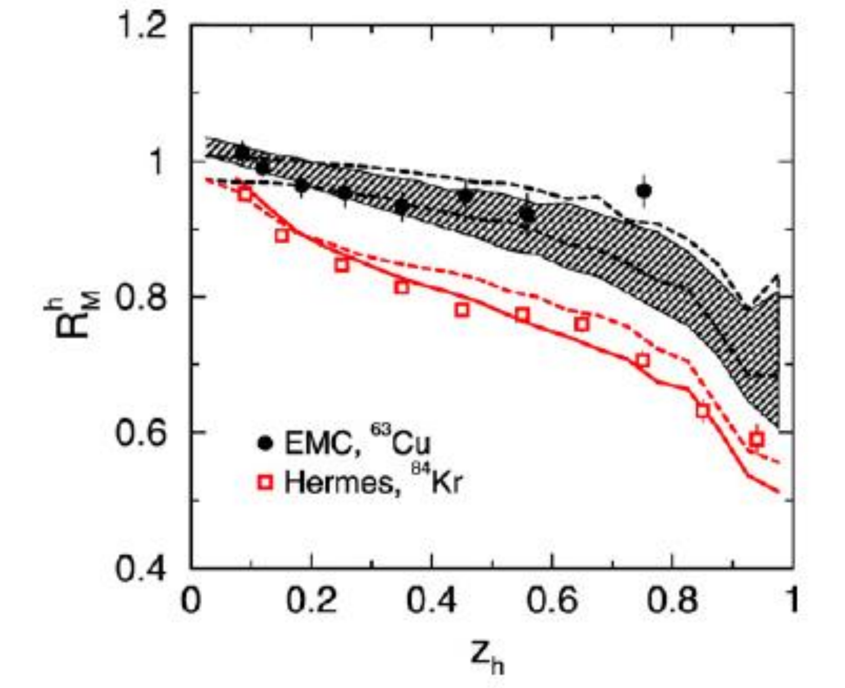
K. Gallmeister, U. Mosel
Nucl. Phys. A801 (2008) 68

Quantum Diffusion Model (QDM)
(Farrar, Strikman et al)

$$\frac{\sigma^*(t)}{\sigma} = X_0 + (1 - X_0) \cdot \left(\frac{t - t_P}{t_F - t_P} \right), \quad X_0 = r_{\mathrm{lead}} \frac{\mathrm{const}}{Q^2},$$

GiBUU default,
for DIS only, not QE !!!!

r_{lead} = number of leading partons/total number of partons
const = 1 GeV^2

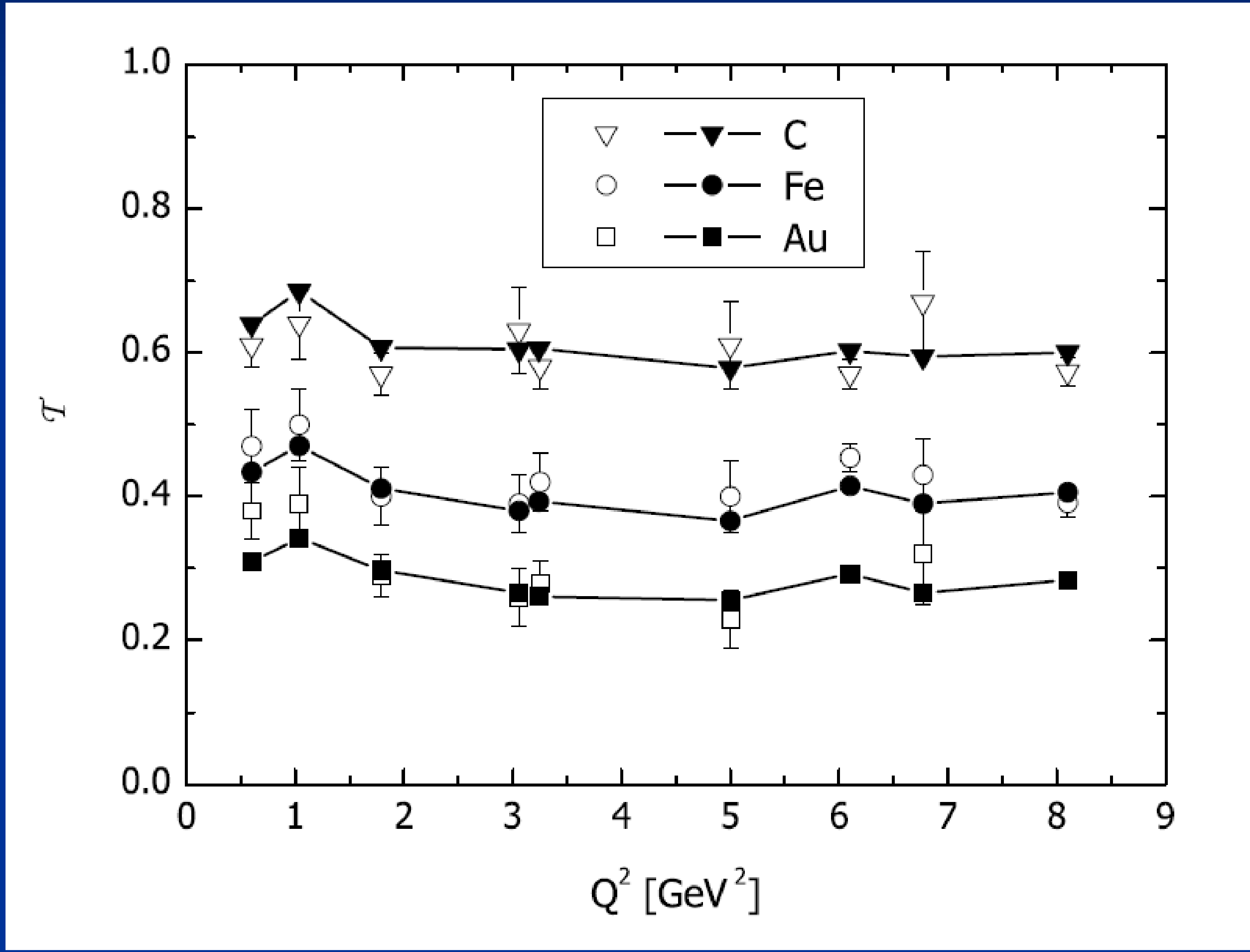


Dashed: quadratic
Solid: QDM

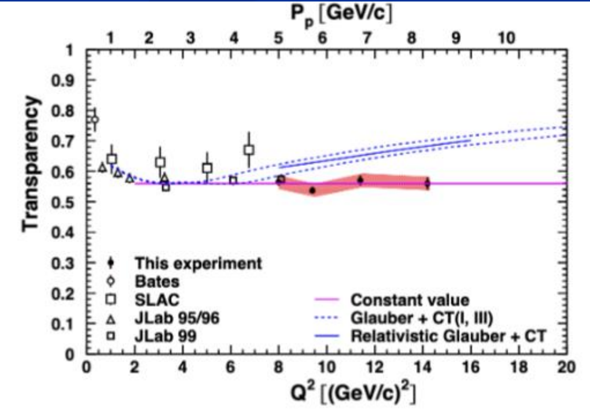
Small effect of X_0

-> weak explicit Q^2 sensitivity

Transparency from (e,e‘p)



