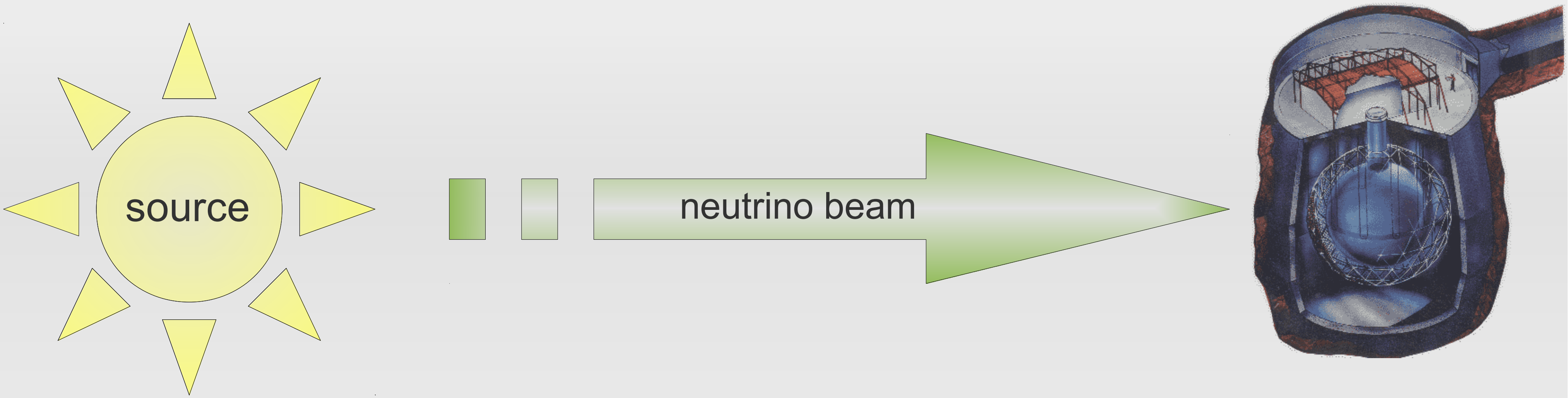
Superscaling
in lepton-nucleus scattering

Ivan Lappo-Danilevski
Tina Leitner, Hendrik v. Hees, Ulrich Mosel

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

DPG Frühjahrstagung
Hadronen und Kerne
Bonn, 15.3.2010

Motivation: neutrino oscillations

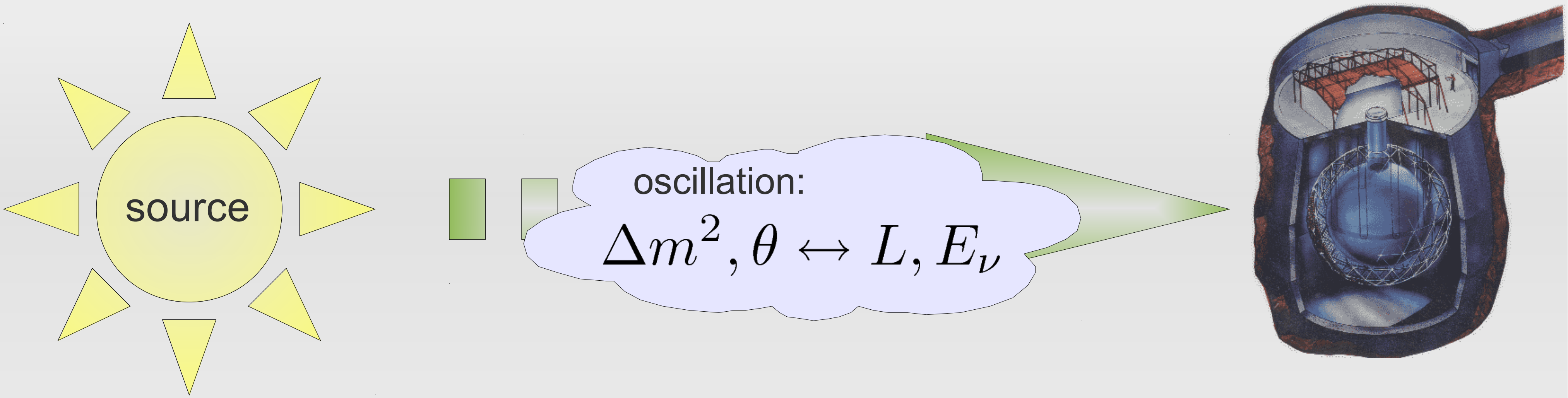


(e.g. Sun, Booster@Fermilab..)

Detector
(e.g. SNO, MiniBooNE@Fermilab)

- Standard model: 3 massless neutrinos (ν_e, ν_μ, ν_τ)

