GiBUU@FASER

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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, allows for off-shell propagation
- 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 2023

  add. details in Gallmeister et al, Phys.Rev. C94 (2016) 3, 035502, Phys.Rev.D 109 (2024) 3, 033008, v 2024 later this year.

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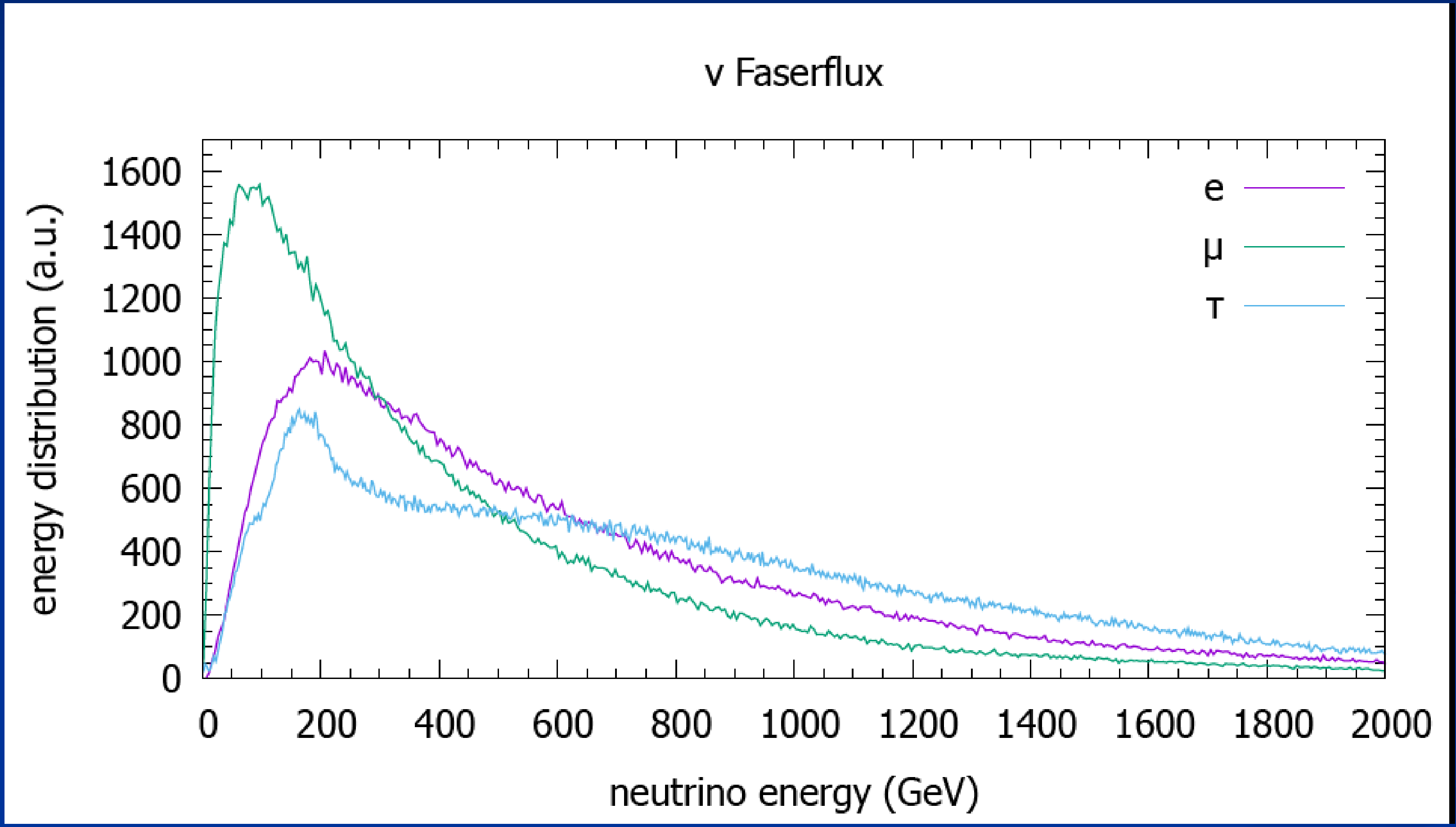
FASER Flux



Flux from:
Max Fieg, UC Irvine

Peaks around 100 – 200 MeV,
Tails out to 2 TeV

Target is heavy nucleus: W

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Physics@FASER

- DIS is dominant, QE, RES, etc negligible
  DIS in GiBUU is handled by PYTHIA string fragmentation

- At these high energies: are the targets relevant??
  Long formation times will cause to create ‚real' hadrons only outside the nucleus?
  - Are final state interactions are essential? :
    - Production and formation times of these hadrons?
      Physical hadrons produced inside or outside the target?

Hadronization

- Central Question: how do the final state hadronic cross sections emerge after a hard elementary process?

- Does the target (W) matter for exclusive events?