Theory: J. Lehr, thesis, 2003
Data: JLAB, SLAC



QE kinematics,
no formation times

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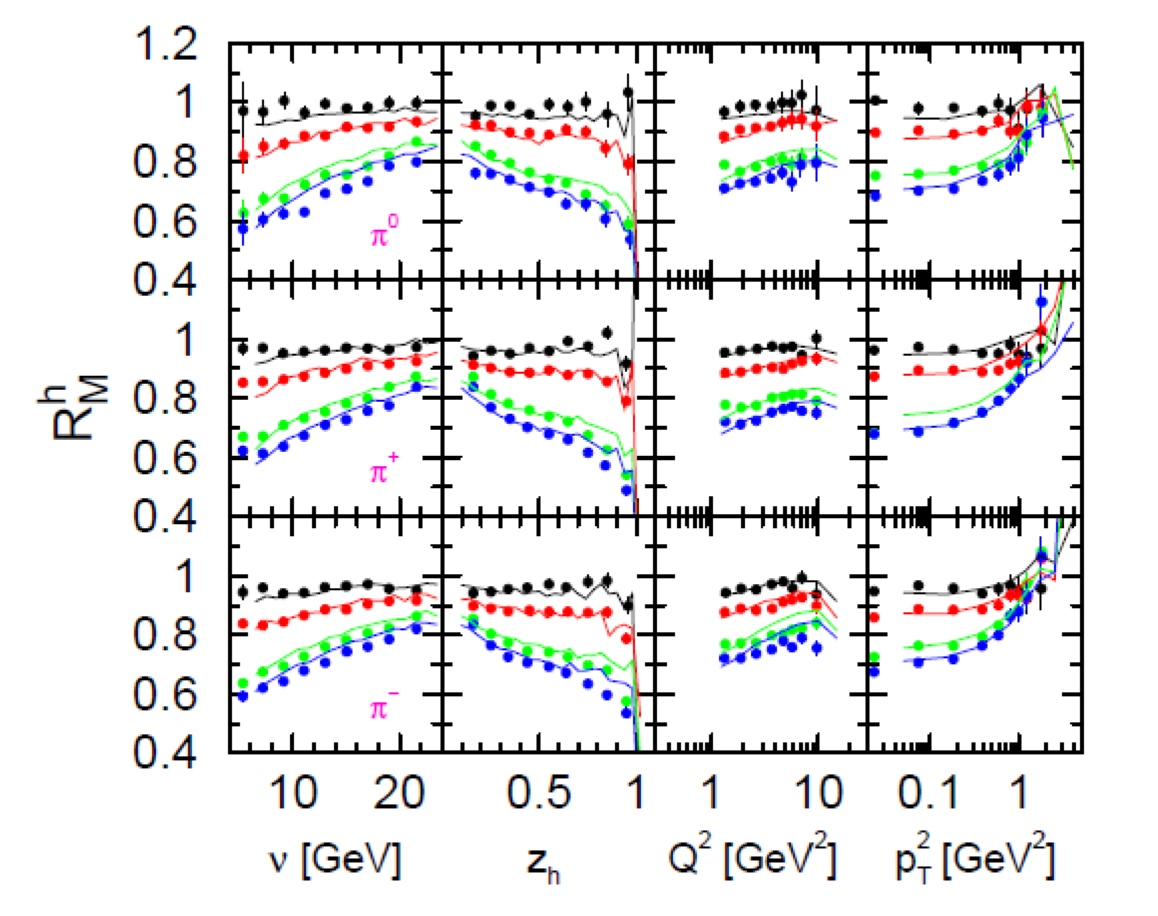
Pions from Hermes (28 GeV)

Most complete set of transparency data

Challenge for any theory



$^4He_2$
$^{20}Ne_{10}$
$^{84}Kr_{36}$
$^{131}Xe_{54}$

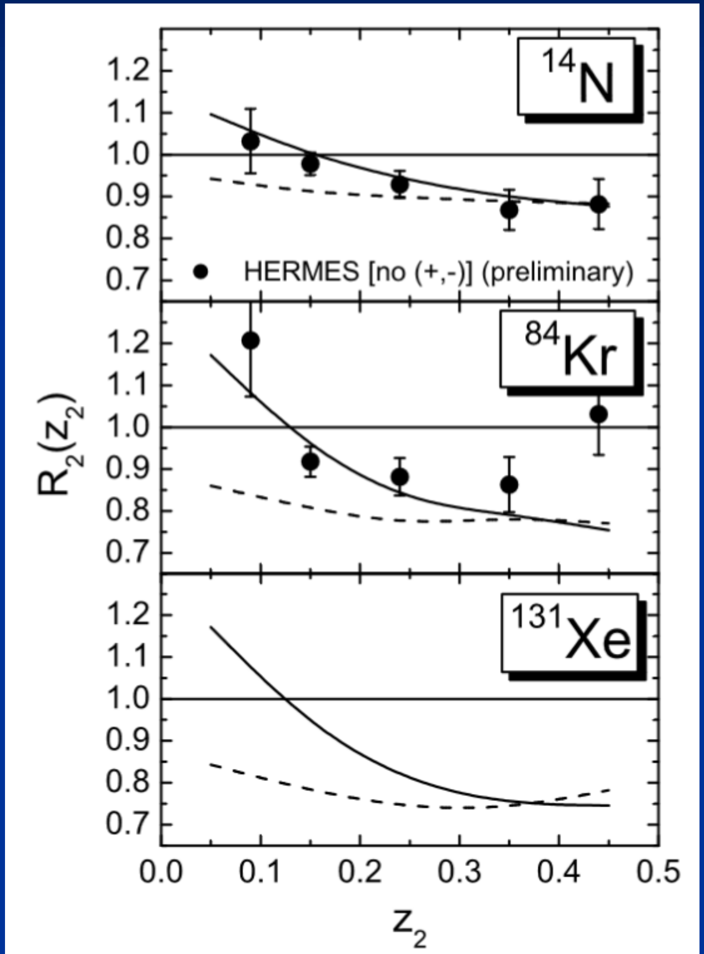
Theory:
K. Gallmeister, U. Mosel
Nucl. Phys. A801 (2008) 68