Motivation: neutrino oscillations

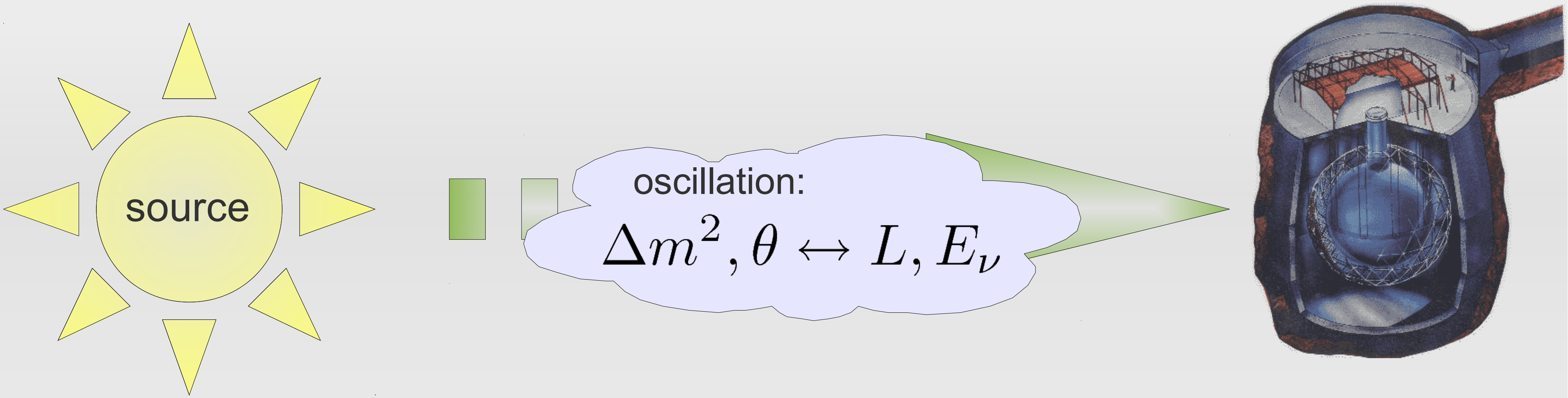


(e.g. Sun, Booster@Fermilab..)

Detector
(e.g. SNO, MiniBooNE@Fermilab)

- Standard model: 3 ~~massless~~ neutrinos (ν_e, ν_μ, ν_τ)
- SNO, Super-K: missing solar neutrinos → neutrinos change flavor → neutrinos must have non-zero mass

Motivation: neutrino oscillations

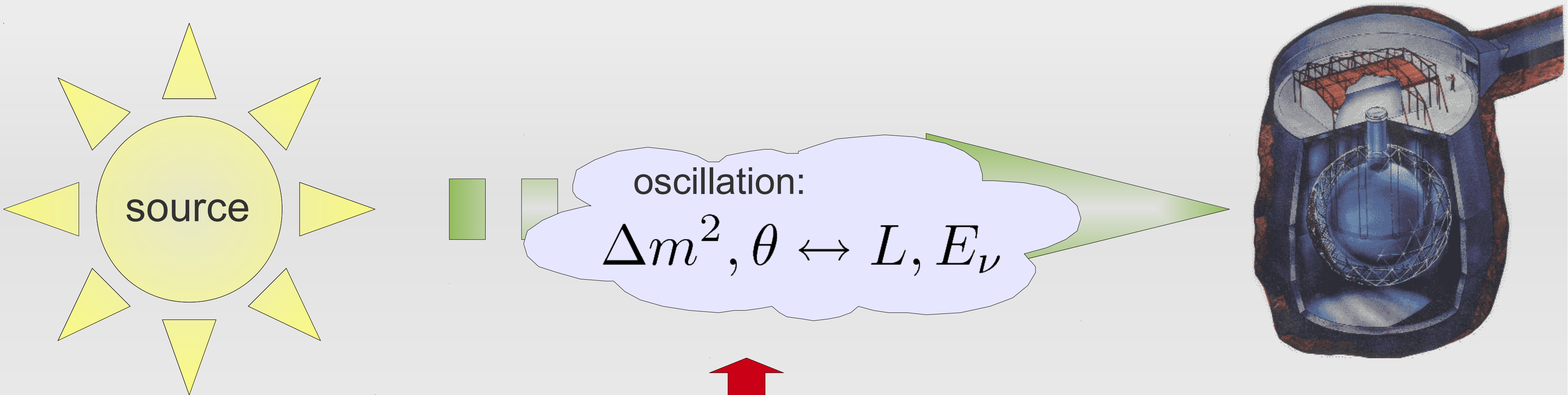


(e.g. Sun, Booster@Fermilab..)

Detector
(e.g. SNO, MiniBooNE@Fermilab)

- Standard model: 3 ~~massless~~ neutrinos (ν_e, ν_μ, ν_τ)
- SNO, Super-K: missing solar neutrinos $\rightarrow$ neutrinos change flavor $\rightarrow$ neutrinos must have non-zero mass
- Current research focused on:
  - Exact determination of oscillation parameters $\Delta m^2, \theta$
    $\rightarrow$ Obstacles:
    flavor identification, neutrinos not monoenergetic

Motivation: neutrino oscillations

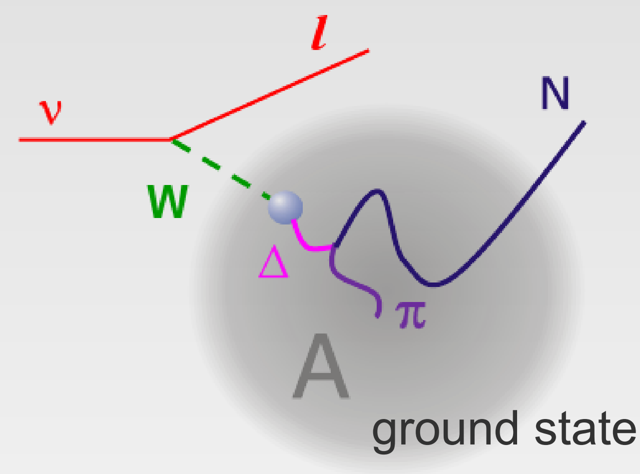


<u>necessary:</u> understanding of neutrino-nucleus interaction

control effects from complex structure of nucleus

Leptons are best probe to test nuclear properties →
better understanding of *both* neutrinos and nuclei
from neutrino-nucleus experiments