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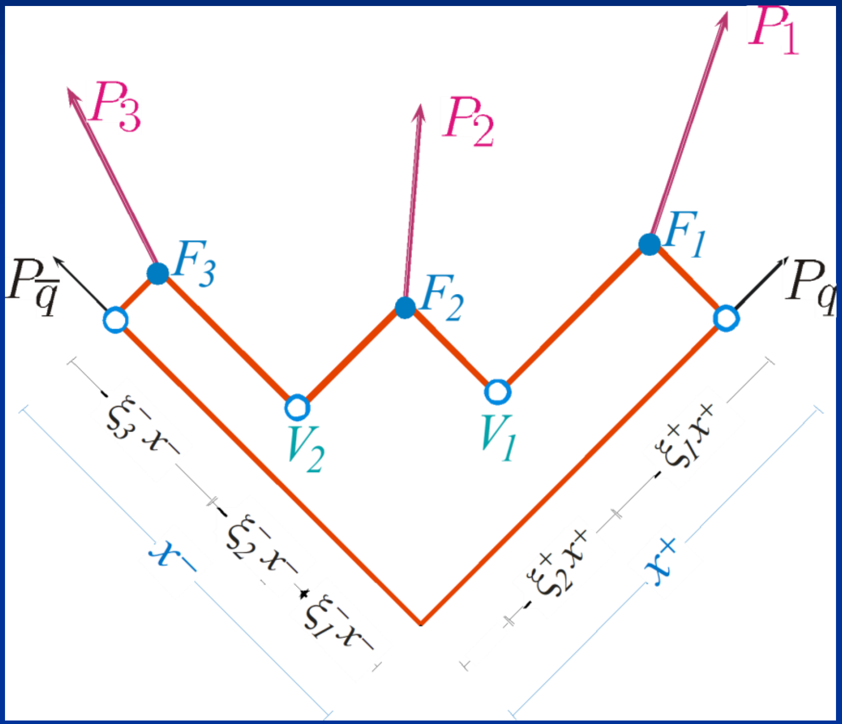
String-breaking in PYTHIA

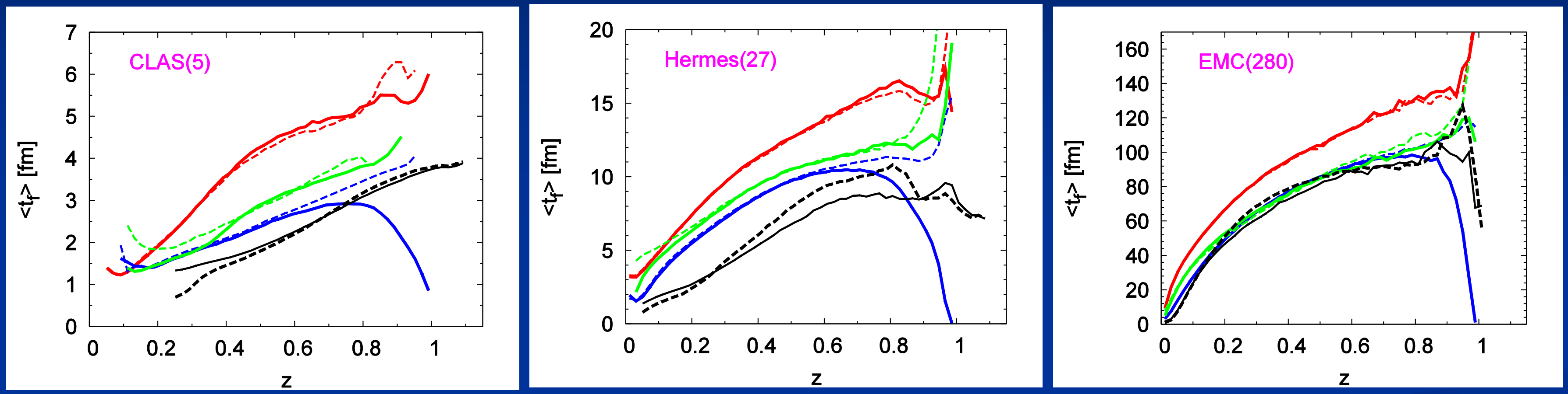


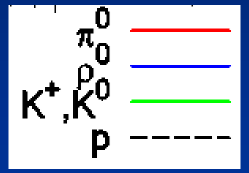
Leading particles connected with hard interaction

