Scaling in quasielastic electron- and neutrino-nucleus scattering

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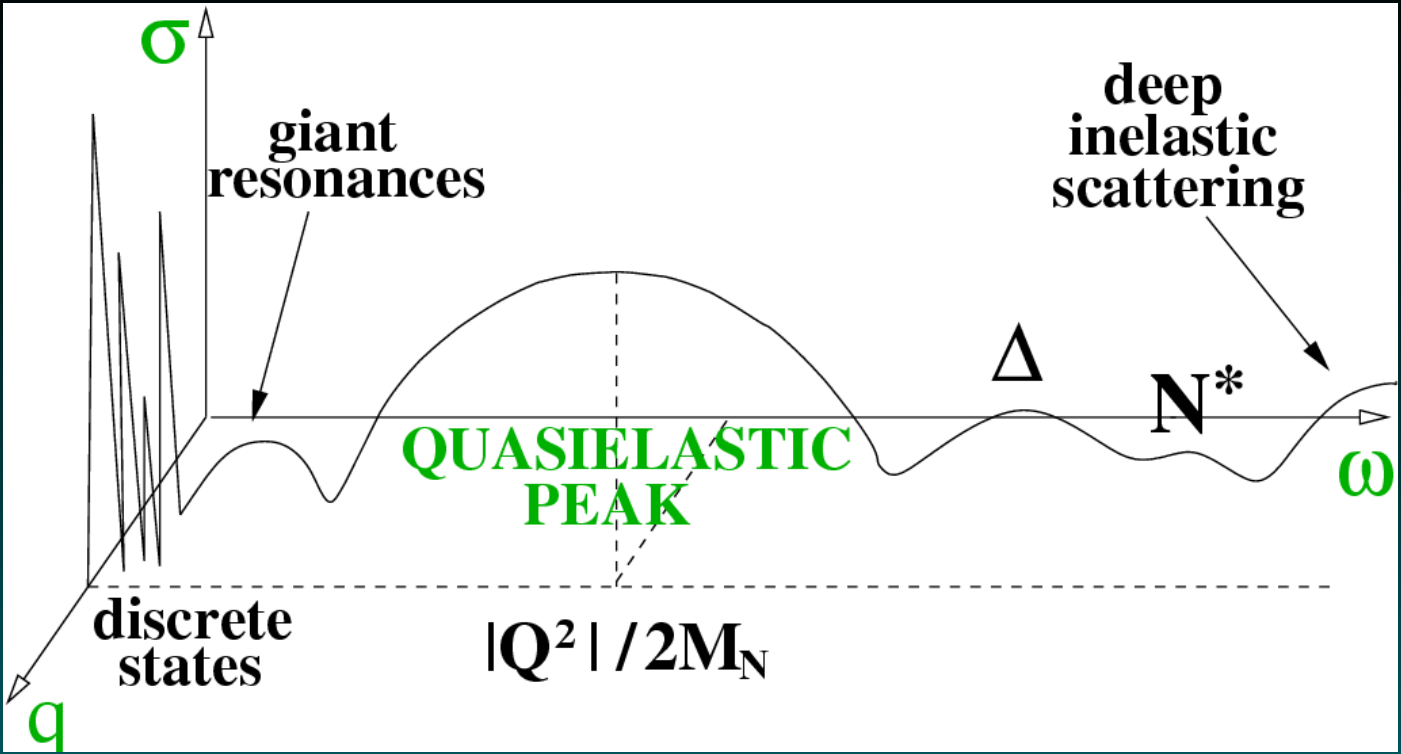
A review of the work of many people from whom I've learnt:
J.A. Caballero, T.W. Donnelly, C. Maieron, J.M. Udías,
and many more!