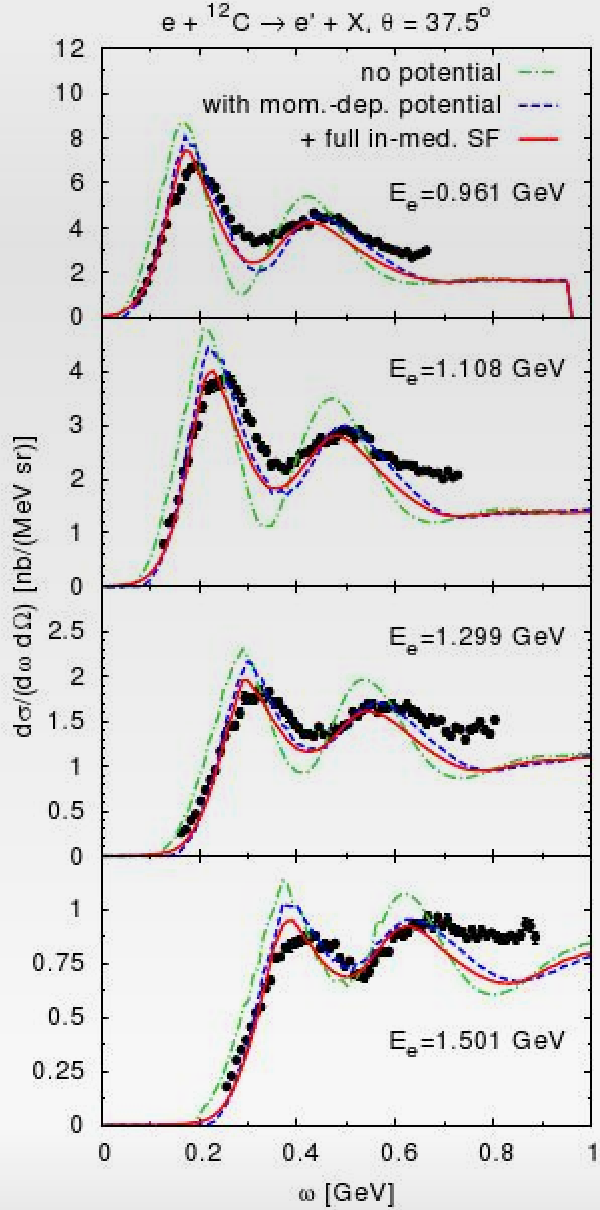
- GiBUU transport model: universal framework for medium and high energy hadron physics
  - heavy ion collisions
  - proton and pion induced
  - photon induced
  - **neutrino and electron induced**



- Based on **impulse approximation**:
  struck nucleon absorbs entire energy transfer
- Consistent treatment of in-medium modifications and final-state interactions, under version control and open source

http://gibuu.physik.uni-giessen.de/

Electron data as test for GiBUU

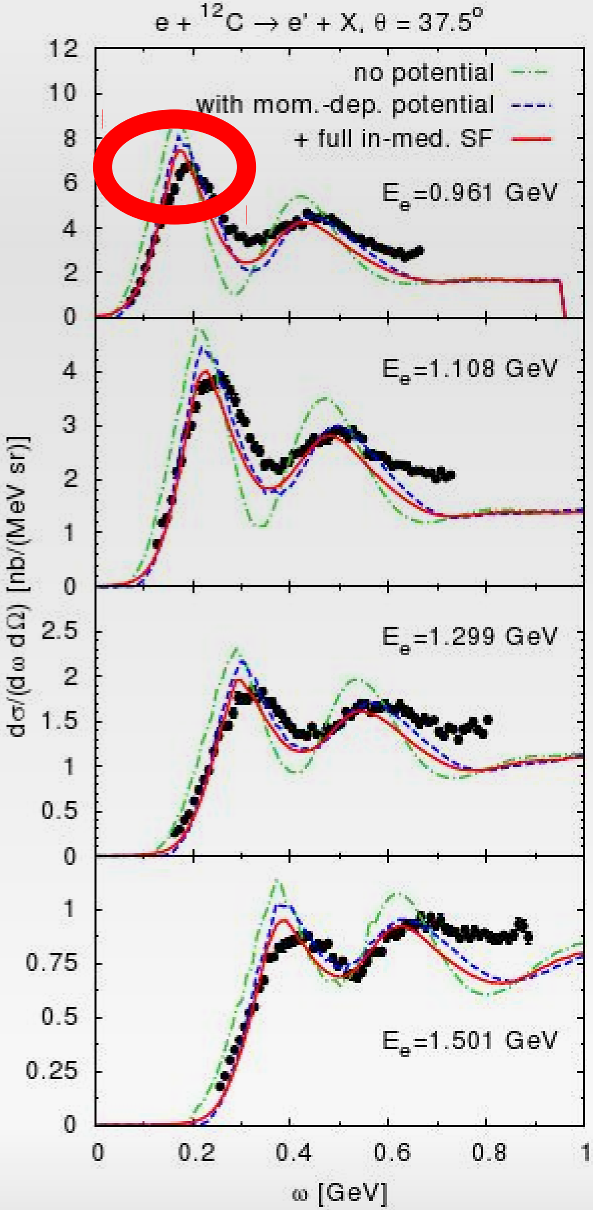


PRC 79, 034601 (2009)

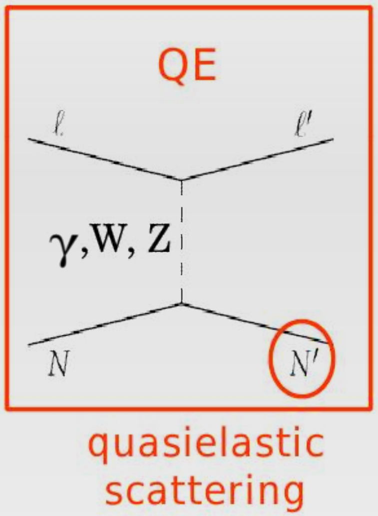
Inclusive cross sections of medium energy (~ 1GeV) lepton reactions

- Can GiBUU reproduce the data?
- Which contributions play a major role?