3 times for each hadron

1. Production V1 : String Breaking
2. Production V2 : String-Breaking
3. Formation: Quark lines meet

PYTHIA‘s formation times





K. Gallmeister, T. Falter
Phys.Lett.B 630 (2005) 40-48
Times extracted from PYTHIA

$Z = E_h / \nu$

The higher the hadron‘s energy the larger the formation time

➔ high z hadrons form outside the nuclear target -> no FSI

➔ Low z hadrons (high multiplicity events) form inside the nuclear target

-> Final State Interactions may be relevant

depends on ‚prehadronic‘ interactions during formation

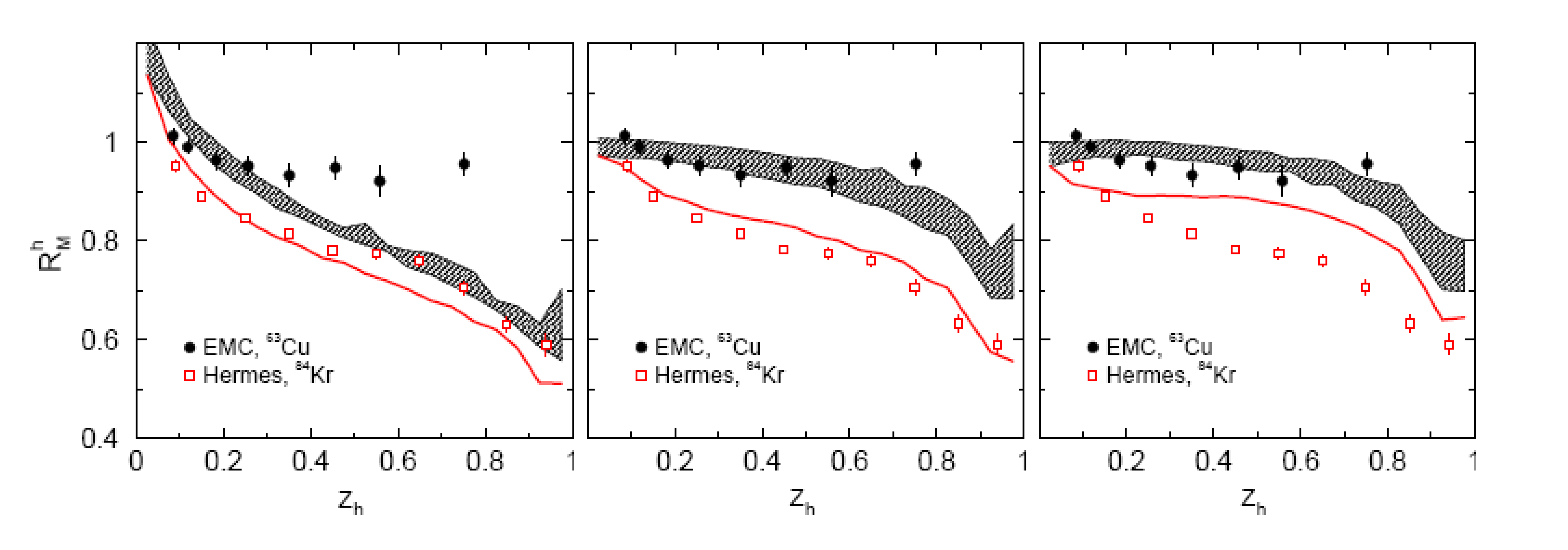
Hadronization in DIS events

- GiBUU can (has) been used to study hadronization at
  - HERMES (28 GeV) and EMC (280 GeV),
    uses nuclear radius to determine formation times and prehadronic cross sections.

Prehadron Cross Sections

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

$\sigma(t)$ ~ constant linear quadratic



$z = E_h/\nu$

K. Gallmeister, U. Mosel, Nucl.Phys.A 801 (2008) 68-79, MDPI Physics 4 (2022) 2, 440-450

Only linear dependence on time fits data over wide kinematical range!

Cross Section during Hadronization

Dominated by DIS , have to worry about Color Transparency in FSI:

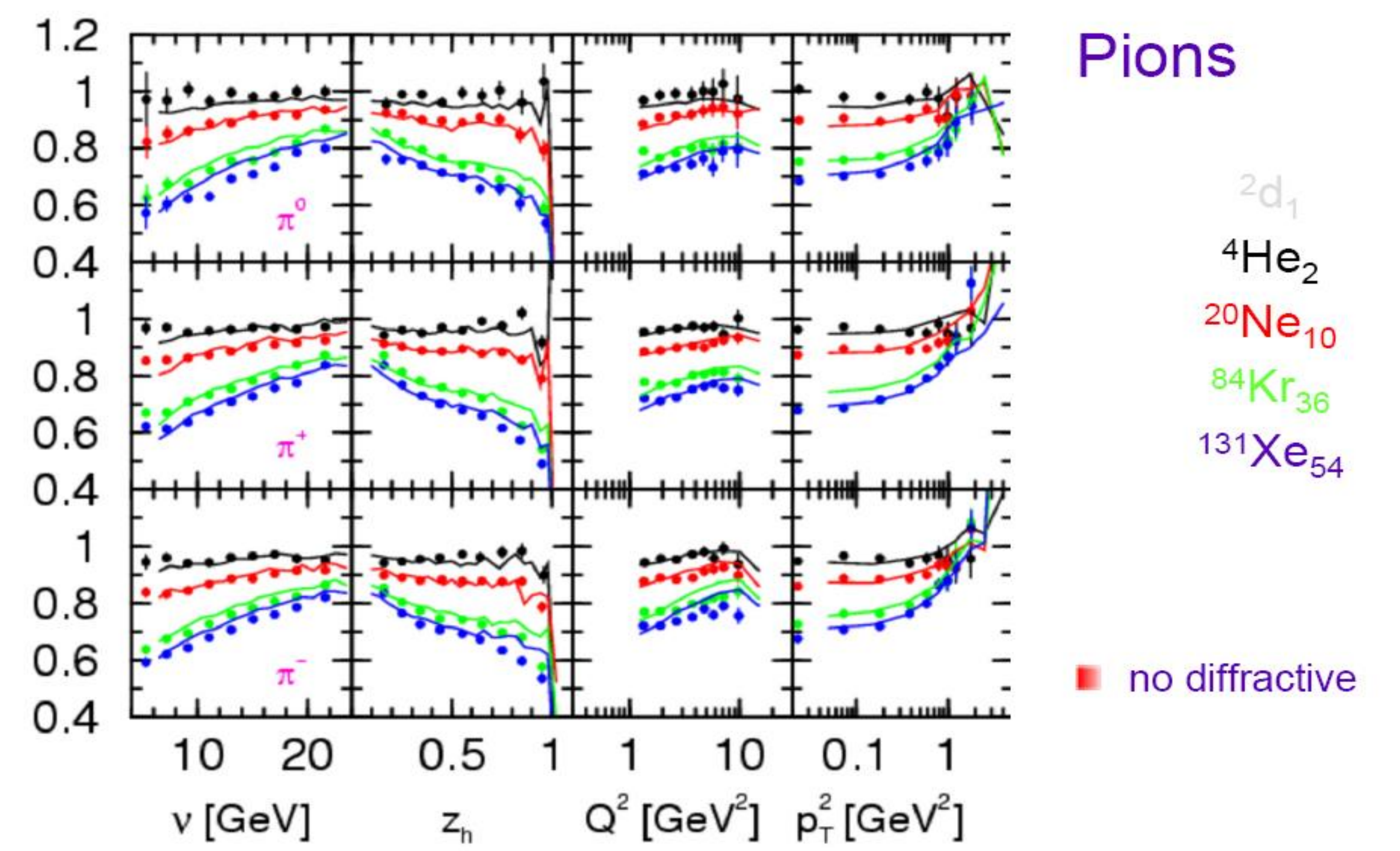
$$\frac{\sigma^*(t)}{\sigma} = X_0 + (1 - X_0) \cdot \left(\frac{t - t_P}{t_F - t_P} \right), \quad X_0 = r_{\text{lead}} \frac{\text{const}}{Q^2},$$