Double Hadron Attenuation at HERMES

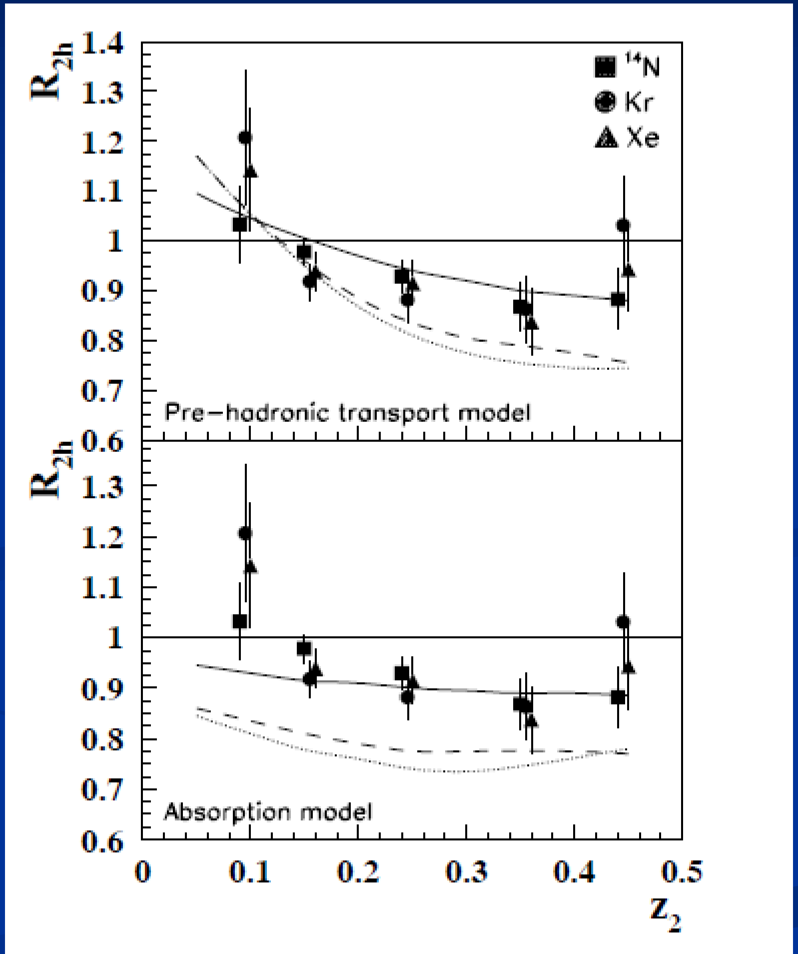
Prediction 2004

Low-z hadrons show pile-up through final state interactions

Glauber : fails at low z_2



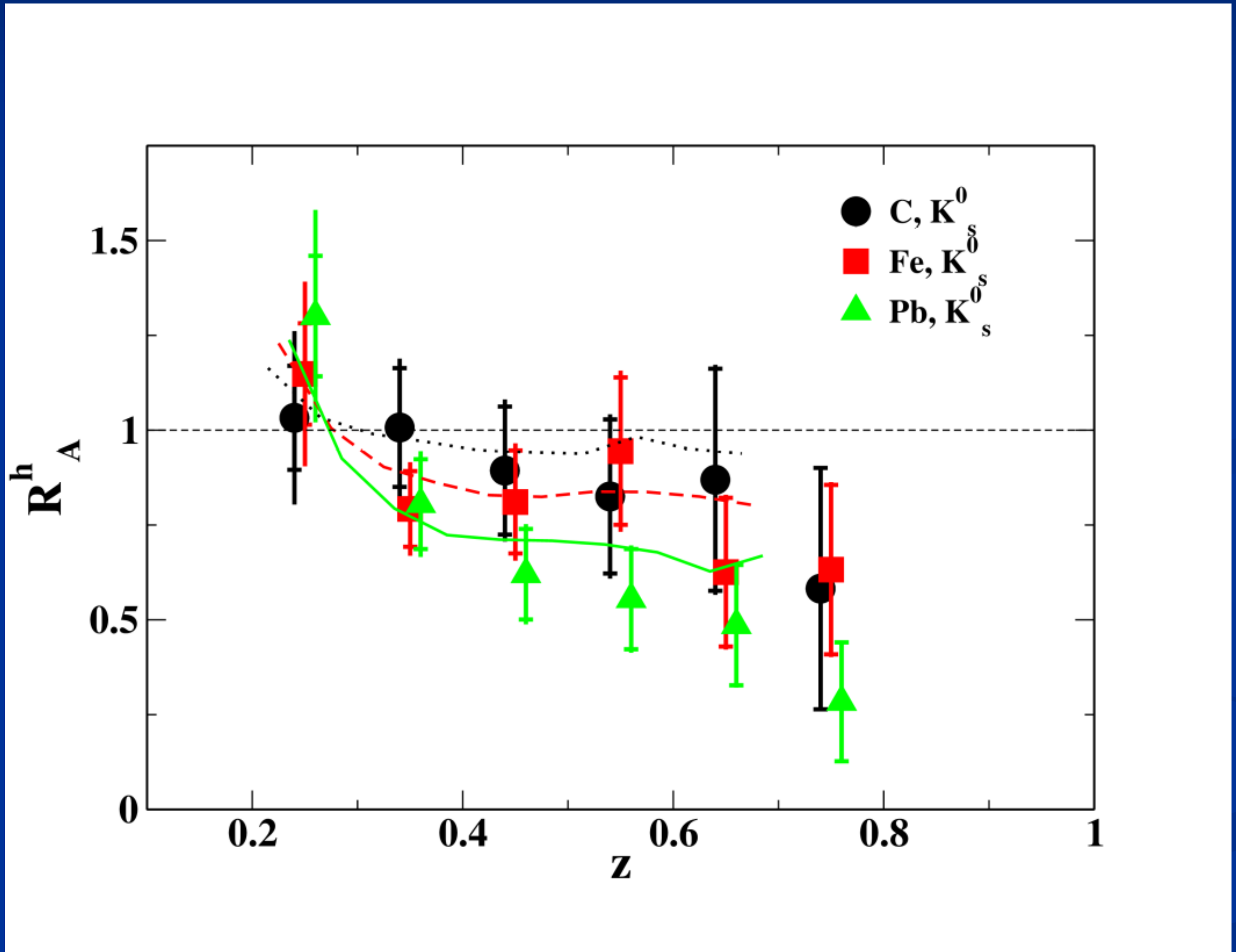
HERMES 2005: *Phys.Rev.Lett.* 96 (2006)



Falter et al, *Phys.Rev.C* 70 (2004) 054609

CLAS@5, Kaons

Data:
A. Daniel et al,
PLB 706 (2011)26



Predictions:
Kai Gallmeister, U.M.,
NPA801(2008) 68

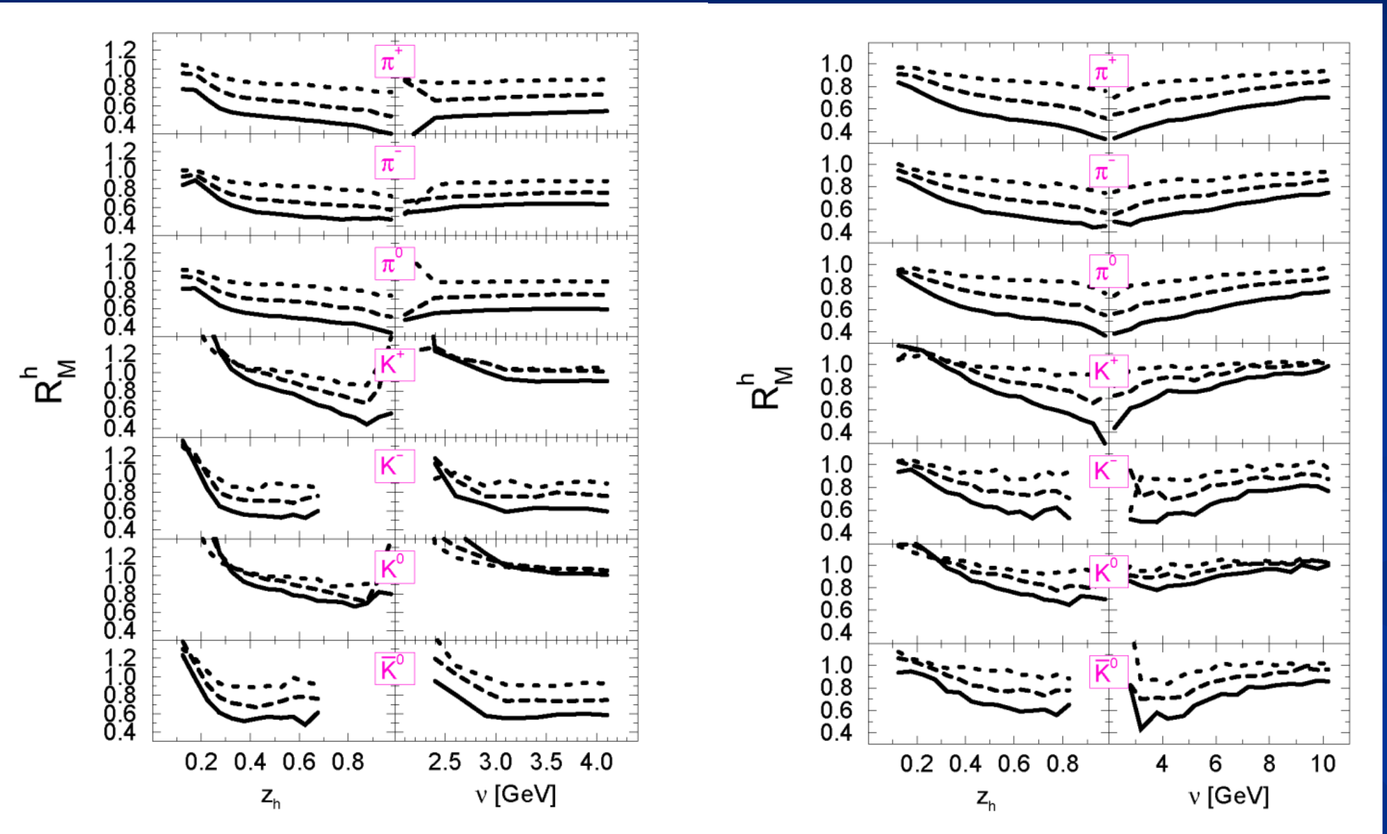
JLAB

5 GeV 12 GeV

CLAS acceptance corrected

Prediction 2004

prelim data: Brooks et al, Hafidi et al



C
Fe
Pb

Gallmeister, Mosel, **Nucl.Phys.A801:68-79,2008**.

