Superscaling
in lepton-nucleus scattering

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DPG Frühjahrstagung

Hadronen und Kerne

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Aim:
investigate lepton-nucleus scattering

Assess effects from complex structure of nucleus

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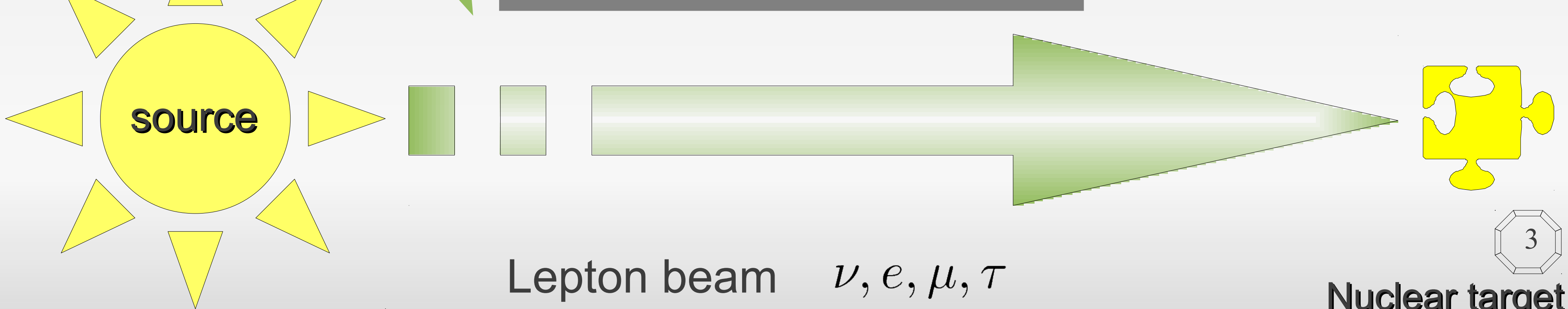
No experiments on pure H
→ contributions from rest nucleus

understanding of lepton-nucleon interaction

Data analysis
strongly depends
on models

scattering experiments



Aim:
investigate lepton-nucleus scattering

Assess effects from complex structure of nucleus

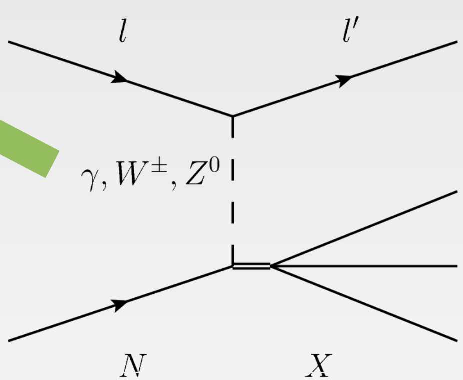
No experiments on pure H
→ contributions from rest nucleus

Disentangle single-nucleon from nucleus effects

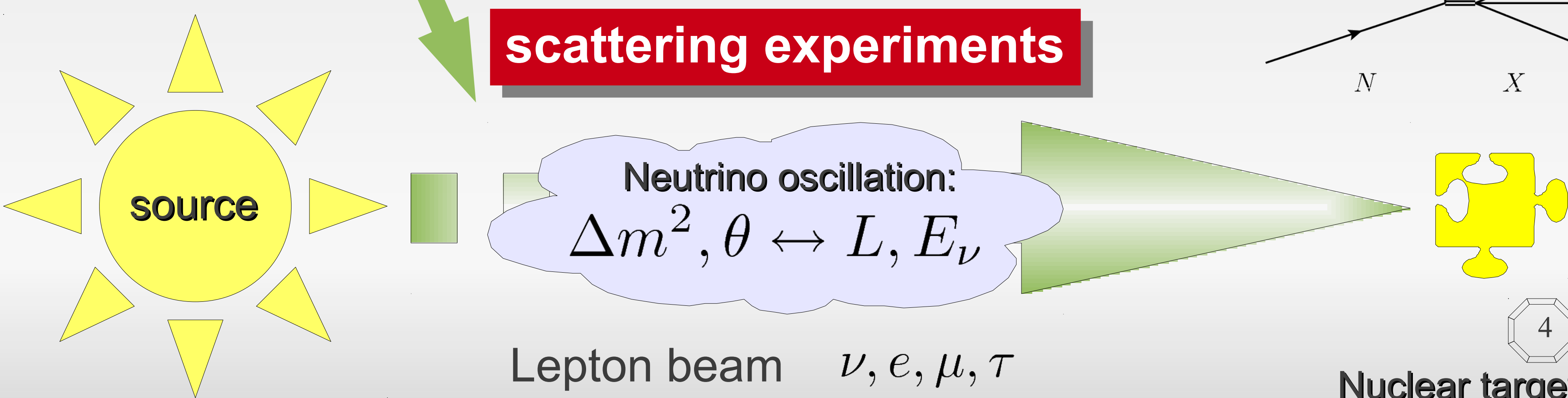
understanding of lepton-nucleon interaction

Data analysis strongly depends on models

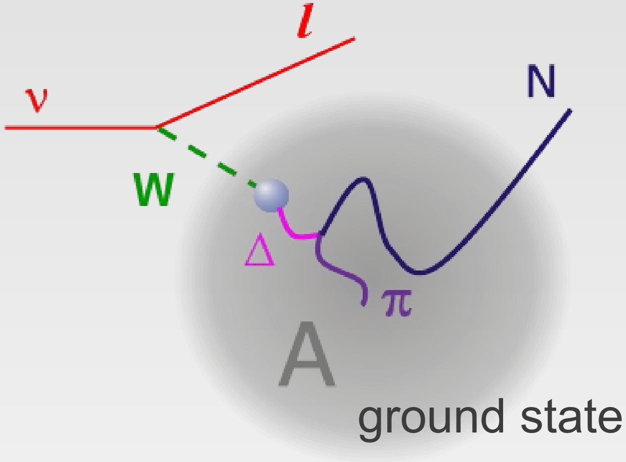
Model parameters are fit to a few experiments