Farrar, Strikman et al

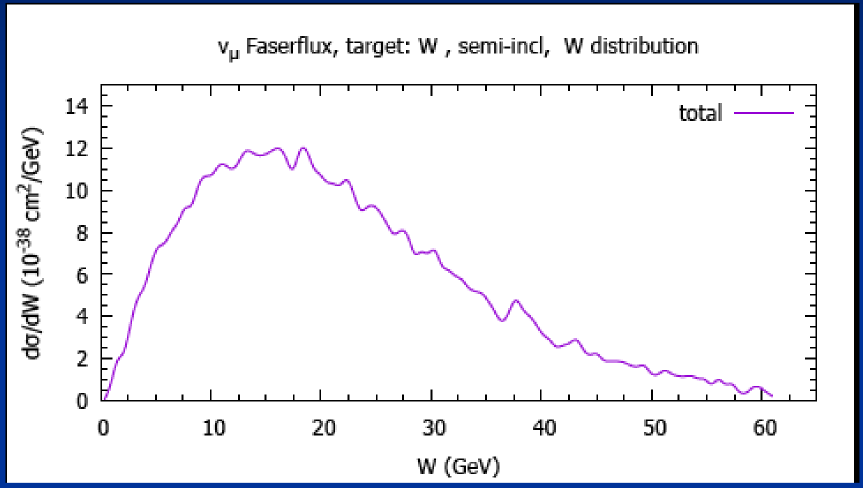
describes JLAB and HERMES hadronization data, also EMC

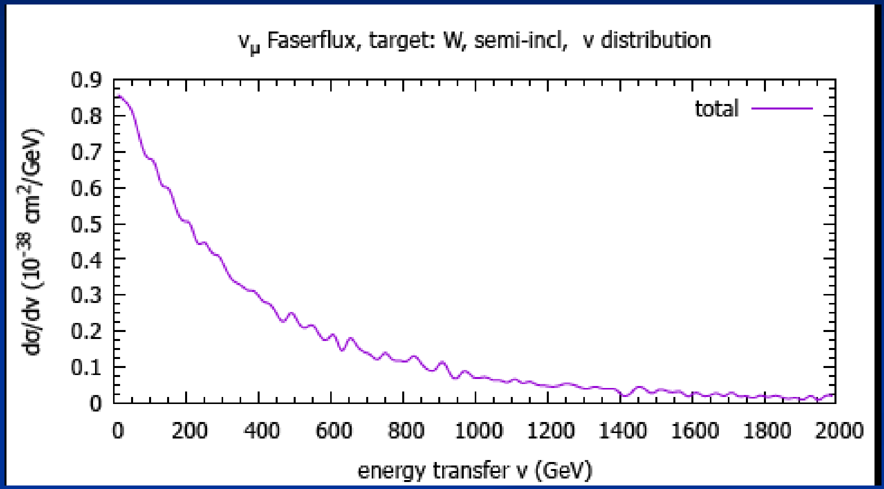
HERMES@27 GeV

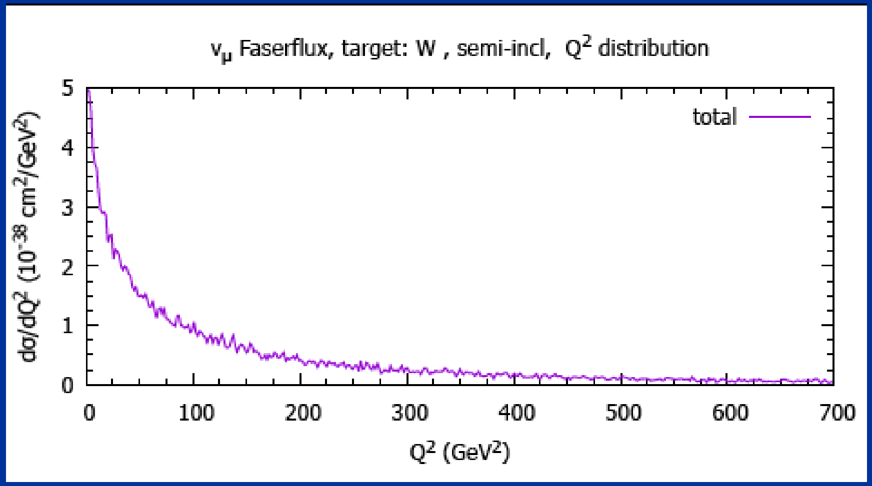
Airapetian et al.