Electron data as test for GiBUU



PRC 79, 034601 (2009)

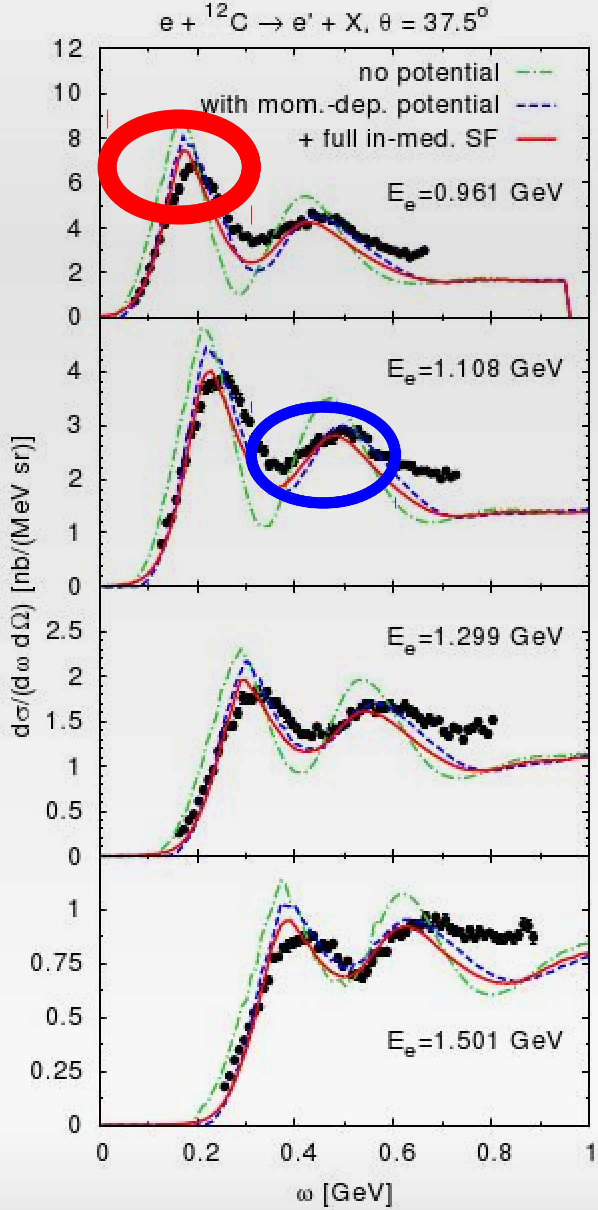


quasi-elastic peak (QEP)

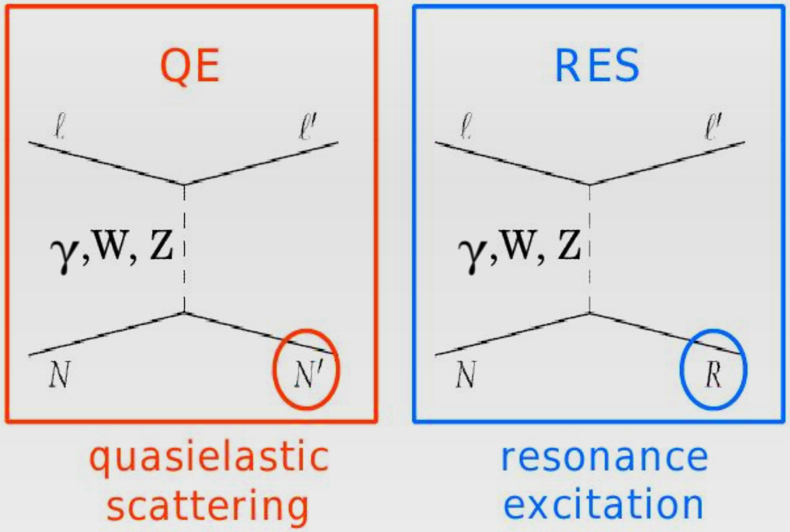
Inclusive cross sections of medium energy (~ 1GeV) lepton reactions

- Can GiBUU reproduce the data?
- Which contributions play a major role?

Electron data as test for GiBUU



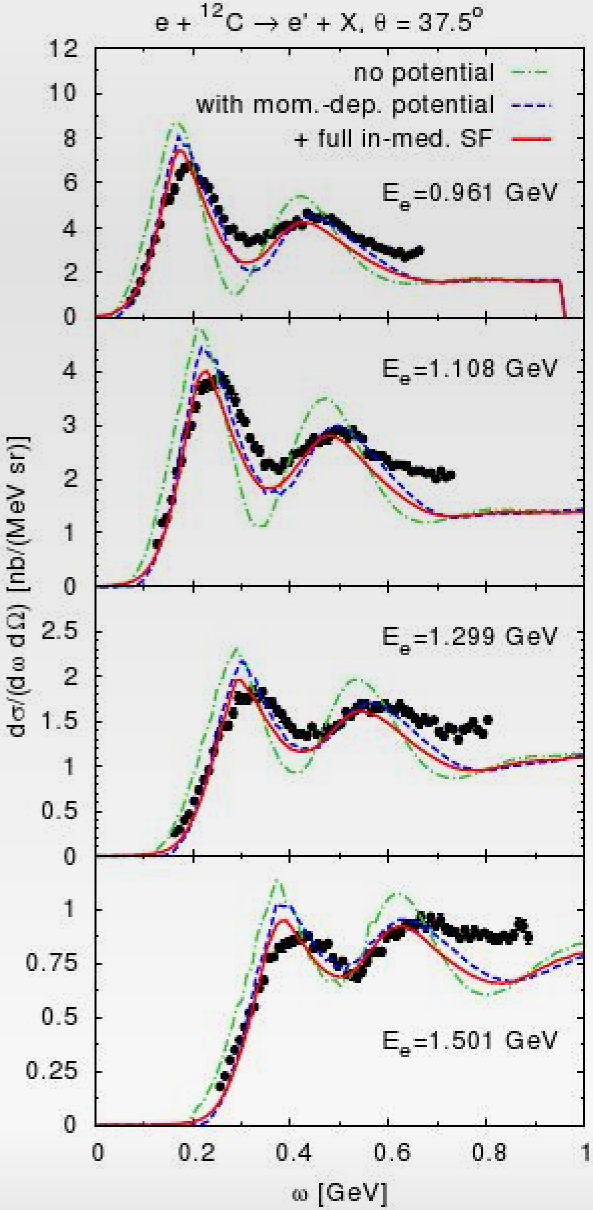
PRC 79, 034601 (2009)



Inclusive cross sections of medium energy (~ 1GeV) lepton reactions

- Can GiBUU reproduce the data?
- Which contributions play a major role?