At 5 GeV strong nuclear effects: Fermi motion, overpopulation of low z

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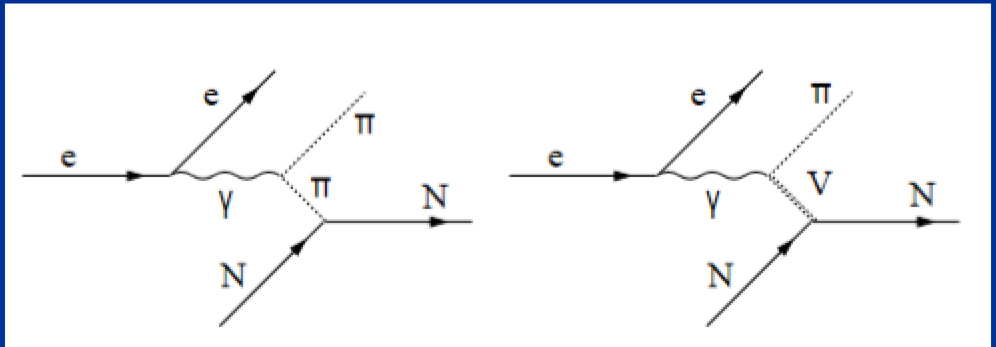
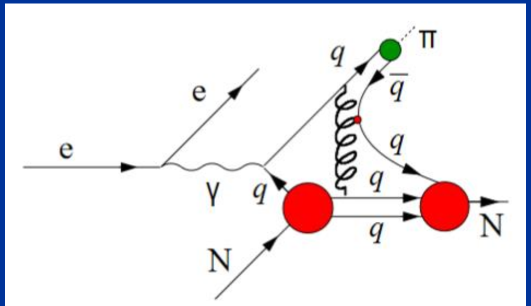
π Production: elementary cross section

- Elementary Cross section:

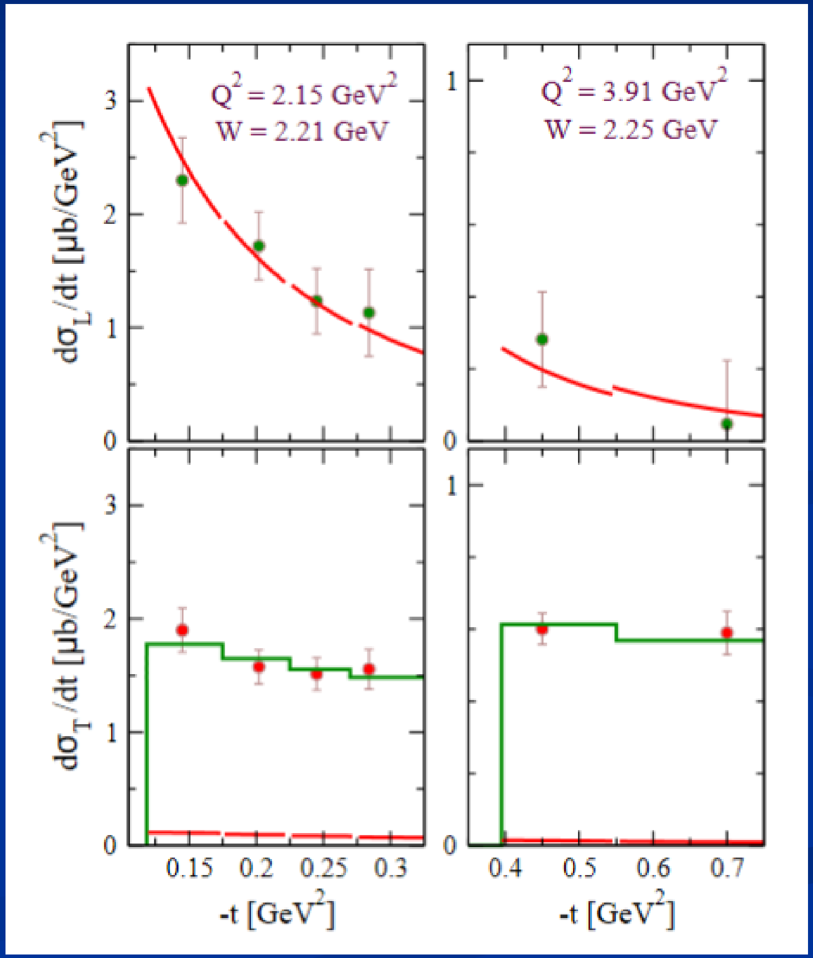


Soft hadronic : Regge param

+



Hard hadronic DIS : Lund string break



Soft

hard

Transverse is nearly all DIS

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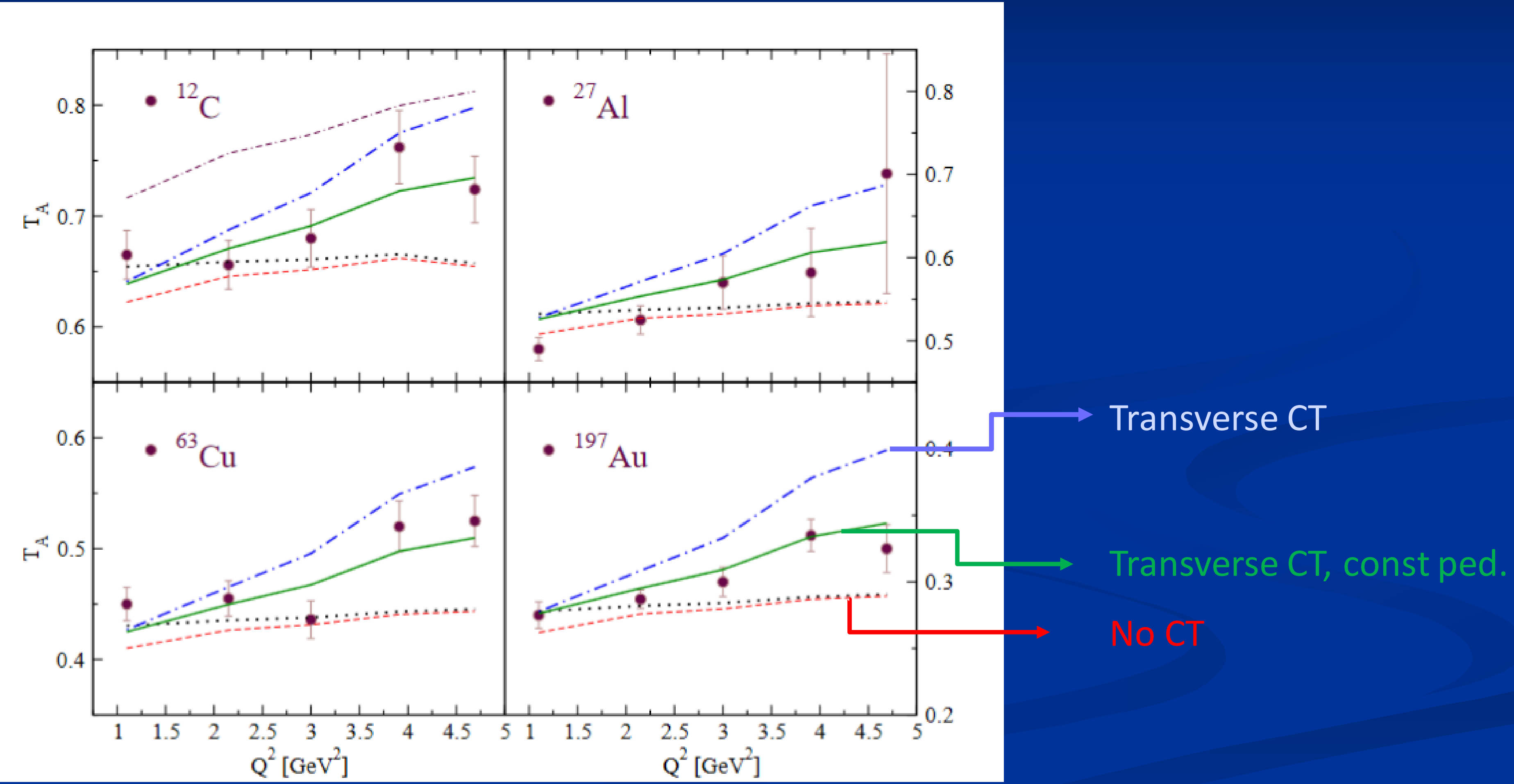
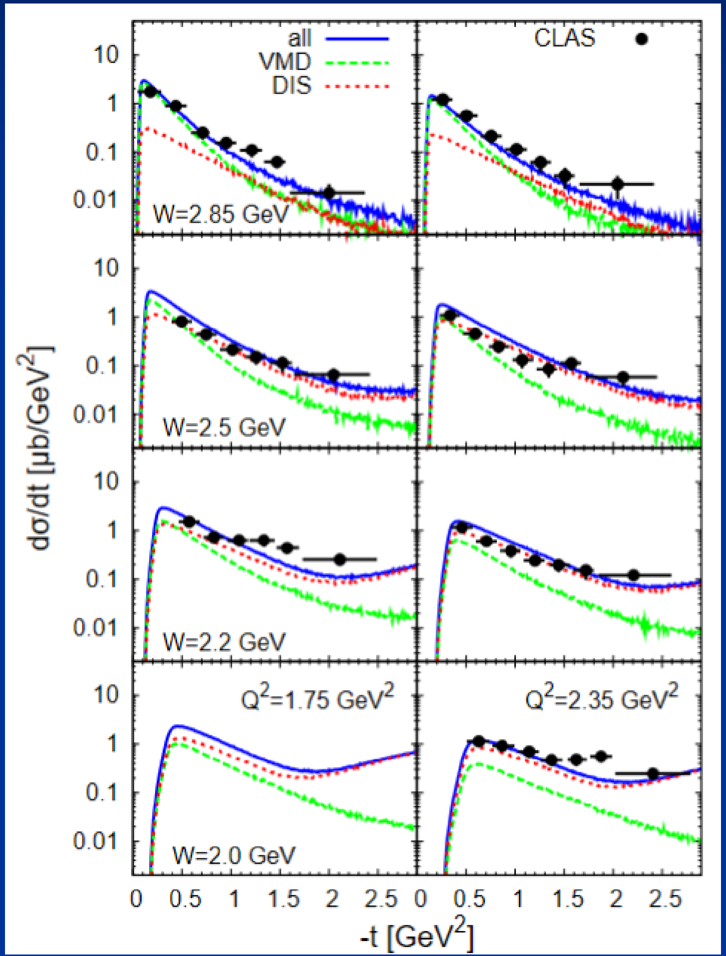
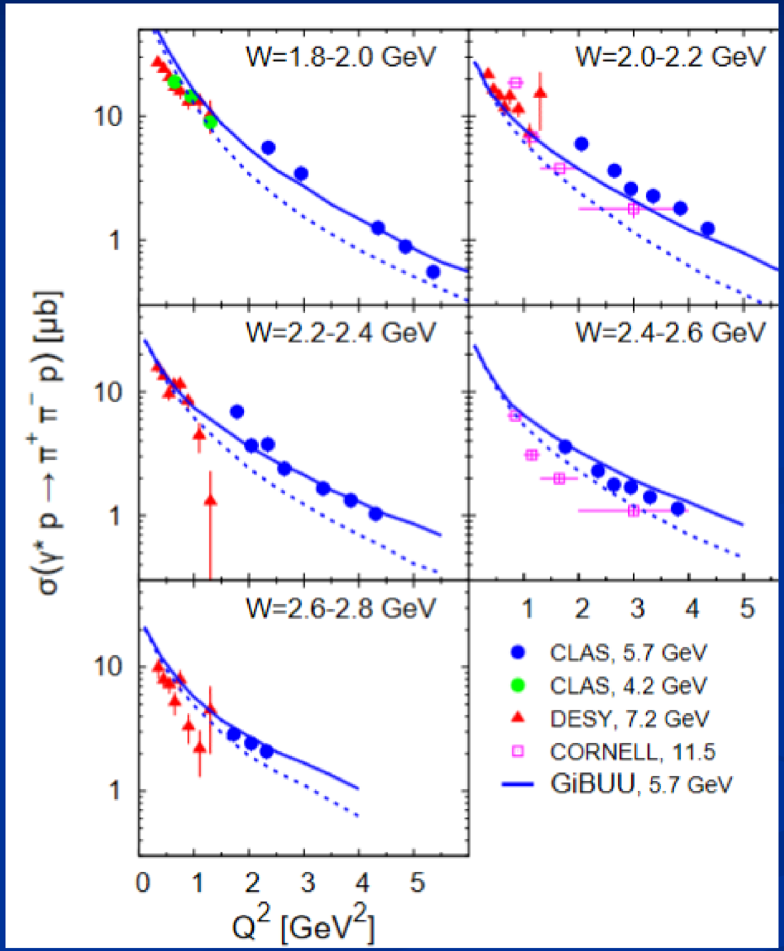
π Production