Gordon Conference on Photonuclear Reactions, Tilton, August 2008

Outline

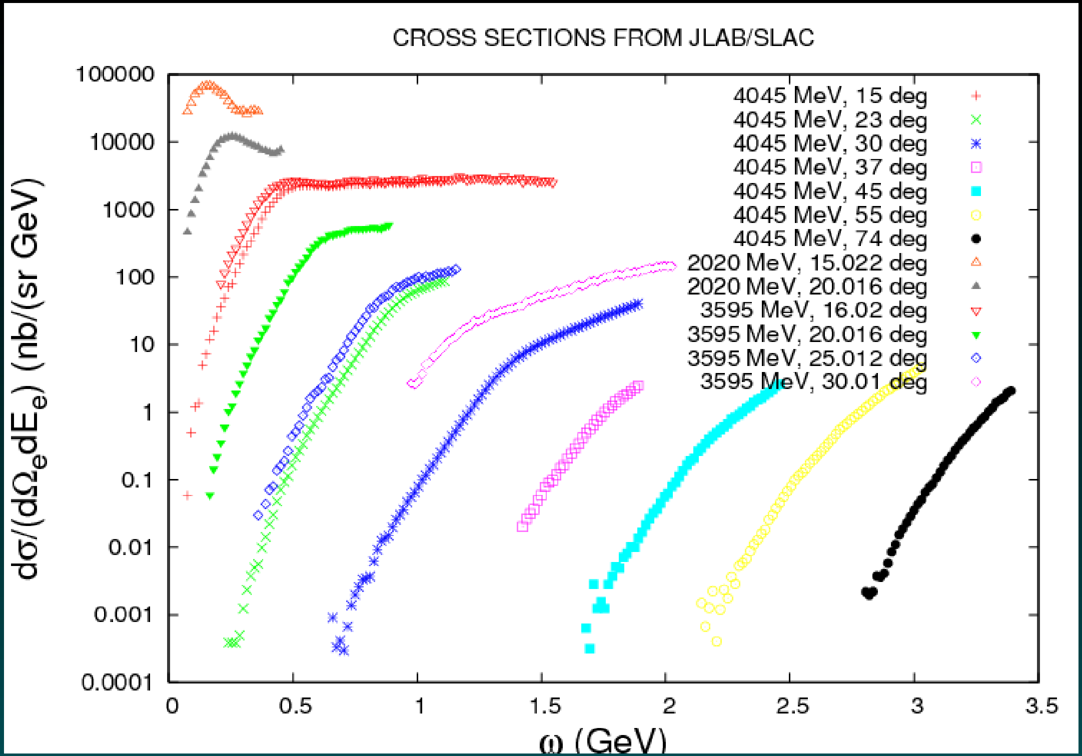
- **(Understanding...) Scaling in electron-nucleus scattering**
- **(Applying...) Scaling in neutrino-nucleus interactions**