Electron data as test for GiBUU



PRC 79, 034601 (2009)

GiBUU is able to:

- describe most important contributions in the medium-energy regime
- give correct particle-production cross sections using the transport approach

Questions that remain:

- what are reasons for slight deviations?
- universal property underlying all lepton-nucleus scattering?

  → guidance for model-building

  (like Bjorken scaling for quark model)

Superscaling: universal nuclear property

- Scaling variable and function (arise in impulse approximation):

$\Psi \approx$ **minimum** parallel longitudinal **momentum** that a nucleon inside the target nucleus must have to take part in scattering reaction $\approx$ minimal kinetic energy (0 at QEP)

Kinematic variables:

$$\kappa \equiv q/2M_N, \lambda \equiv \omega/2M_N$$

$$\tau = \kappa^2 - \lambda^2 = \frac{|Q|^2}{4(M_N)^2}$$

$$\eta_F = p_F/M_N, \varepsilon_F = \sqrt{1+\eta_F^2}$$

$$\psi = \frac{1}{\varepsilon_F - 1} \frac{\lambda - \tau}{\sqrt{(1+\lambda)\tau + \kappa\sqrt{\tau(\tau+1)}}}$$

$$E(|\mathbf{p}|_{\min})_{\mathrm{kin}} = M_N \psi^2 (\varepsilon_F - 1)$$

Superscaling: universal nuclear property

- Scaling variable and function (arise in impulse approximation):

$\Psi \approx$ **minimum** parallel longitudinal **momentum** that a nucleon inside the target nucleus must have to take part in scattering reaction $\approx$ minimal kinetic energy (0 at QEP)

$f(\Psi) =$ inclusive cross section divided by single nucleon contributions $\approx$ **nuclear momentum distribution**

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}E'\mathrm{d}\Omega} \propto \left\langle \sum_{\text{f states}} |\langle f|H_i|i\rangle|^2 \right\rangle_{\text{i states}} \rho_{\text{phase space}}$$

$$\to \sigma_{\text{point}} \times X(\omega,q)_{\text{nucleon structure}} \times S(y(\omega,q))_{p\text{ distribution}}$$

$$\approx \sigma_{\text{point}} \times X(\omega,q)_{\text{nucleon structure}} \times (1-\Psi^2)\theta(1-\Psi^2)\frac{3\xi_F}{\eta_F^3}$$

$$f(\Psi) = \frac{k_F \times \mathrm{d}^2\sigma/\mathrm{d}E'\mathrm{d}\Omega}{\sigma_{\text{point}} \times X(\omega,q)_{\text{nucleon structure}}}$$

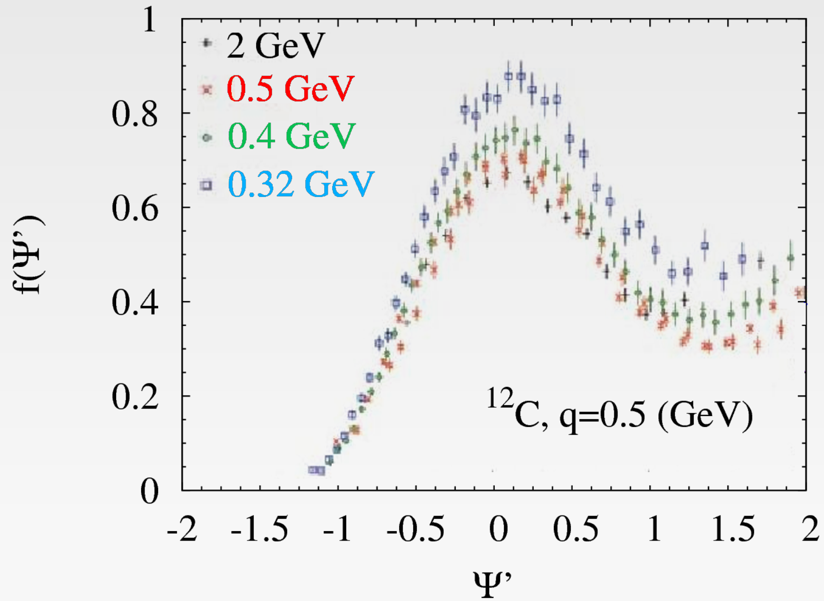
Superscaling: universal nuclear property

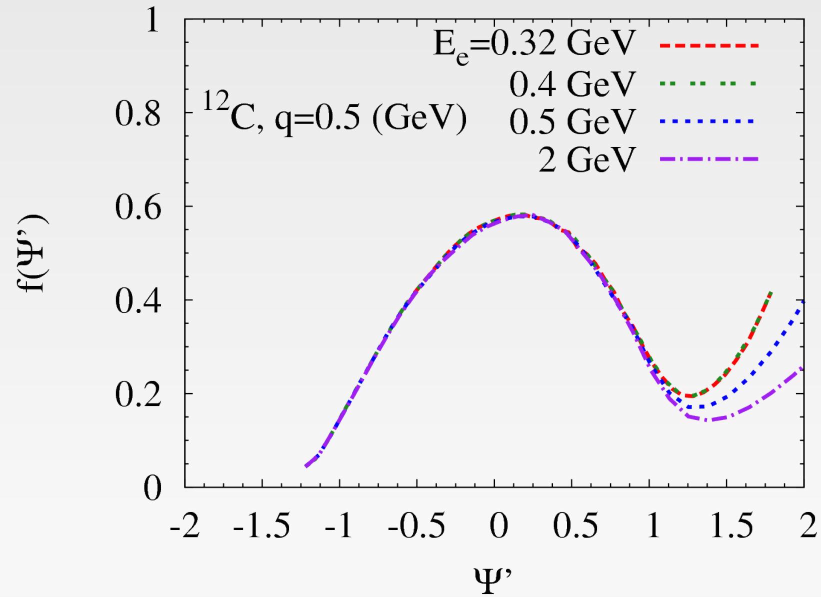
- Scaling variable and function (arise in impulse approximation):