Data: Clasie et al,
PRL 99 (2007) 242502
Theory: Kaskulov et al,
Phys. Rev. C79 (2009) 015207

ρ Production: elementary cross section





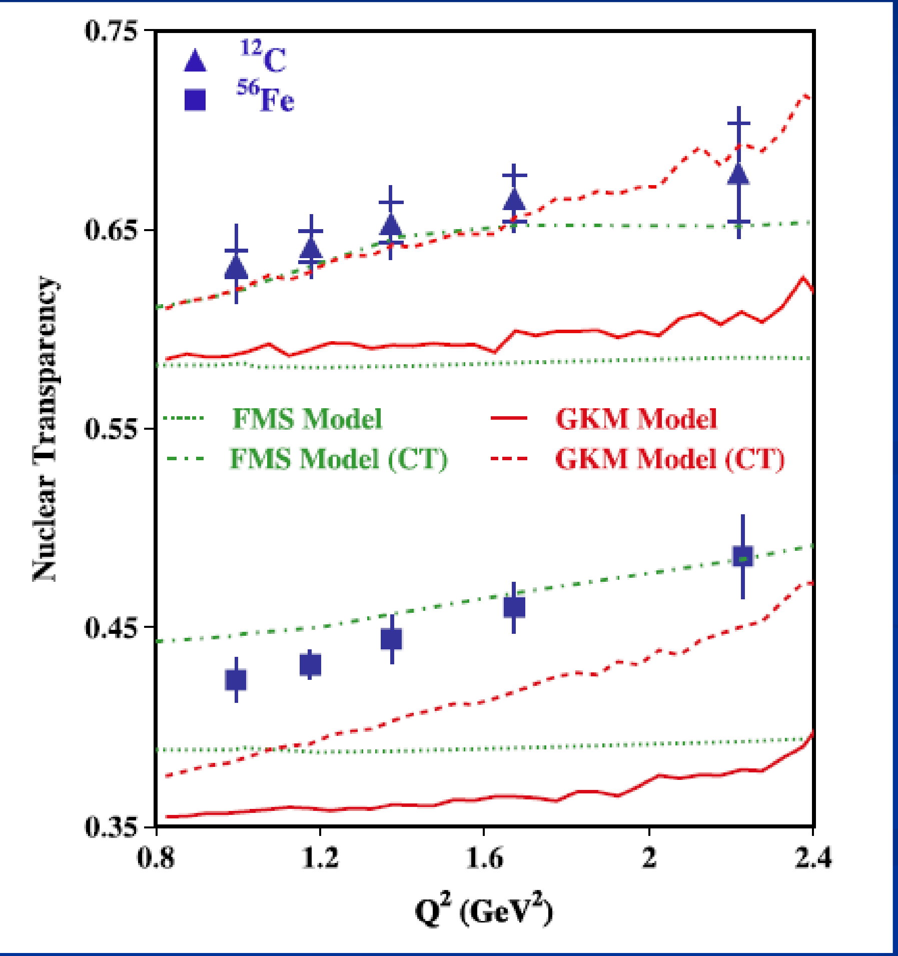
Dashed: neutron X-sect

K. Gallmeister et al,
Phys. Rev. C83 (2011) 015201

p(γ*,ρ)p

Again: hard DIS is essential

ρ Production



FMS: Frankfurt, Miller, Strikman
GKM: Gallmeister, Kaskulov, Mosel (GiBUU)

Data: El Fassi et al (CLAS), PL B 712 (2012)

Summary

- Transport theory is the state-of-the-art method for non-equilibrium, semi-inclusive nuclear reactions, widely used in QGP physics and neutrino astrophysics
- Transport goes beyond Glauber: not only absorption, but also info on where the particles go: essential for energy-spectra and particle production and thus for CT studies

Summary

- Prehadronic cross sections rise with *t*, no ‚free step‘ as in other generators. Linear rise required by data in different energy regimes

- GiBUU uses CT (prehadronic attenuation) for DIS events only, ‚explains‘ absence of CT for QE (e,e‘p), Feynman mechanism?