scattering 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**



- Lepton part 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/

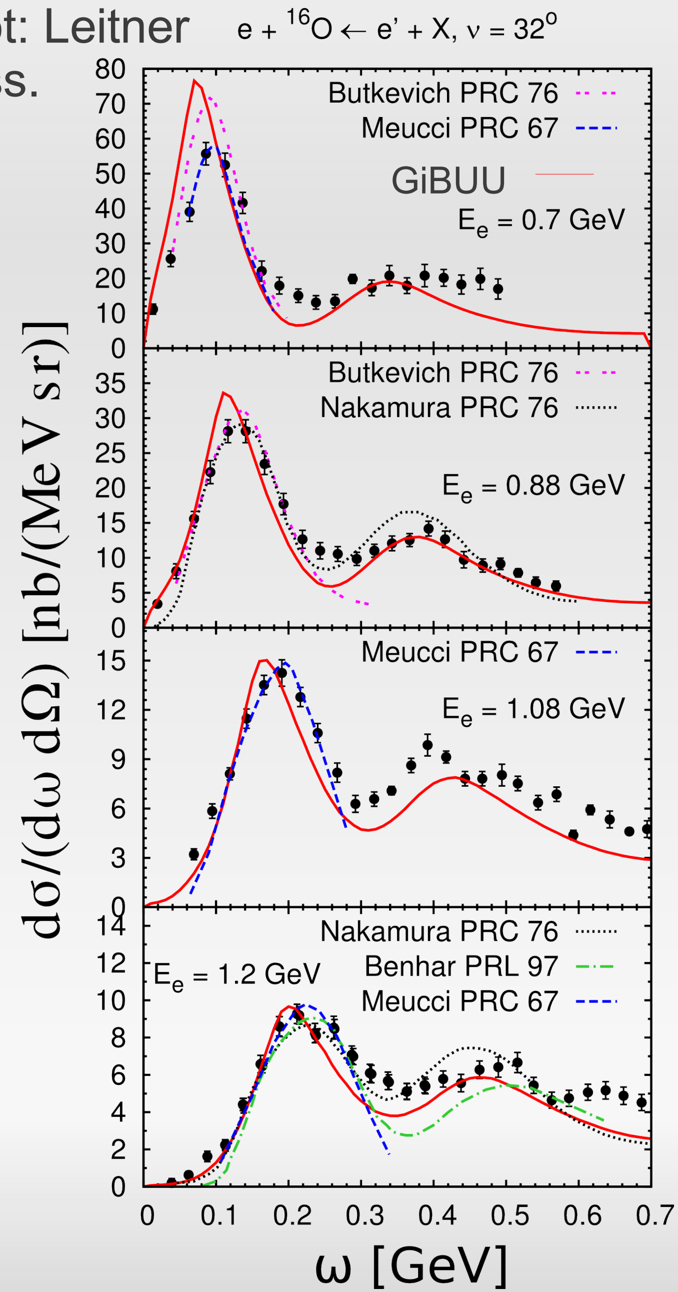
Electron data as a test for GiBUU

Focus:
inclusive electron-nucleus-scattering-cross sections at medium energy (~ 1GeV)

- Can GiBUU reproduce the data?
- Which contributions play a major role?
- How to explain and then reduce the discrepancies?

Electron data as a test for GiBUU

Plot: Leitner Diss.



Focus: inclusive cross sections of medium energy (~ 1GeV) lepton reactions

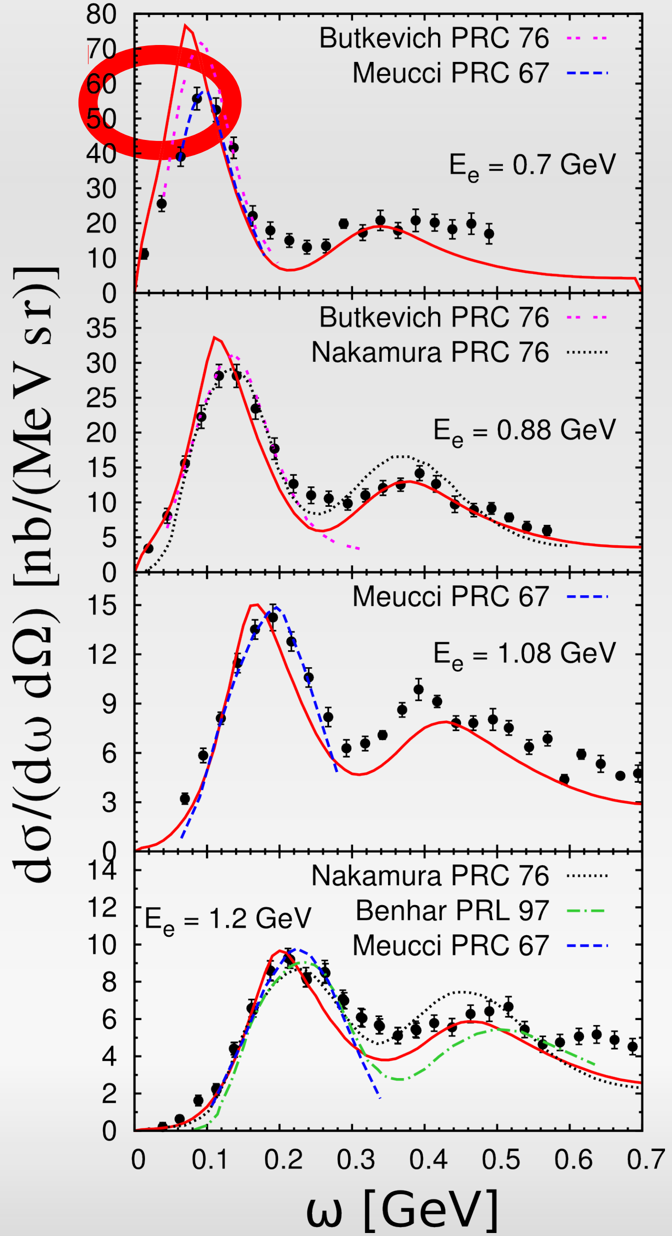
- Can GiBUU reproduce the scattering data? Yes! On par with specific models.
- Which are the basic ingredients?
  - Impulse approximation: struck nucleon absorbs energy transfer
  - ground-state initialisation: local Thomas-Fermi gas

$$k_{\mathrm{Fermi}} \propto \rho^{\frac{1}{3}}$$

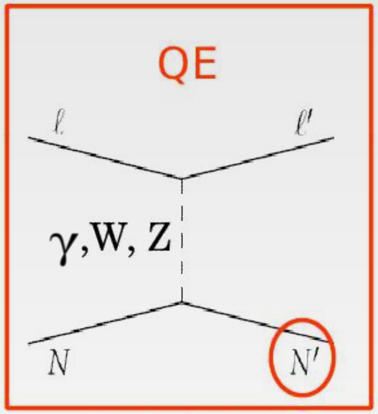
  - Many-body effects: in-medium width, hadronic mean-field potential