$\Psi \approx$ **minimum** parallel longitudinal **momentum** that a nucleon inside the target nucleus must have to take part in kinematic reaction ≈ minimal kinetic energy (0 at QEP)

$f(\Psi) =$ inclusive cross section divided by single nucleon contributions ≈ **nuclear momentum distribution**

PRC 60, 065502 (1999)





GiBUU results

first kind-scaling: identical *f(Ψ)* for different kinematics

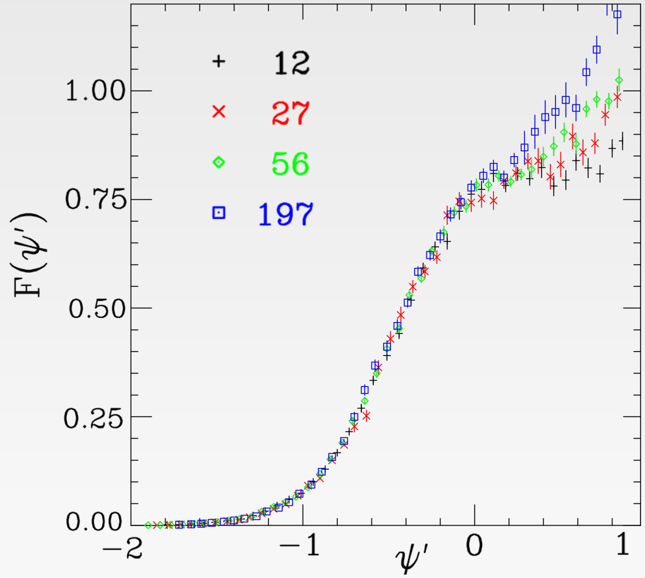
Superscaling: universal nuclear property

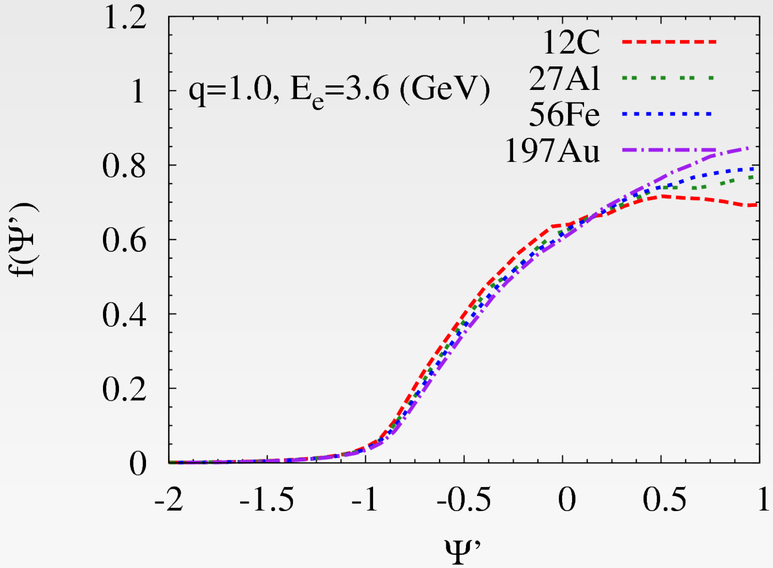
- Scaling variable and function (arise in impulse approximation):

$\Psi \approx$ **minimum** parallel longitudinal **momentum** that a nucleon inside the target nucleus must have to take part in kinematic reaction ≈ minimal kinetic energy (0 at QEP)

$f(\Psi) =$ inclusive cross section divided by single nucleon contributions ≈ **nuclear momentum distribution**

PRC 60, 065502 (1999)





GiBUU results

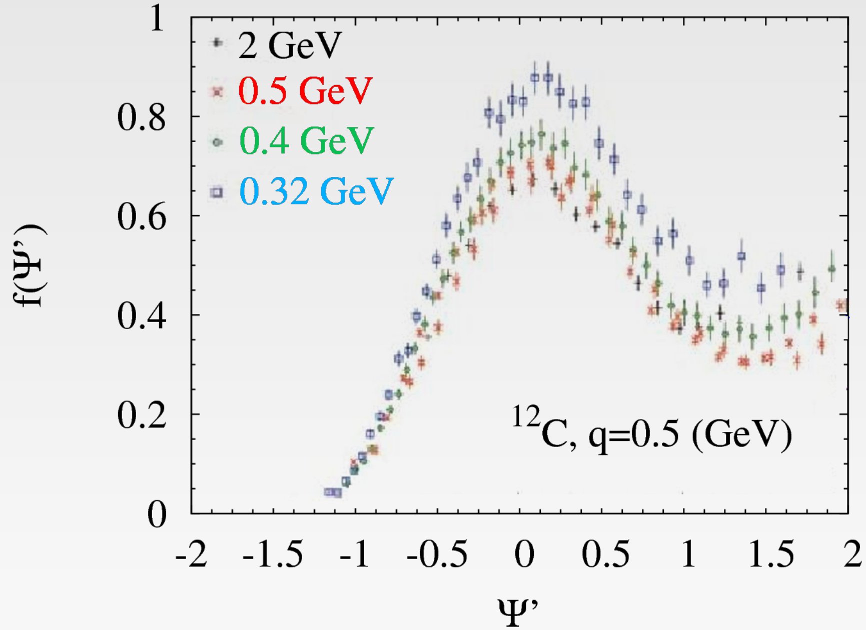
first-kind scaling: identical *f(Ψ)* for different kinematics