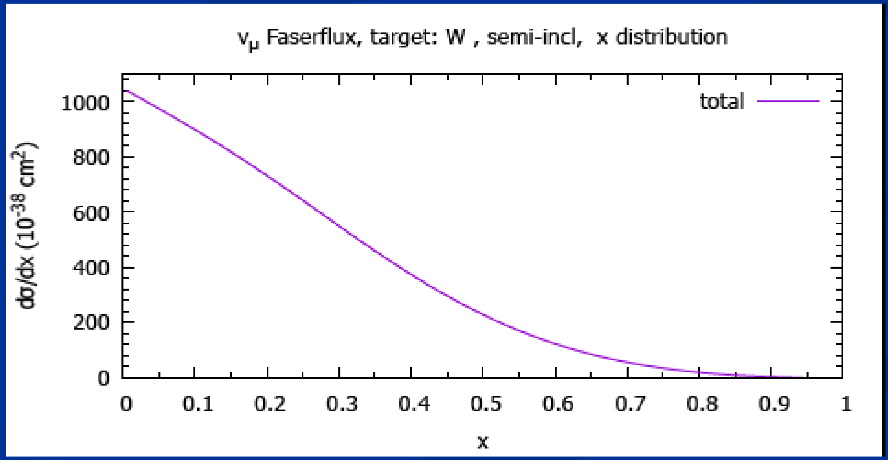


FASER inclusive kinematics

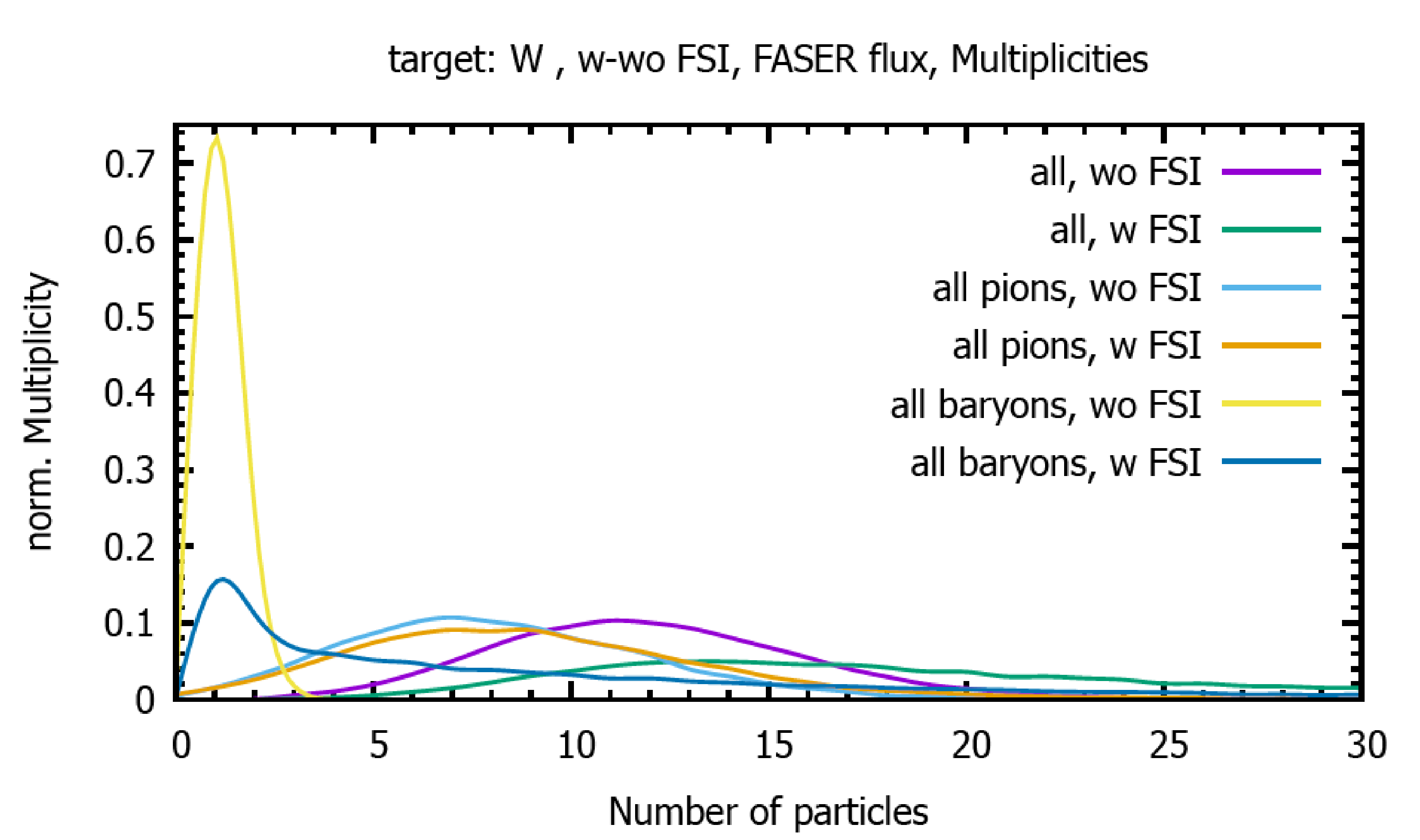








Multiplicities at FASER: FSI



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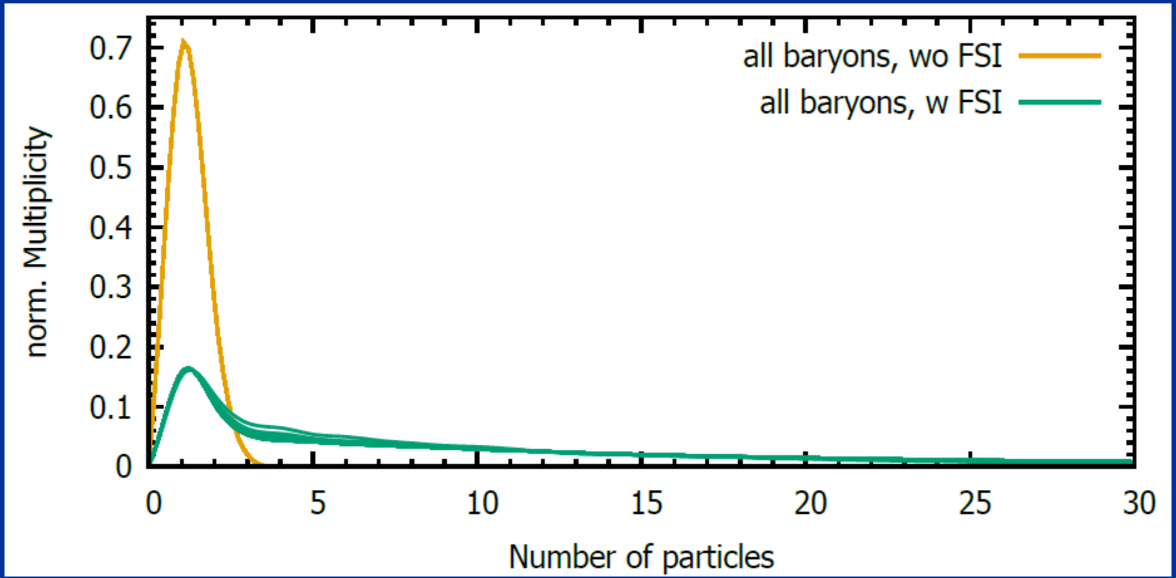
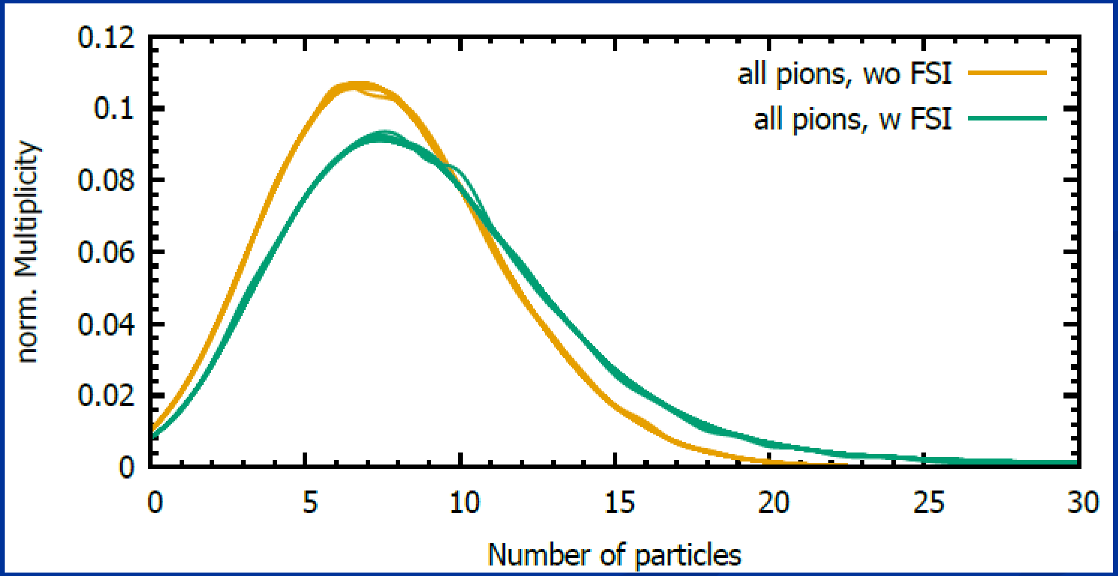
FSI effects on multiplicities at 1 TeV