Electron data as test for GiBUU

Anghiolfi data $e + {}^{16}O \leftarrow e' + X$, $\nu = 32^o$



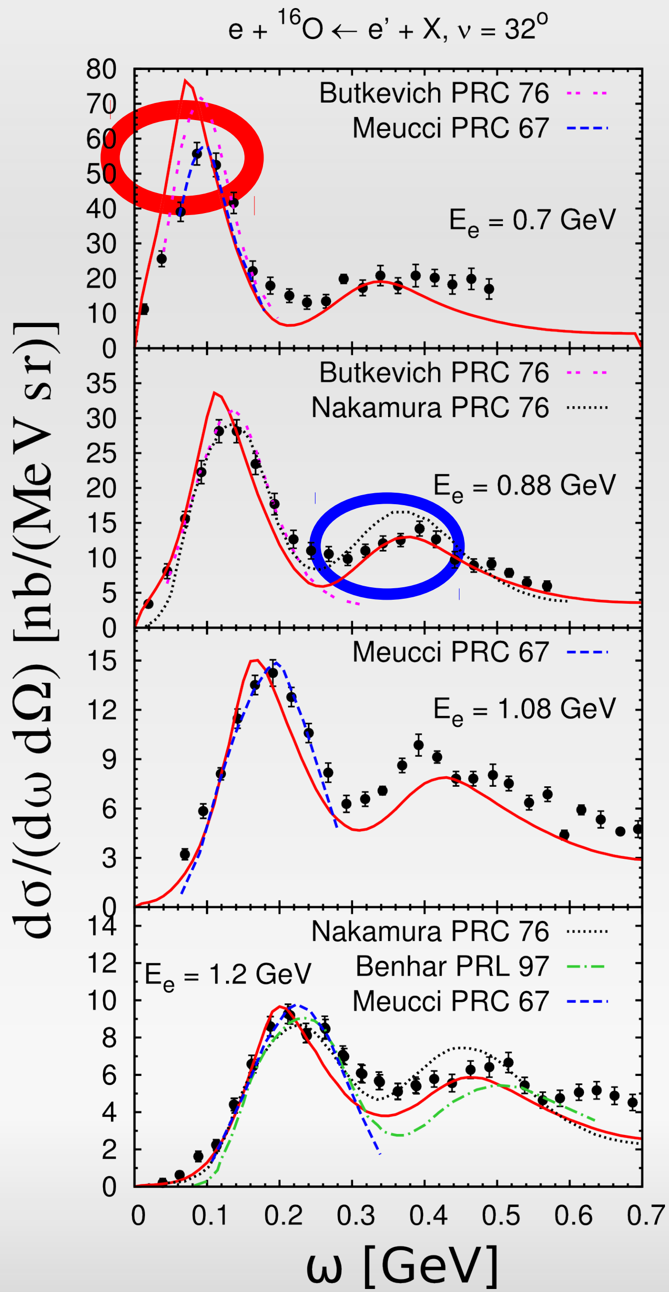
- Can GiBUU reproduce the data?
- Which contributions play a major role?



quasielastic scattering

quasi-elastic peak (QEP)

Electron data as test for GiBUU



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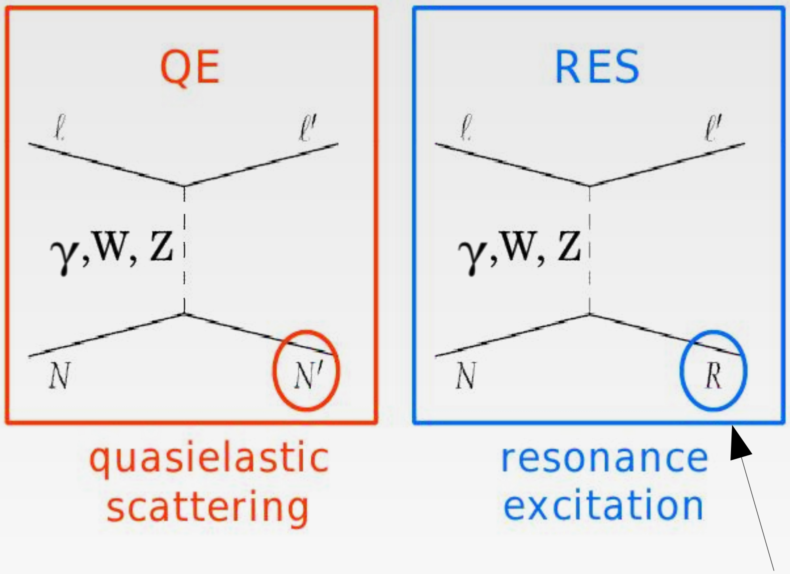
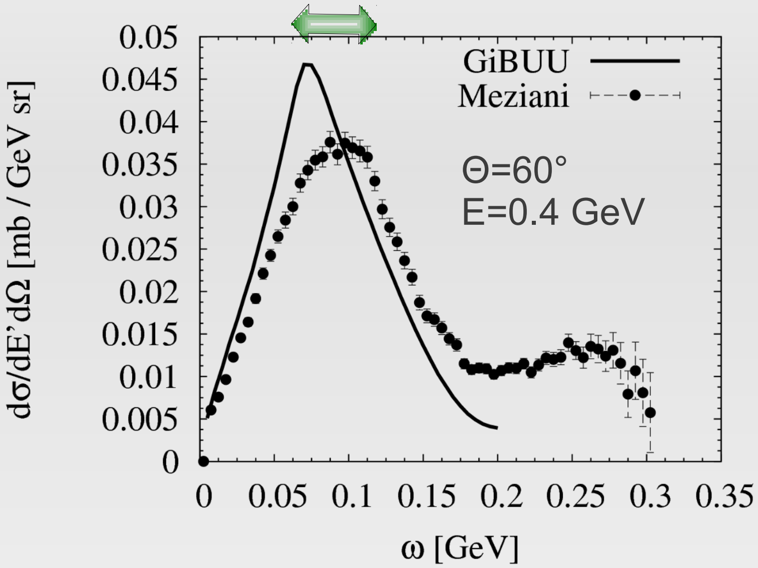


e.g. a Delta resonance: $\Delta^{++} = (u\uparrow u\uparrow u\uparrow)$

Electron data as test for GiBUU

Data: PRL 52 (1984) N° 24

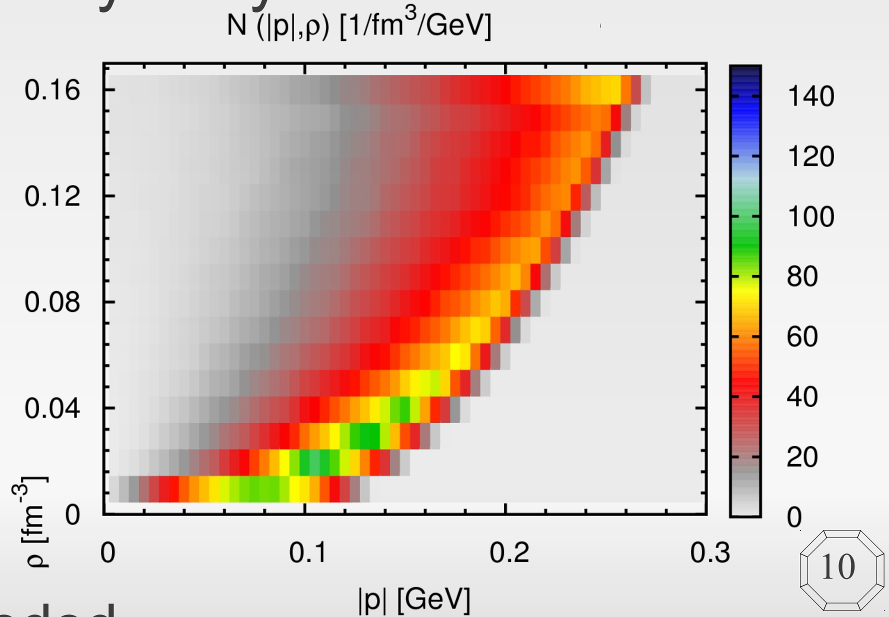


- Can GiBUU reproduce the data?
- Which contributions play a major role?
- How to explain and overcome the discrepancies?