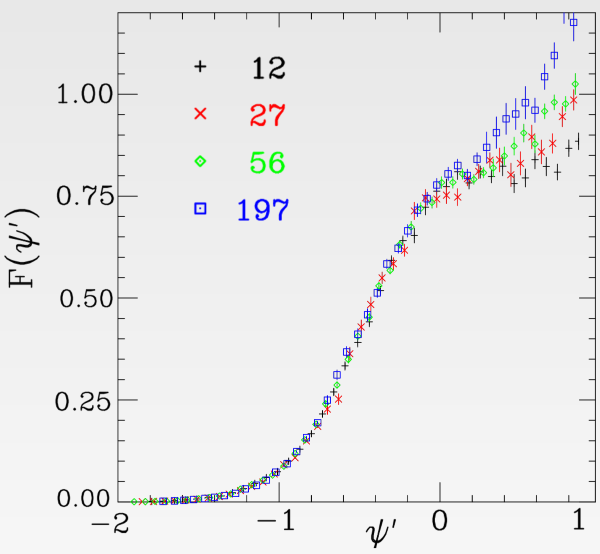
second-kind scaling: identical *f(Ψ)* for different nuclei

Superscaling: universal nuclear property

- Both kinds of scaling together = **superscaling**
- Important test for any theory for medium-energy scattering
- Present in GIBUU, due to impulse approximation

PRC 60, 065502 (1999)





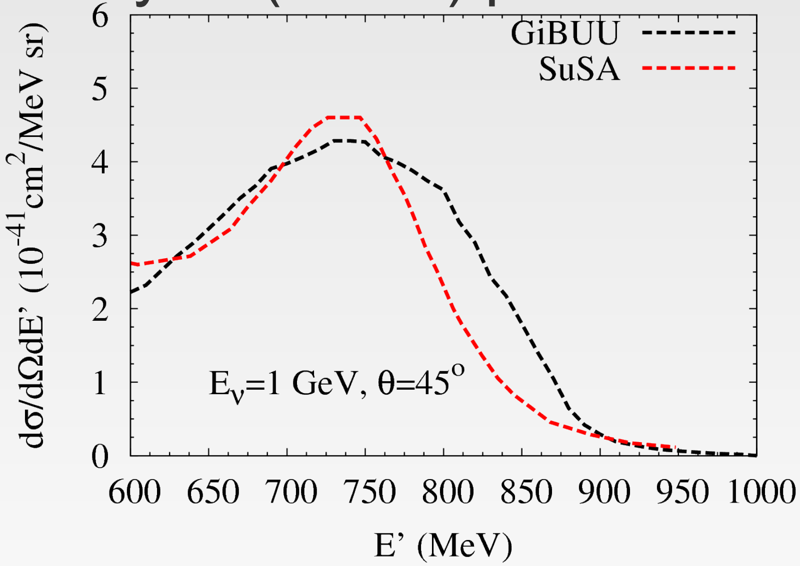
first-kind scaling: identical *f(Ψ)* for different kinematics
second-kind scaling: identical *f(Ψ)* for different nuclei

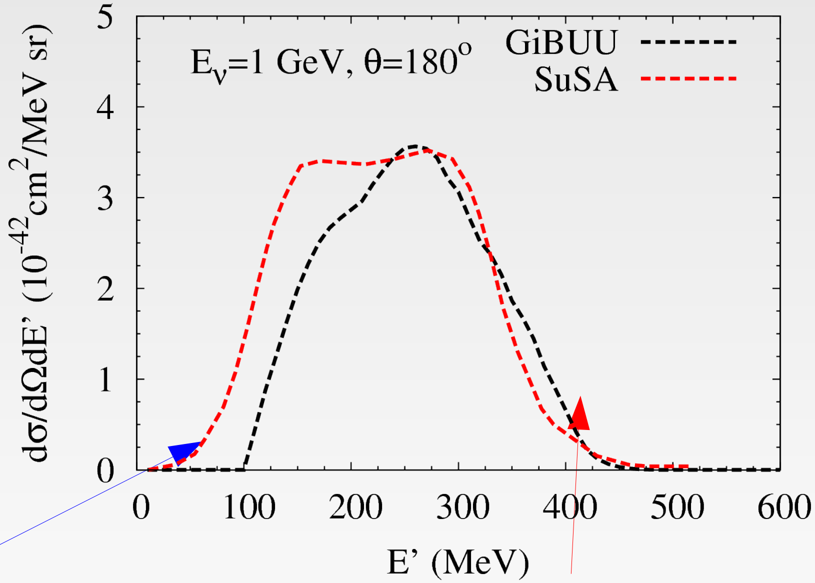
From analysis to extrapolation

- Amaro et al. [PRC 71, 015501 (2005)]: use superscaling functions from electron scattering to predict **neutrino cross sections** (important for oscillation experiments)
- Scarce available data not conclusive → compare superscaling analysis (SuSA) predictions with our simulation

From analysis to extrapolation

- Amaro et al. [PRC 71, 015501 (2005)]: use superscaling functions from electron scattering to predict **neutrino cross sections** (important for oscillation experiments)
- Scarce available data not conclusive → compare superscaling analysis (SuSA) predictions with our simulation