Dramatic ‚avalanche effect‘ on baryon multiplicity
pions are there from the first (string) decay on, less affected





Target: W, 1 TeV

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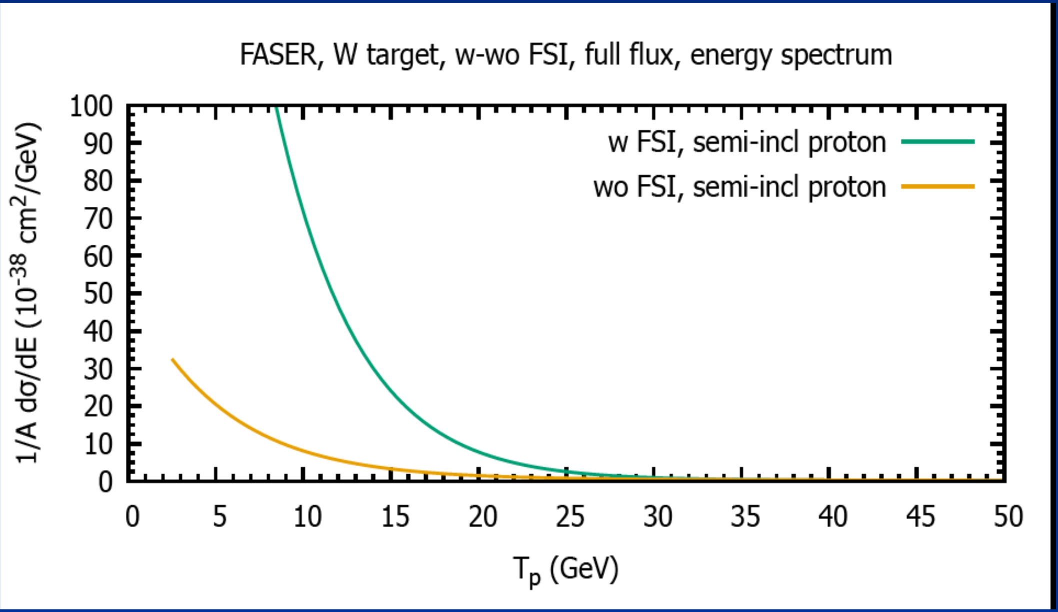
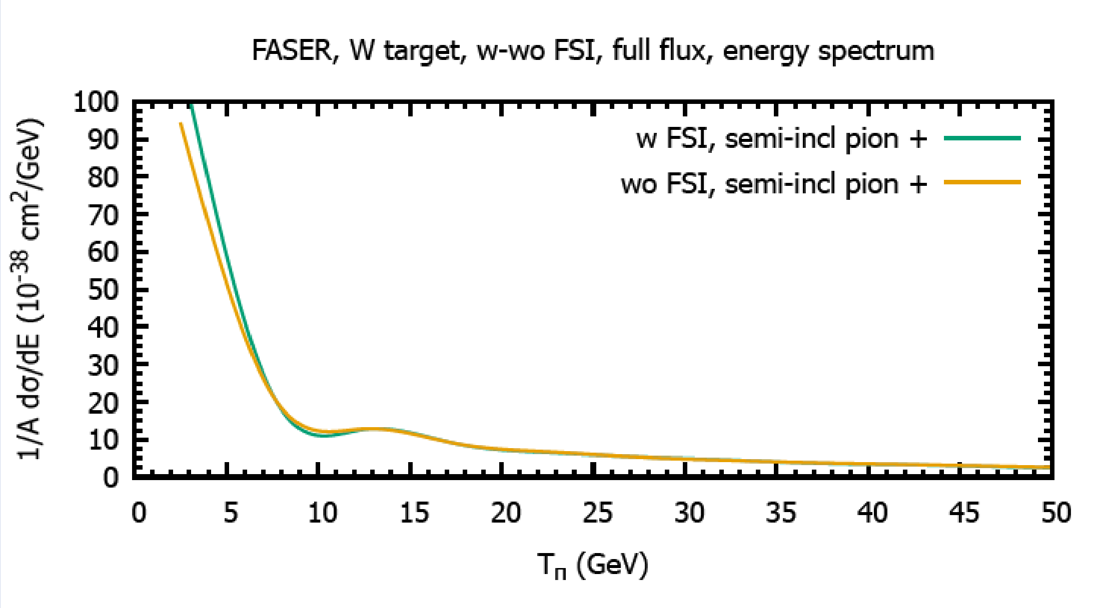
Hadron Spectra at FASER flux