→ First: focus on QEP as it is kinematically easy to handle

- QEP position shifted (binding energy)
- Cause: density/momentum profile of local Thomas-Fermi gas (LTF)
  - Large probability of finding nucleons at low momenta AND low densities → QEP does not feel effect of mean field potential

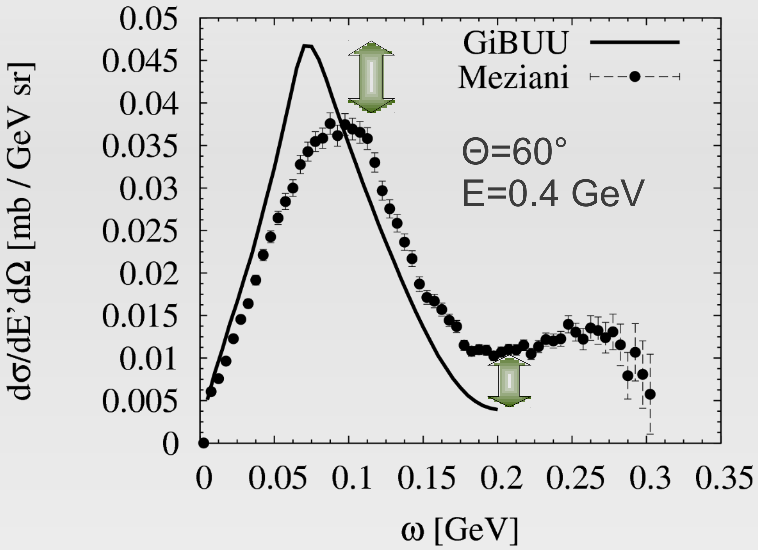
More advanced ground state needed



Plot: Tina Leitner, Dissertation

Electron data as test for GiBUU

Data: PRL 52 (1984) N° 24

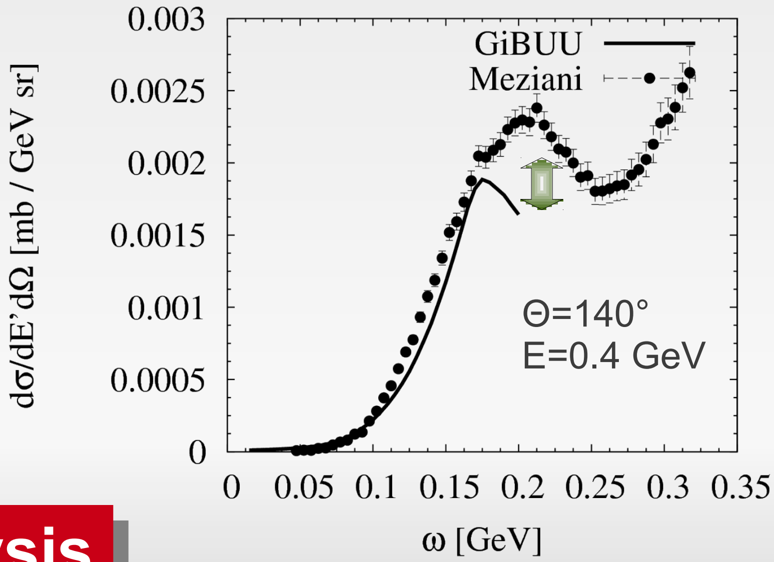


- Can GiBUU reproduce the data?
- Which contributions play a major role?
- How to explain and overcome the discrepancies?

  → First focus on QEP as it is kinematically easy to handle

- Quantitative discrepancy depending on kinematics
- Hint towards physics beyond IA
  - Needed: analysis methods to disentangle trivial & interesting effects
  - compare results for different nuclei and kinematics

→ **Superscaling analysis**



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 ≈ 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**

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

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

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

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

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)

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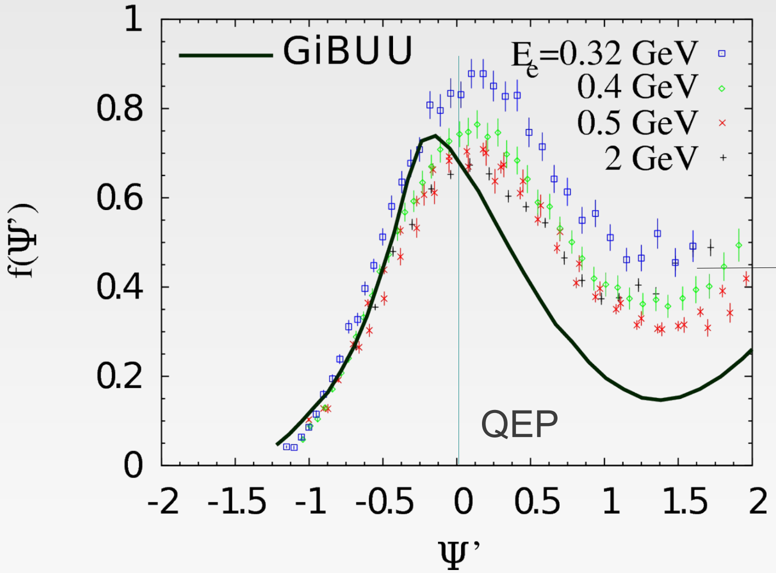
Data: PRC 60, 065502 (1999)



GiBUU shows no energy dependence of scaling function → effects beyond impulse approximation are missing

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

Superscaling: universal nuclear property

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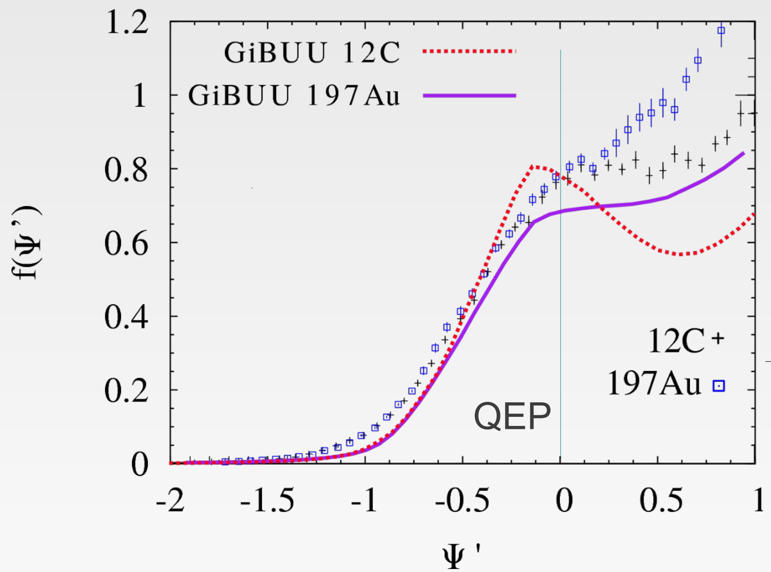