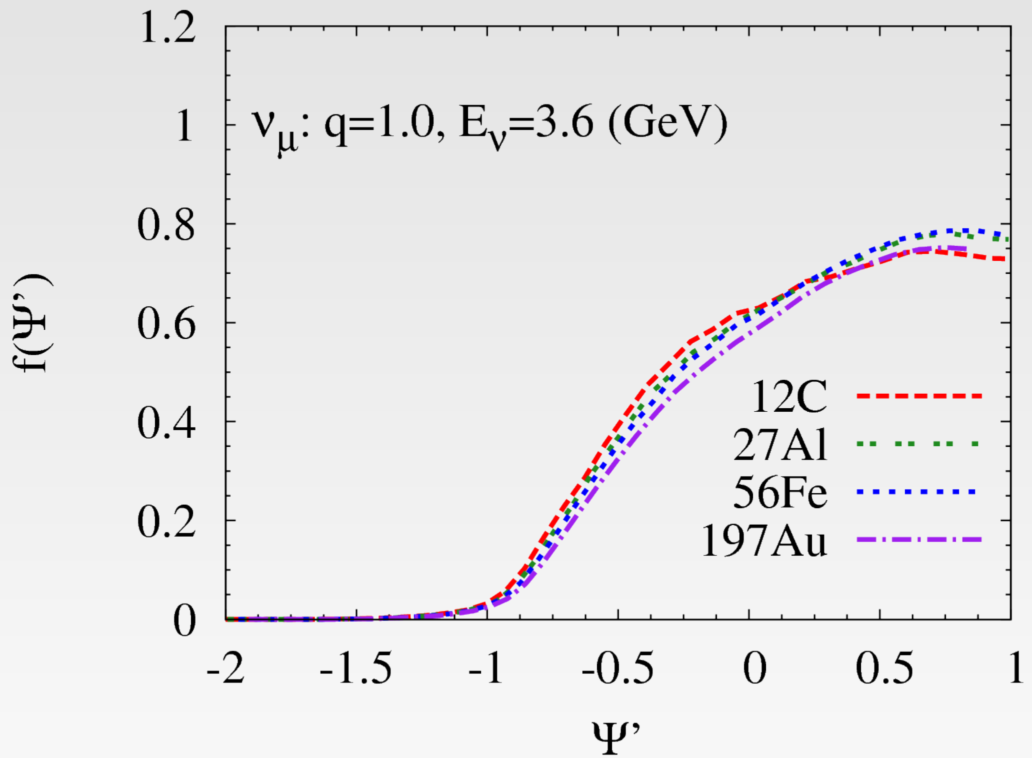


- Results are similar in strength but slightly different in shape due to smaller **resonance contributions,** broader **QEP** in GiBUU

Is SuSA approach justified in neutrino induced reactions?

- neutrino **data: too scarce** to perform superscaling analysis

  → analyze GiBUU simulated data; compare it with electron data



GiBUU results

- Neutrino scaling functions behave almost exactly like electron ones

  → consistency of model

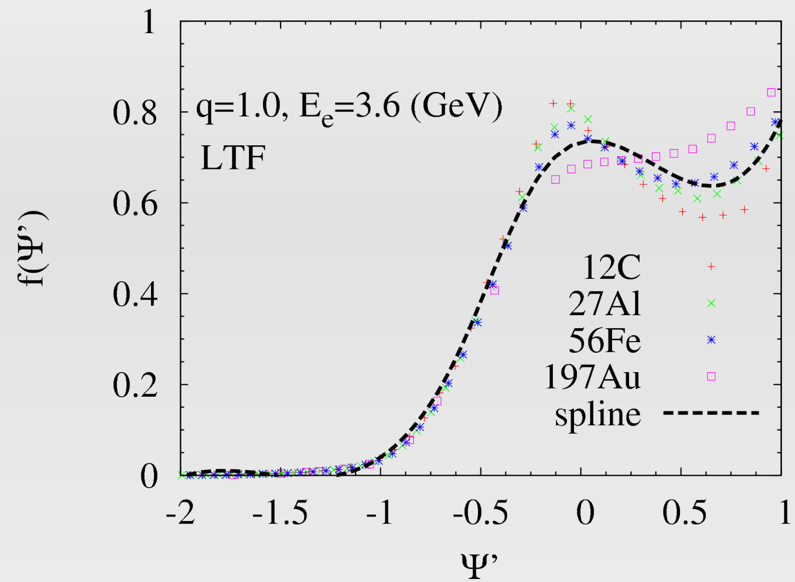
Understanding superscaling

- Two main questions:

  a) **Origin** of exact **shape** of

     scaling function?

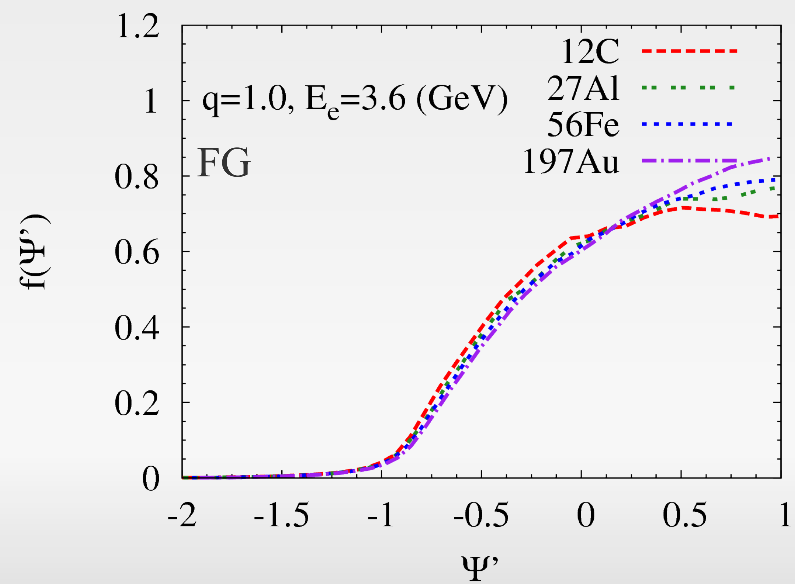
  b) Why is **scaling broken**?



- Possible ways to answer:

  a) study different phase space initialization, quantify scaling (Fermi gas, local Thomas-Fermi...)

  b) separate violations from resonances and transverse channel



Outlook and summary

- GiBUU describes medium-energy electron-nucleus collisions well
- **Superscaling** (fundamental property of lepton-nucleus collisions) is thus **present in GiBUU**
- Superscaling can be used to **predict neutrino cross sections** from electron data (predictions very similar to GiBUU ones)
- GiBUU neutrino data scales just as well as its electron data
- Future:
  - investigate where **scale breaking** comes from
  - Different models for ground state initialization

Outlook and summary

- GiBUU describes medium-energy electron-nucleus collisions well
- **Superscaling** (fundamental property of lepton-nucleus collisions) is thus **present in GiBUU**
- Superscaling can be used to **predict neutrino cross sections** from electron data (predictions very similar to GiBUU ones)
- GiBUU neutrino data scales just as well as its electron data

Thank you for your attention!

- Future:
  - investigate where **scale breaking** comes from
  - Different models for ground state initialization

Backup Slides

- ...