Qualitatively similar to lower neutrino energies (MINERvA)

Protons show ‚avalanche effect' (multiple collisions through final state interactions),

Pions are there from the start, not much affected by FSI

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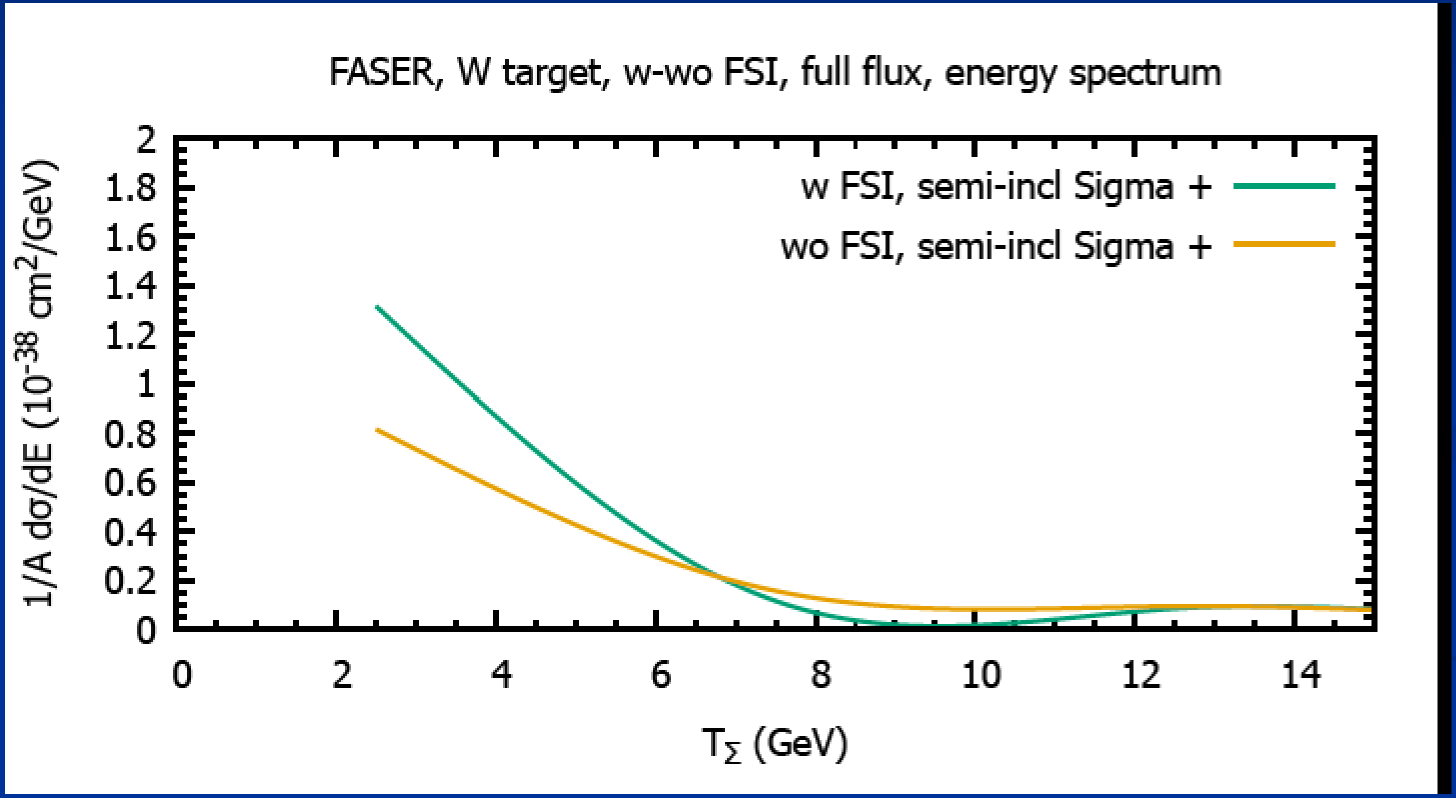
Σ+ Spectrum