Local Thomas-Fermi gas leads to stronger differences Between nuclei than observed in nature

→ refine ground state

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

Superscaling: universal nuclear property

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

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

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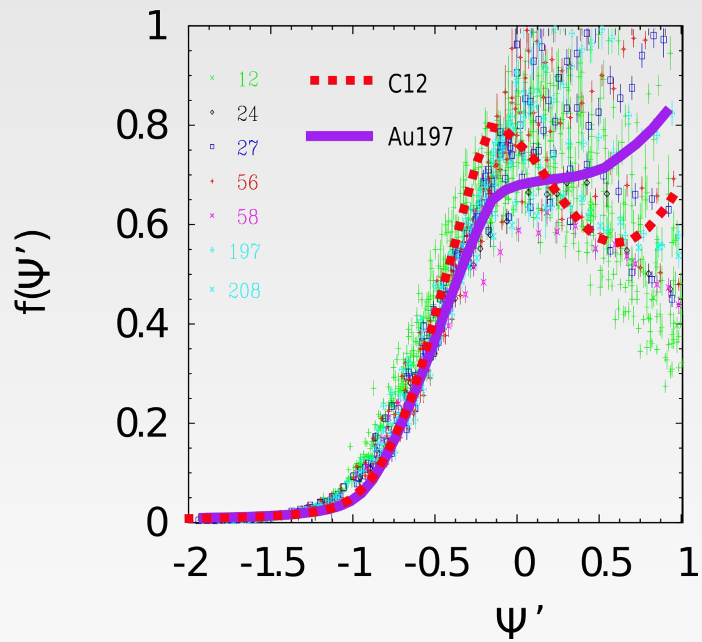


Redo Plot!

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

Second-kind scaling violations

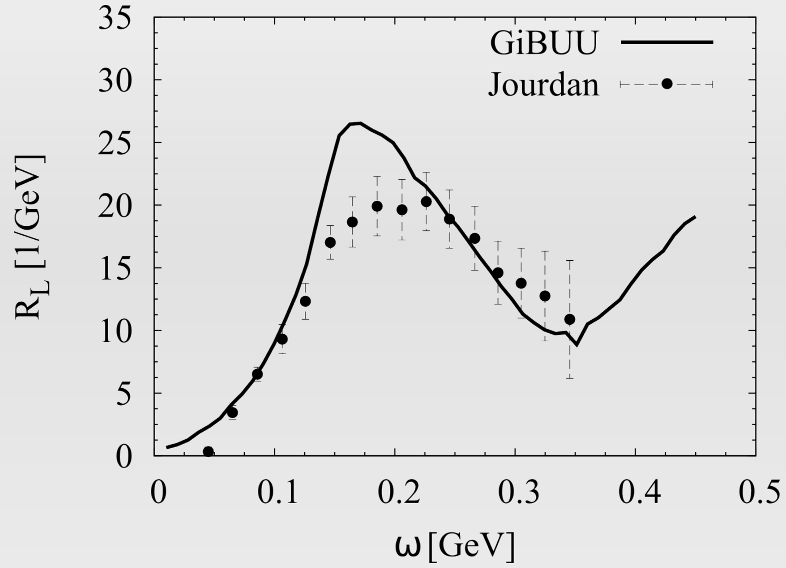
- Interesting to perform longitudinal / transverse separation and compare with experiment

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}E'\mathrm{d}\Omega} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{Mott}} \left[\left(\frac{Q^2}{q^2}\right)^2 R_{\mathrm{L}} + \left(\frac{1}{2}\frac{Q^2}{q^2} + \tan^2\frac{\theta}{2}\right) R_{\mathrm{T}}\right]$$

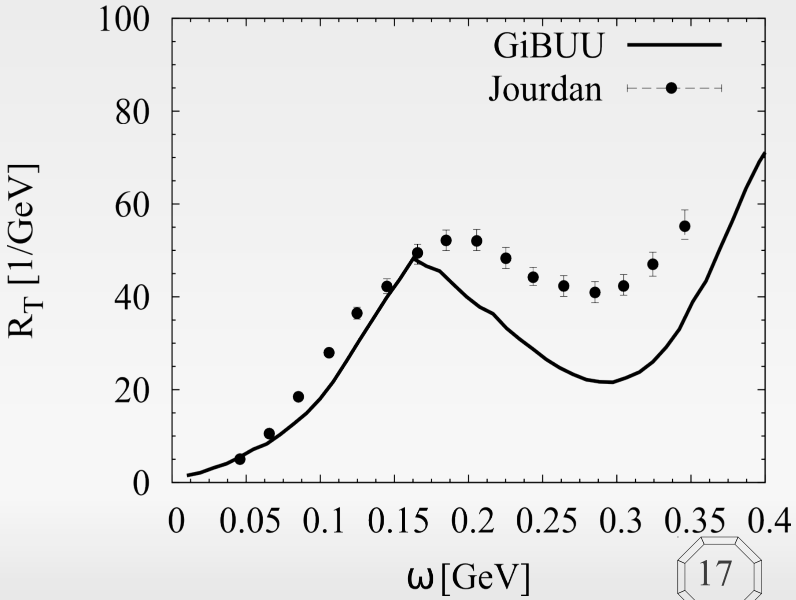
- Longitudinal response overestimated by GiBUU while transverse response underestimated

  → scaling violating effects depend on photon polarization

$$\epsilon = \left(1 + \frac{2q^2}{Q^2}\tan^2\frac{\theta}{2}\right)^{-1}$$



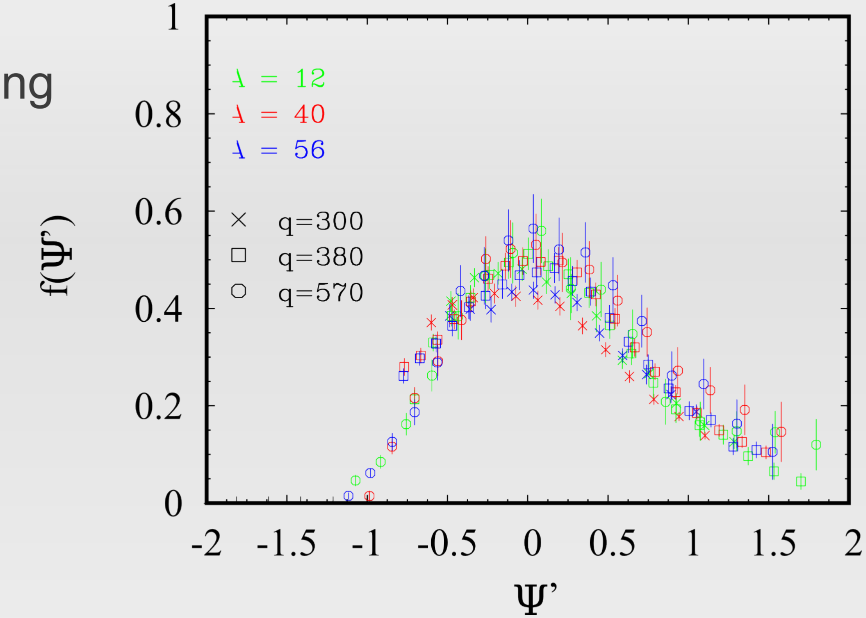
Data: Nucl. Phys. A 603 (1996), N° 2 117-160