- Transparencies well described by GiBUU for hadrons at JLAB, HERMES and EMC. JLAB 12 GeV data can add to understanding, less inflence of Fermi motion

Backups

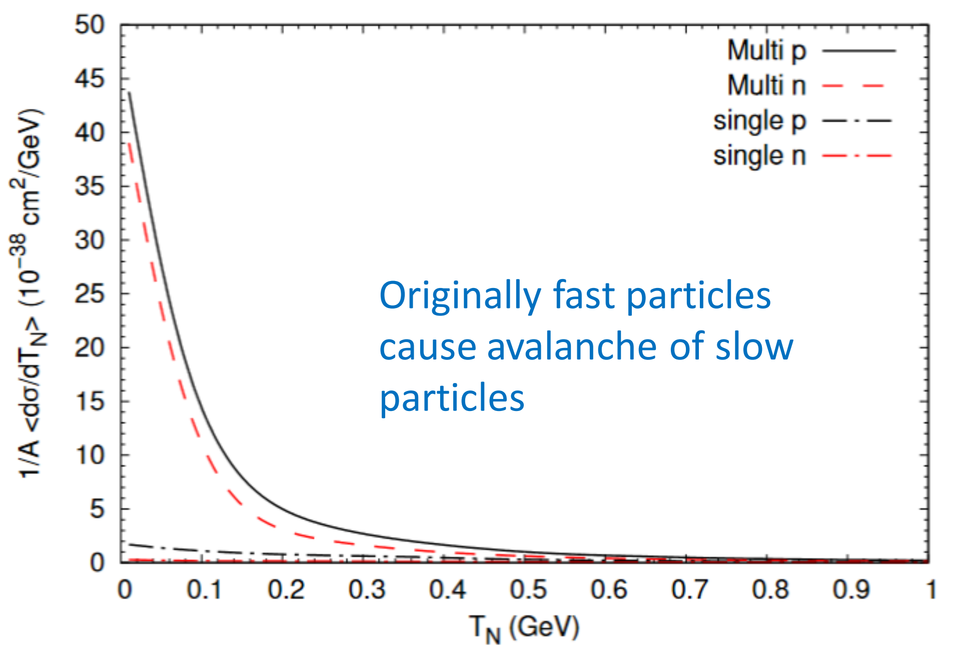
GiBUU

- Essential References:
  1. Buss et al, Phys. Rept. 512 (2012) 1
     contains both the theory and the practical implementation of transport theory
  2. Gallmeister et al., Phys.Rev. C94 (2016), 035502
     contains improvements in GiBUU2016
  3. Mosel, Ann. Rev. Nucl. Part. Sci. 66 (2016) 171
     short review, contains some discussion of generators
  4. Mosel, J. Phys. G 46 (2019) 11
     critical review of generators for electron and neutrino reactions

Transport vs Glauber

- Transport allows for FSI with:
  - Elastic scattering
  - Inelastic excitations
    - Particle production
    - Collisions
- Not just absorption (Glauber)
- Essential for semi-inclusivee

Illustration: νA with DUNE flux



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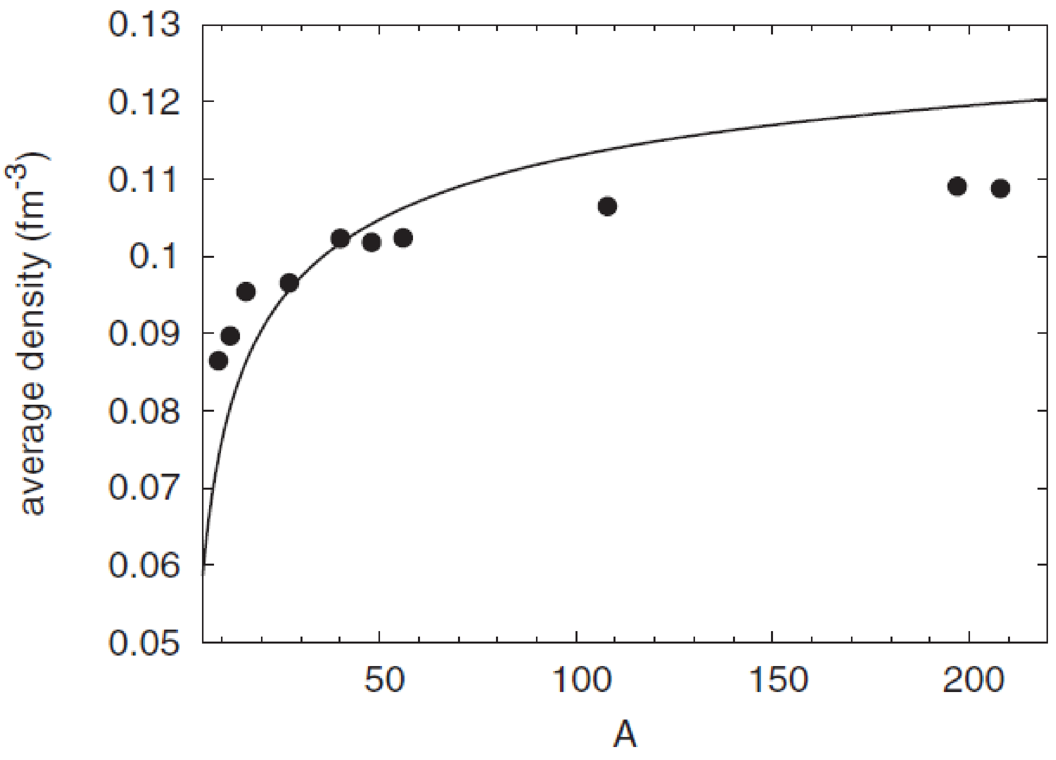
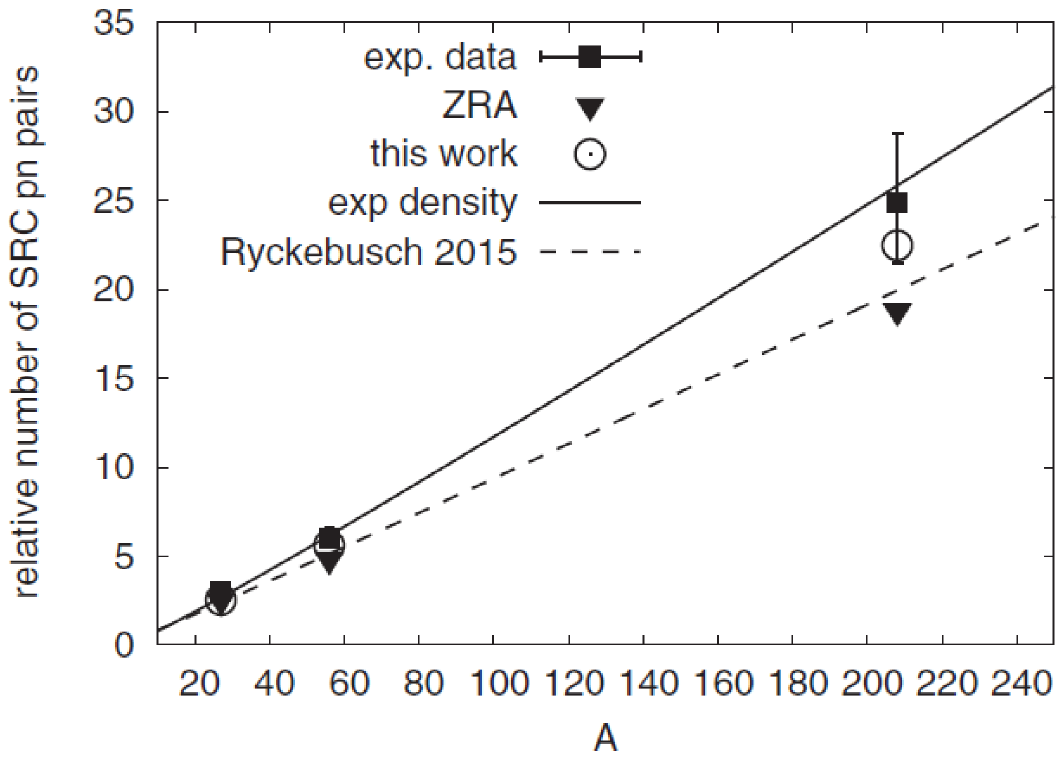
Geometry of SRC
number of zero-range pairs