Normal slowing down

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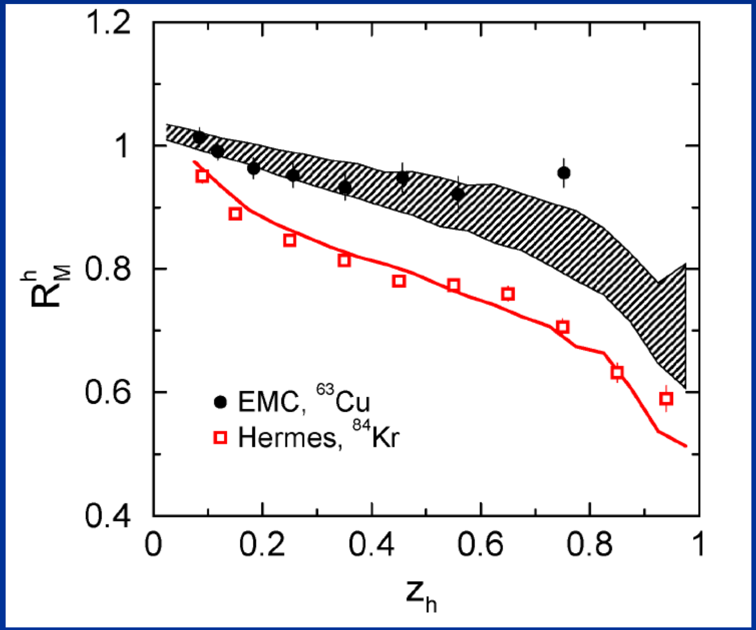
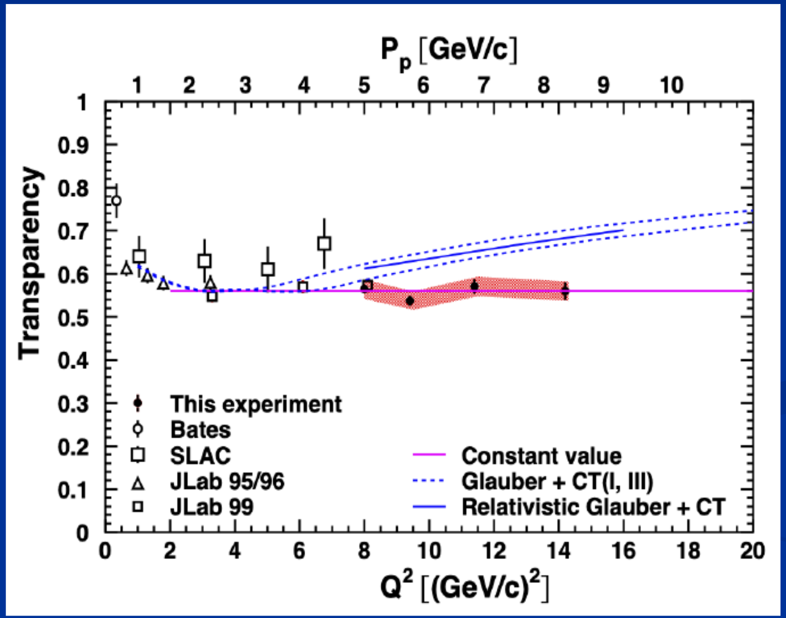
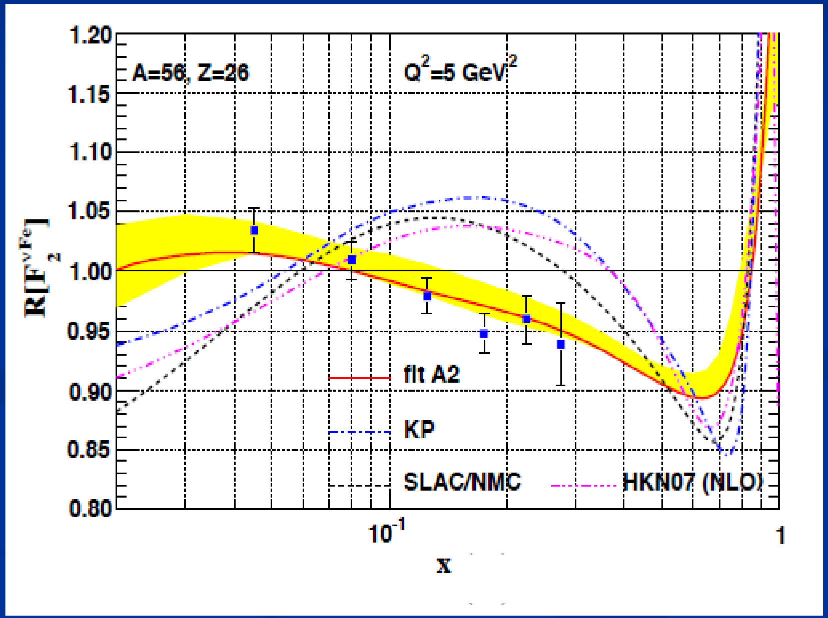
νA Questions for FPF

JLAB 2021







Where isColor Transparency ???

EMC effect for neutrinos, tension with electrons

K. Gallmeister, U.M., Nucl. Phys. A 801 (2008) 68

Time Dependent Hadronization via HERMES and EMC Data Consistency

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Final state interactions; Problems

- Frozen density approximation, used e.g. in mean free path approaches ???
- At very high energies target nucleus will break up
  → Target is ‚time-dependent‘, target nucleons also have to be propagated
- GiBUU allows for such a ‚time-dependent target‘ , and density change
- BUT: approximate this by changing so far only target A
  (saves computer time!)

Summary

- FASER flux baryon spectra are sensitive to formation times and prehadronic cross section developments

  ➔ FSI are essential even at very high energies of FASER
- FASER may add to solutions of problems of
  - Color Transparency and
  - EMC effect for neutrinos
  - Hadronization times at low z
- Same physics at EIC: also there FSI are essential, but – so far – have not been considered in detail.

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