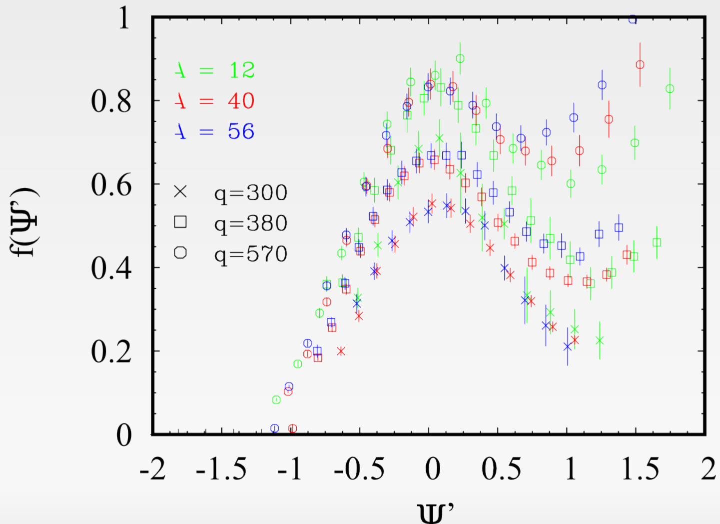


Second-kind-scaling violations

- Again more insight through **superscaling analysis** of separated reponses
- In impulse approximation longitudinal and transverse scaling functions are identical
  - → Take longitudinal scaling function as ”impulse approximation compatible” response, try to reproduce it

f long



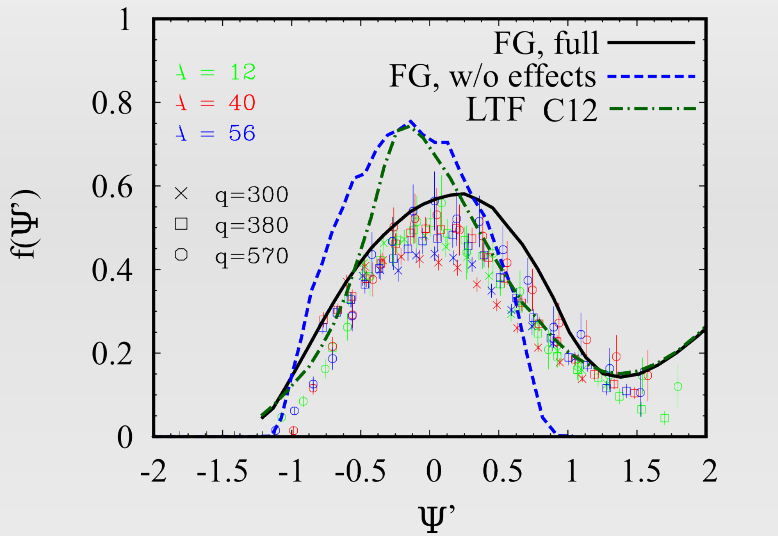


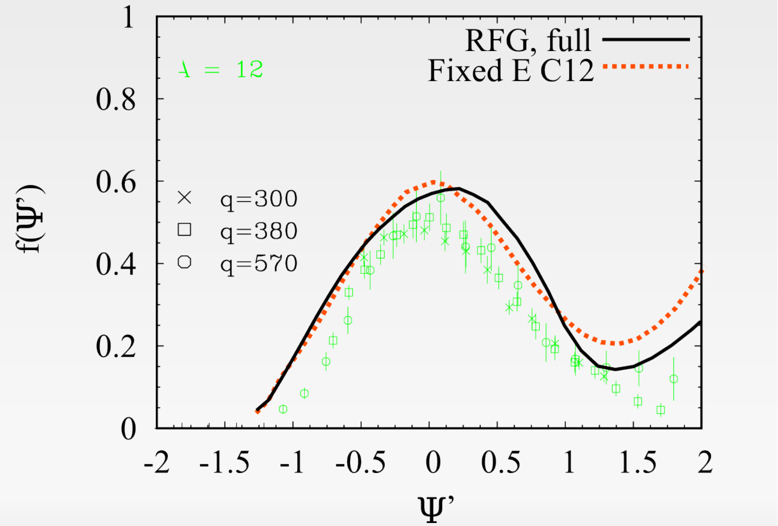
f trans

Plots: PRC 60, 065502 (1999)

Ground state refinement

- Aim to match peak position and height of longitudinal scaling function at QEP
- Simple approach: global Fermi Gas
  - QEP position not reproduced: too much influence from mean field potential
- NEW approach: local Thomas-Fermi approximation with fixed energy
  - position well reproduced as well as general shape
  - physical interpretaion: all nucleons feel potential, but momentum distribution still realistic due to density profile