$$P_{NN} = \int d^3r\, \rho^2(\mathbf{r}) = A\,\langle\rho\rangle,$$

$$\langle\rho\rangle(A) = 0.145 - 0.147A^{-1/3} \quad (\mathrm{fm}^{-3}),$$

$$P_{NN}(A) = 0.145A - 0.147A^{2/3}$$

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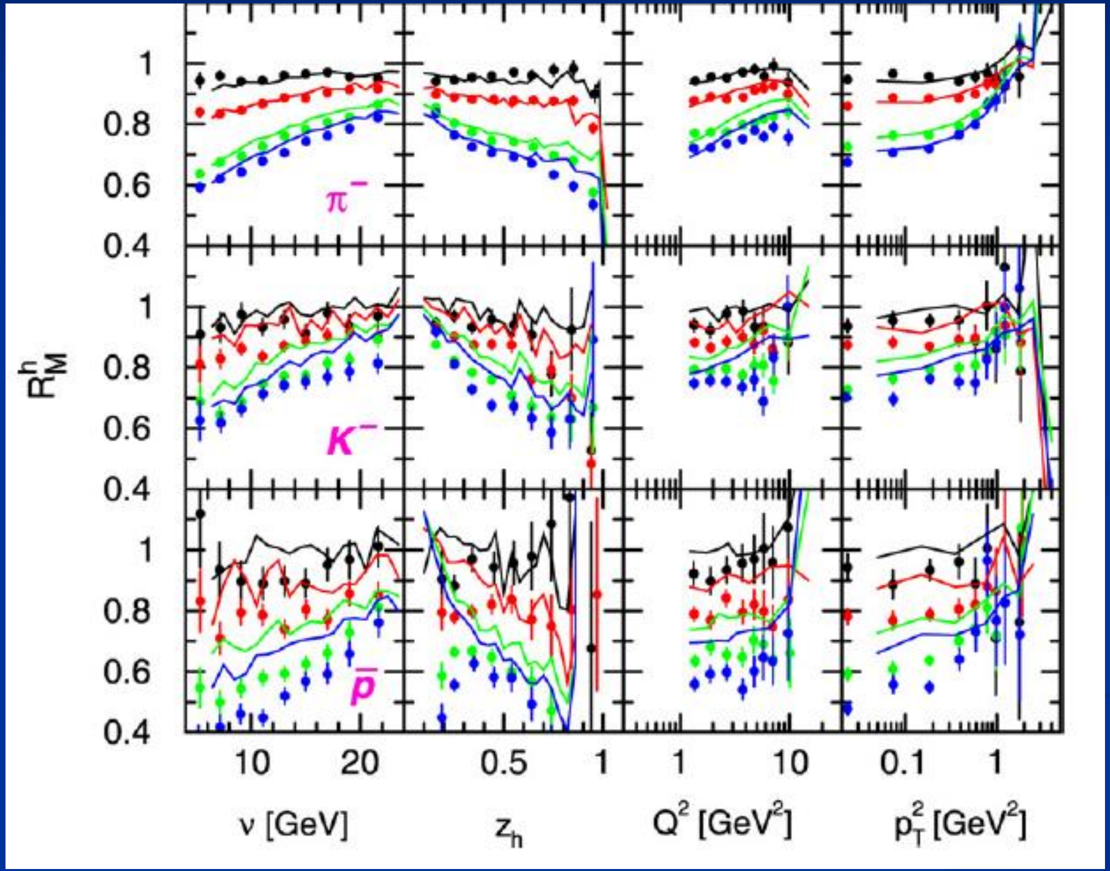
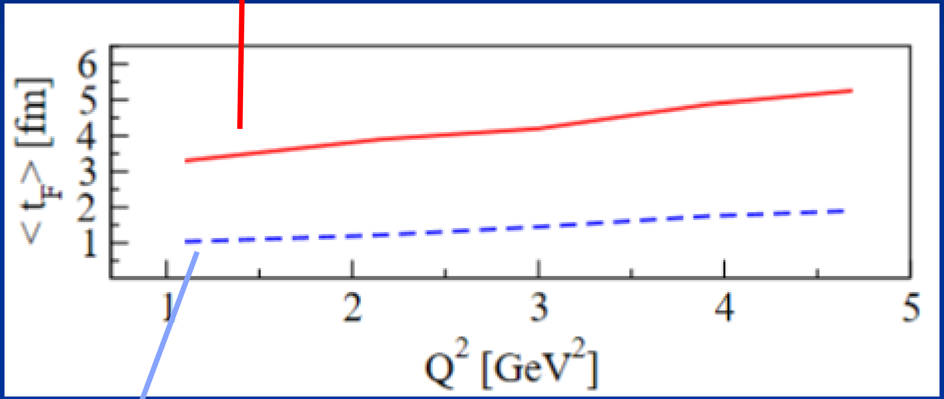
Test with HERMES Data



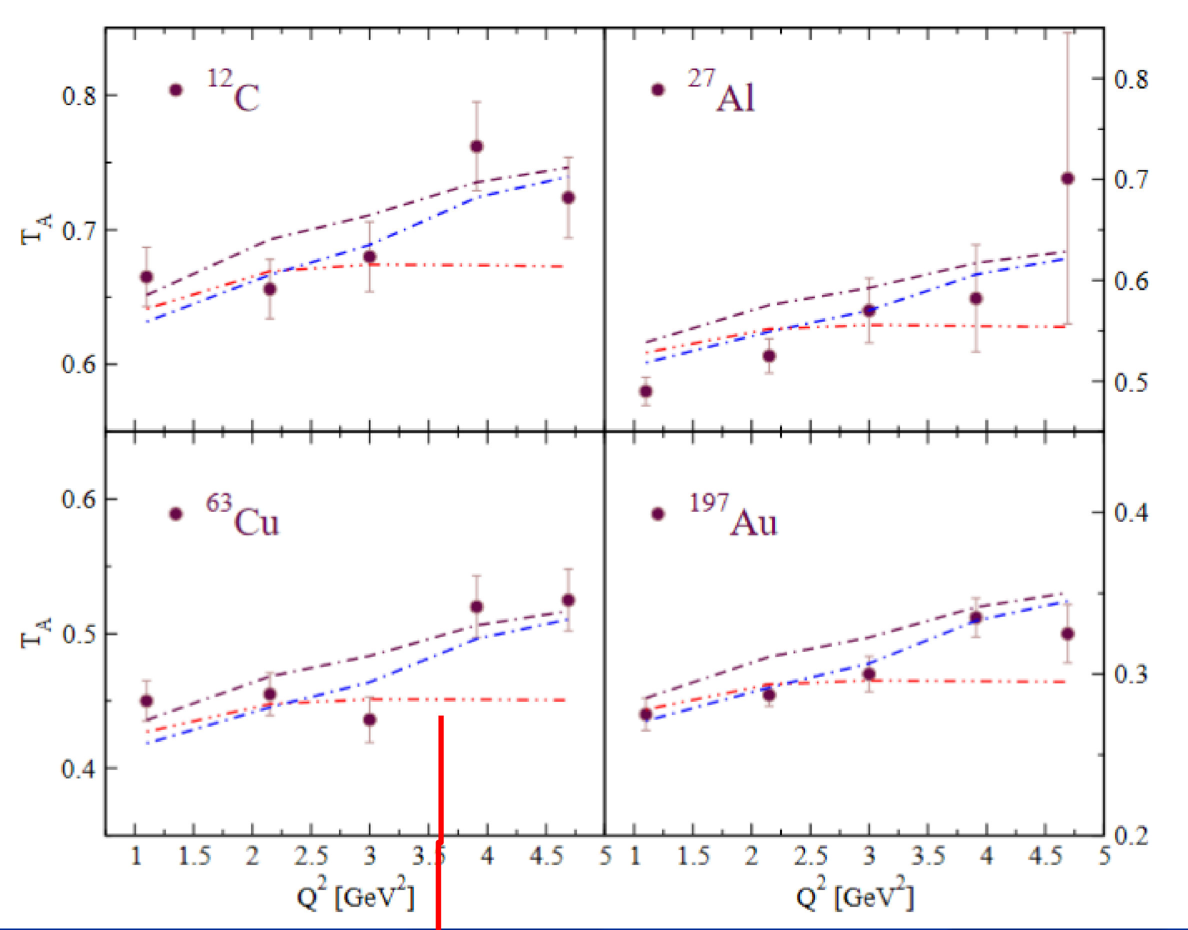
π Production: Sensitivity to Formation Time