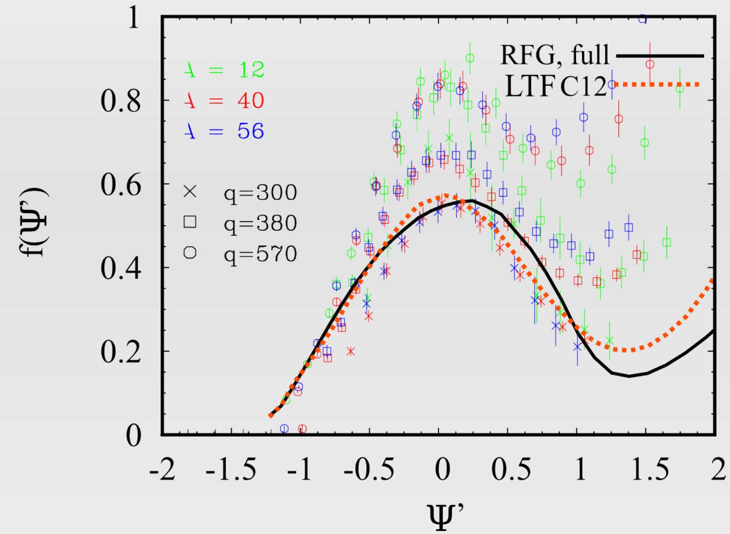


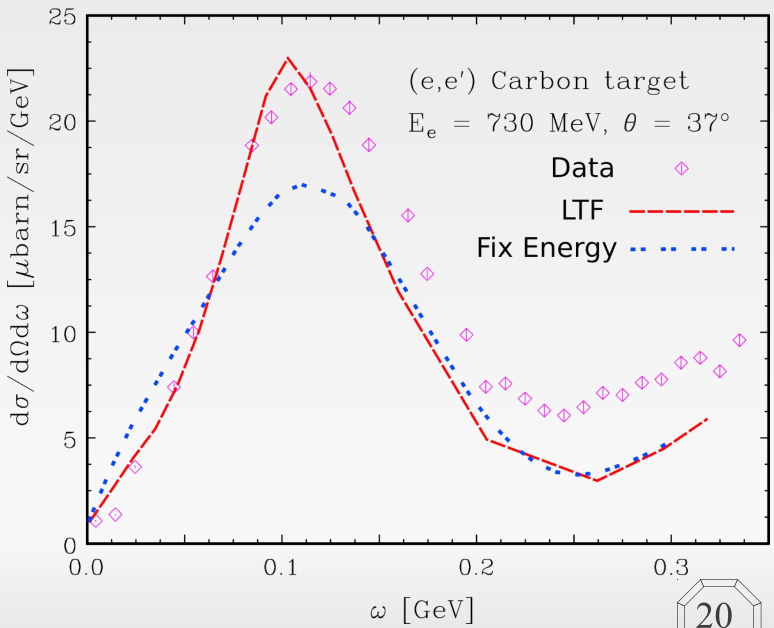


Data: PRC 60, 065502 (1999)

Fitting experimental data

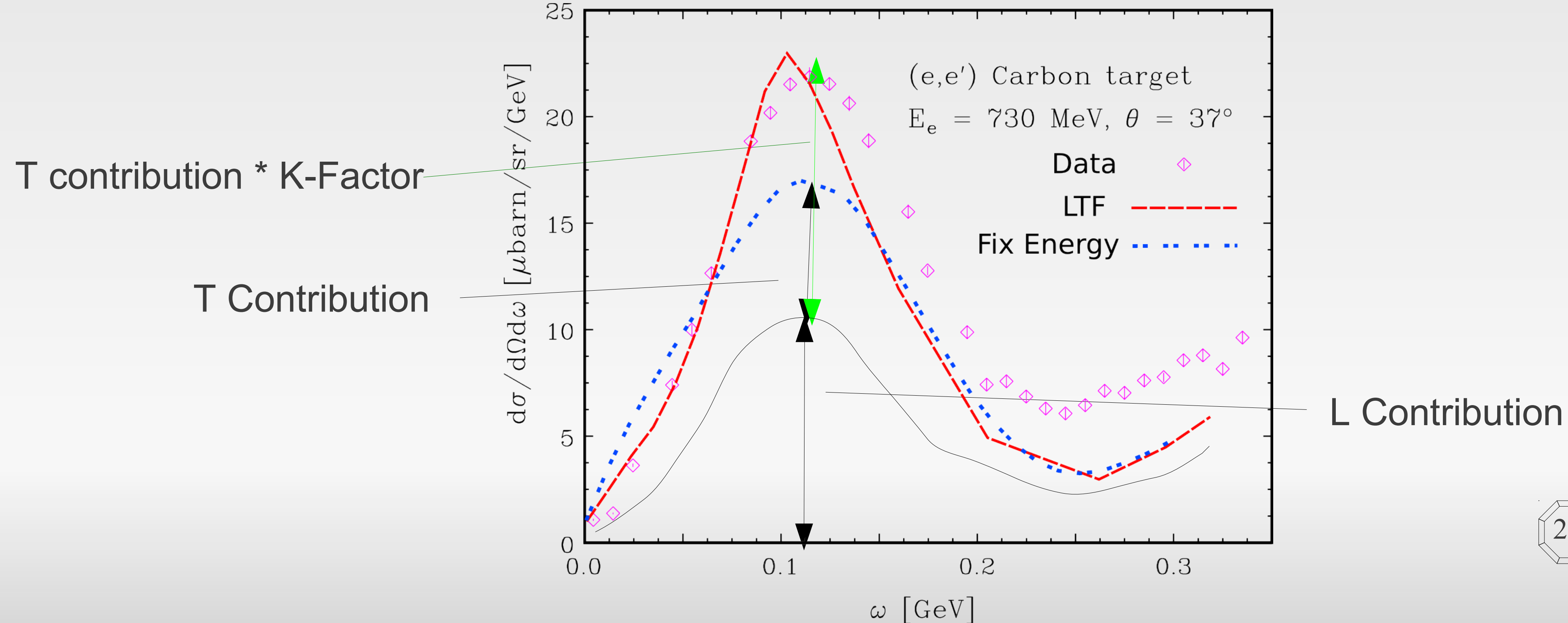
- New ground state describes the lowest curves → ansatz underestimates most of the data, since excess transverse strength not included
- Ways to implement these effects:
  - Wanted: Modifiy the initial vertex (off-shell cross section) → Possible in GiBUU, but needs ansatz for the off-shell cross section
  - Phenomenological: Fit the transverse excess to data