Lund formation time



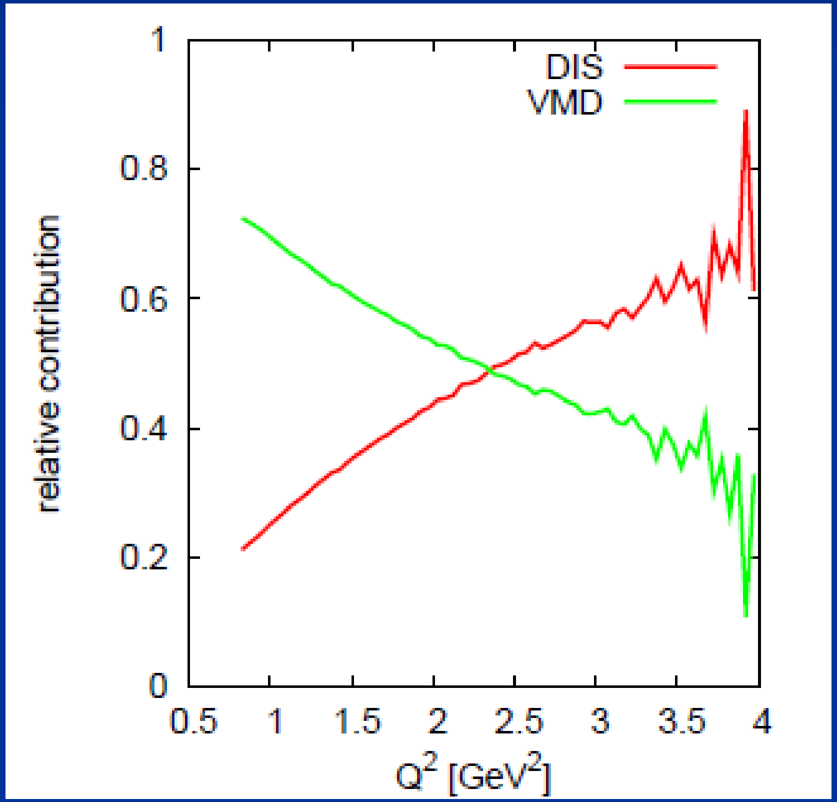
$$t_F = \frac{2k'}{m_\pi^{*2} - m_\pi^2}$$

$$m_\pi^* - m_\pi = 1GeV$$



Only long CT

VMD/DIS as function of Q^2 for ρ production



Relative Contribs change with Q^2

Different plcs for DIS and VMD???

Different behavior in CT??

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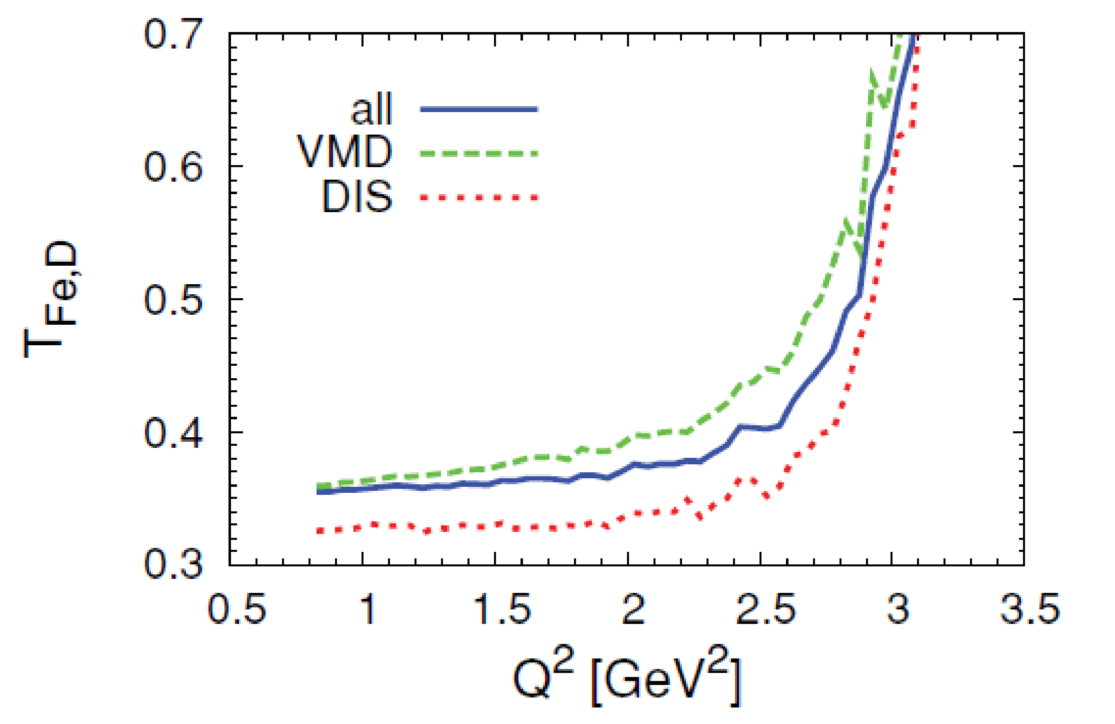
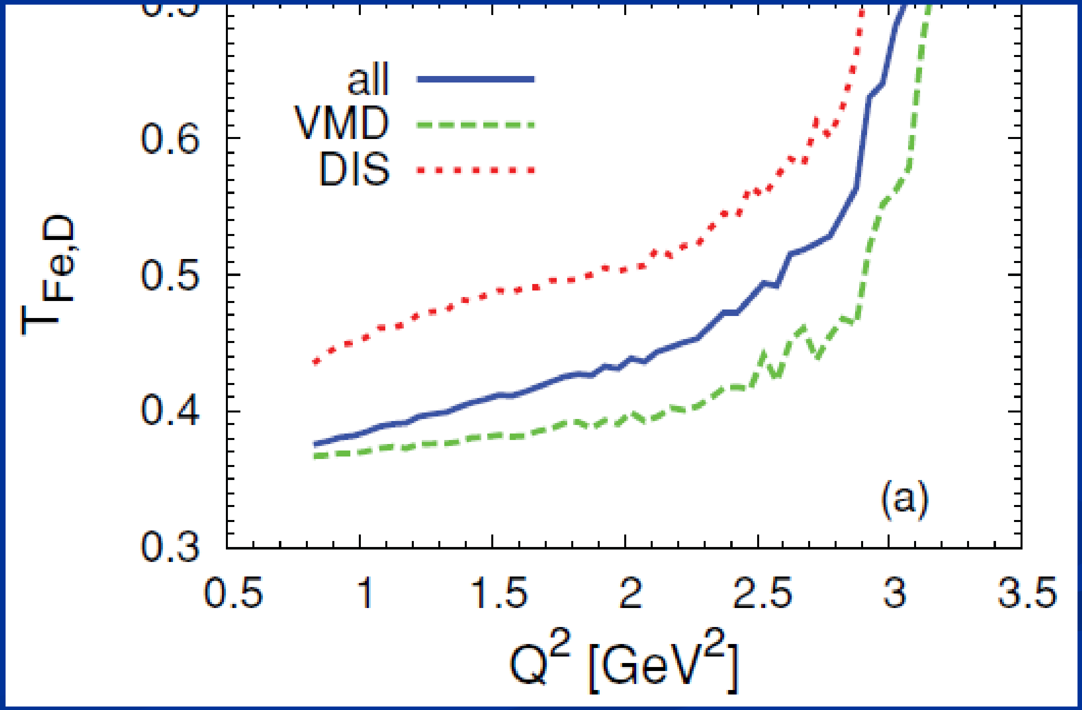
Experimental Acceptance and Transparency

(i) $W > 2$ GeV to avoid the resonance region,
(ii) $t > -0.4$ GeV^2 to be in the diffractive region,
(iii) $t < -0.1$ GeV^2 to exclude coherent production off the nucleus,
(iv) $z = E_\rho/\nu > 0.9$ to select the elastic process; here E_ρ is the energy of the ρ^0 meson produced.

Acceptance alone produces CT-like signal



No CT



With CT