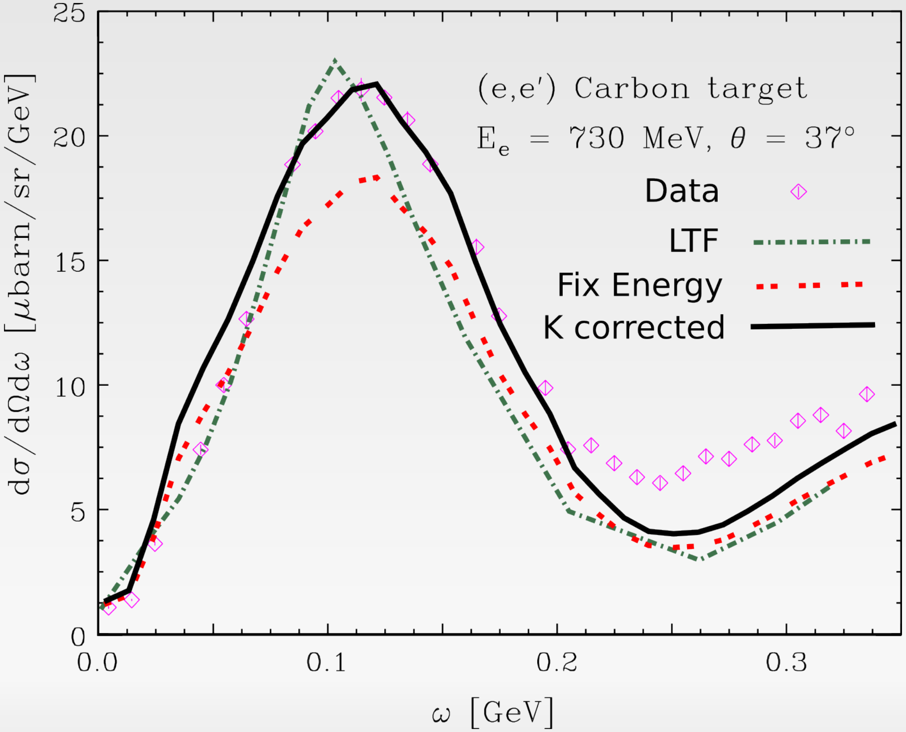
Fitting experimental data

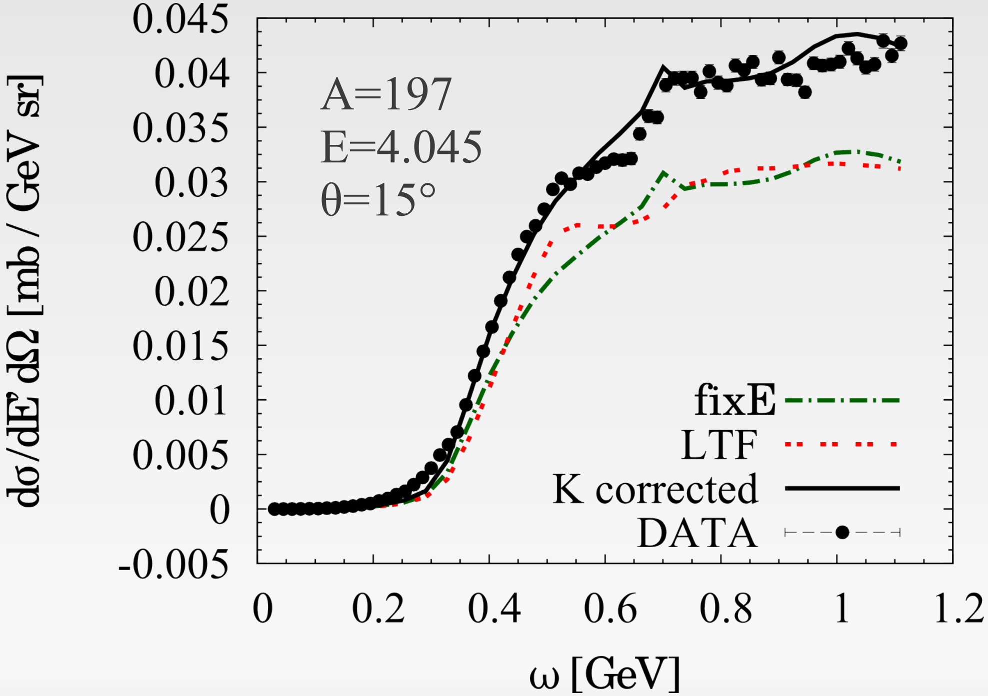
- Simple Ansatz: q dependent K-Factor to account for missing transverse strength
- Using extrapolation from the scaling functions to obtain the separated responses
- Better than fitting to transverse scaling functions, since L/T separation is experimentally demanding



Fitting experimental data

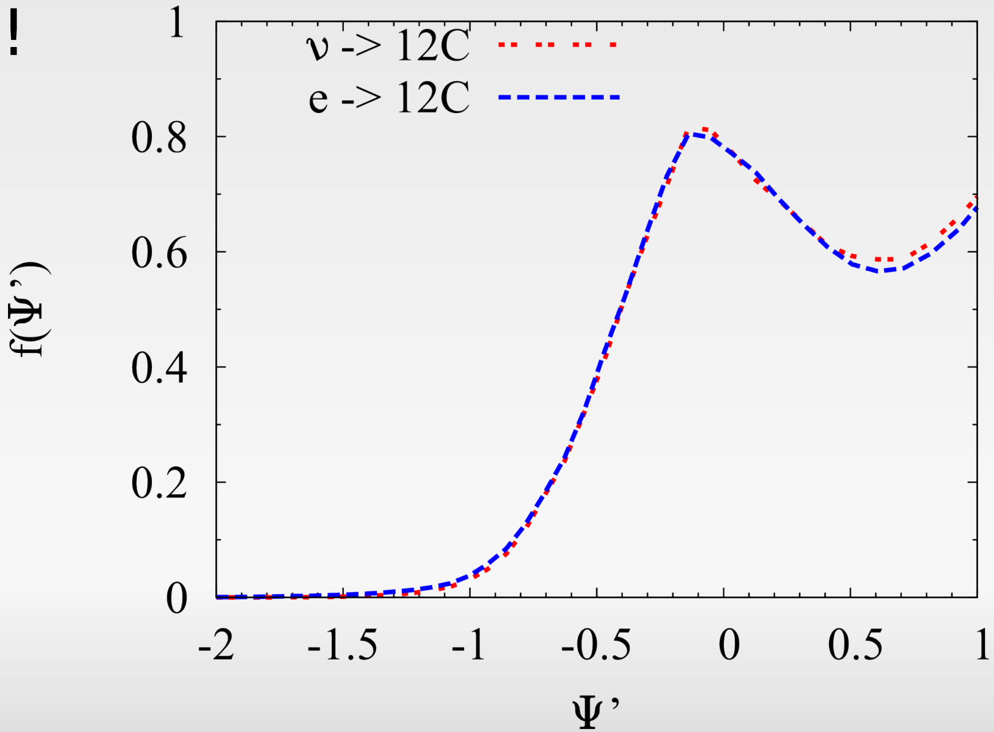
- K-factor-corrected cross sections reproduce position of QEP and fit better in the dip and the resonance region
- K only depending on q, not on A and ε





Outlook: From electron analysis to neutrino extrapolation

- Needed for **neutrino oscillation experiments**: exclusive particle production cross sections.
- Can be obtained with GiBUU using a transport approach after initialization with ansatz described above (Leitner, PRC 038501 (2009)).
- Simulated inclusive neutrino cross sections also superscale!



Outlook: From electron analysis to neutrino extrapolation

- Idea: excess transverse strength might explain surprisingly large neutrino-scattering cross sections from the **MiniBooNE** experiment w/o need for huge **axial mass**

- Contributions from 2p2h, meson exchange currents, can be included for both neutrino and electron calculations

- more kinematical freedom at vertex → not just two response types → interesting field for model building

Summary

- GiBUU can be used to describe **medium-energy electron-nucleus** collisions
- Making use of the **superscaling analysis** one can compare results for electrons and neutrinos scattered on various targets and at various kinematics
- Using methods that go beyond the impulse approximation and the local Thomas-Fermi approach one can **fit the data even better**
- GiBUU can also be used to predict exclusive cross sections, that are imortant in **neutrino scattering experiments**

Outlook

- Current results:
  - Partly published as thesis, can be downloaded at http://theorie.physik.uni-giessen.de/
  - **Stay tuned:** article in preparation
- Future plans:
  - Investigate in-medium neutrino-nucleon vertex
  - Improve way of implementing excess transverse strength
  - Deeper theoretical understanding of in-medium effects