Inclusive electron scattering on nuclei



Many things may happen to the nucleus, depending on the values of q and ω

Inclusive ^{12}C quasielastic electron data



Day *et al*, PRC48(1993)1849

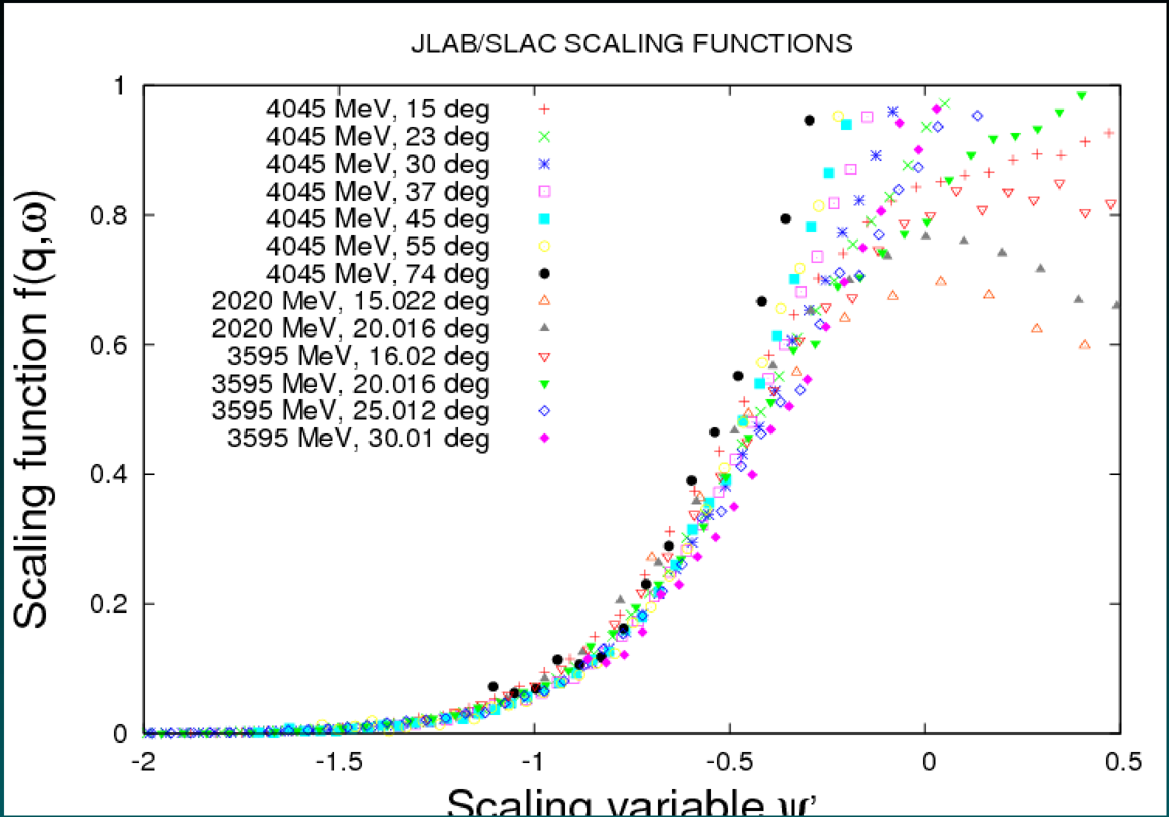
Arrington *et al*, PRL82(1999)2056

$0.5 < q < 4$ GeV/c

$$f(q,\omega) \propto \frac{\left[\frac{d\sigma}{d\Omega_e dE_e}\right]}{\overline{\sigma}_{electron-nucleon}}$$

Inclusive ^{12}C quasielastic electron data

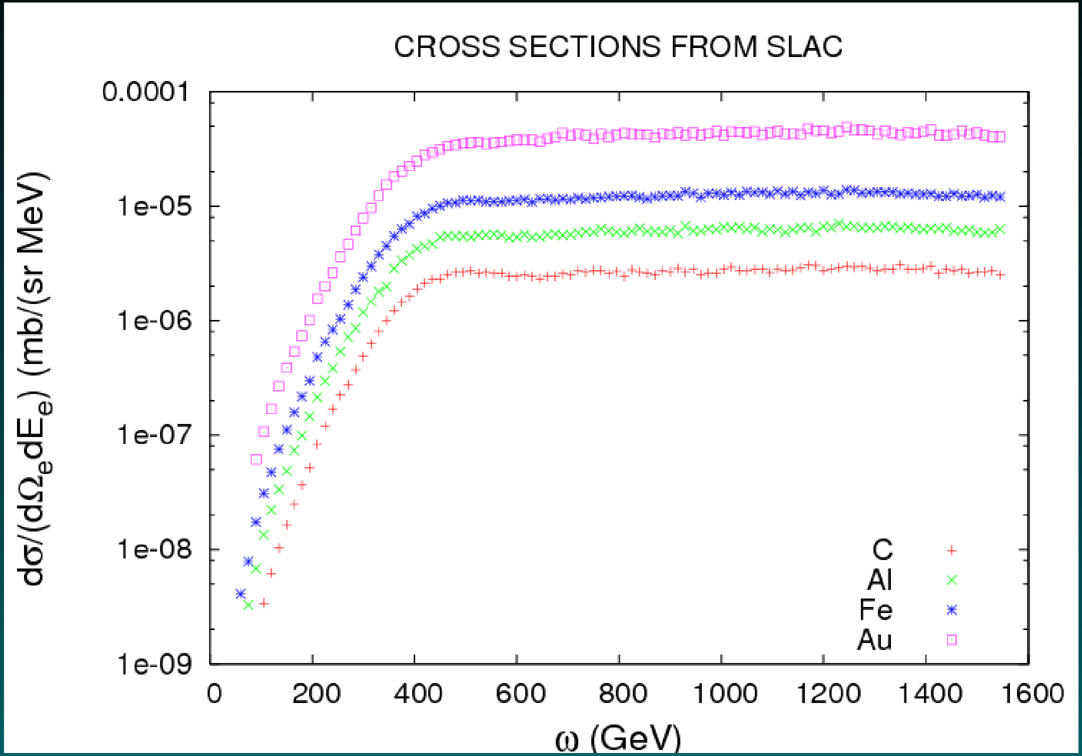
SCALING BEHAVIOR



Quite good scaling for negative scaling variable (y-scaling). Large violations for large energy transfers due to the transverse response

More inclusive quasielastic electron data

Same transferred momenta, different targets (C, Al, Fe, Au)

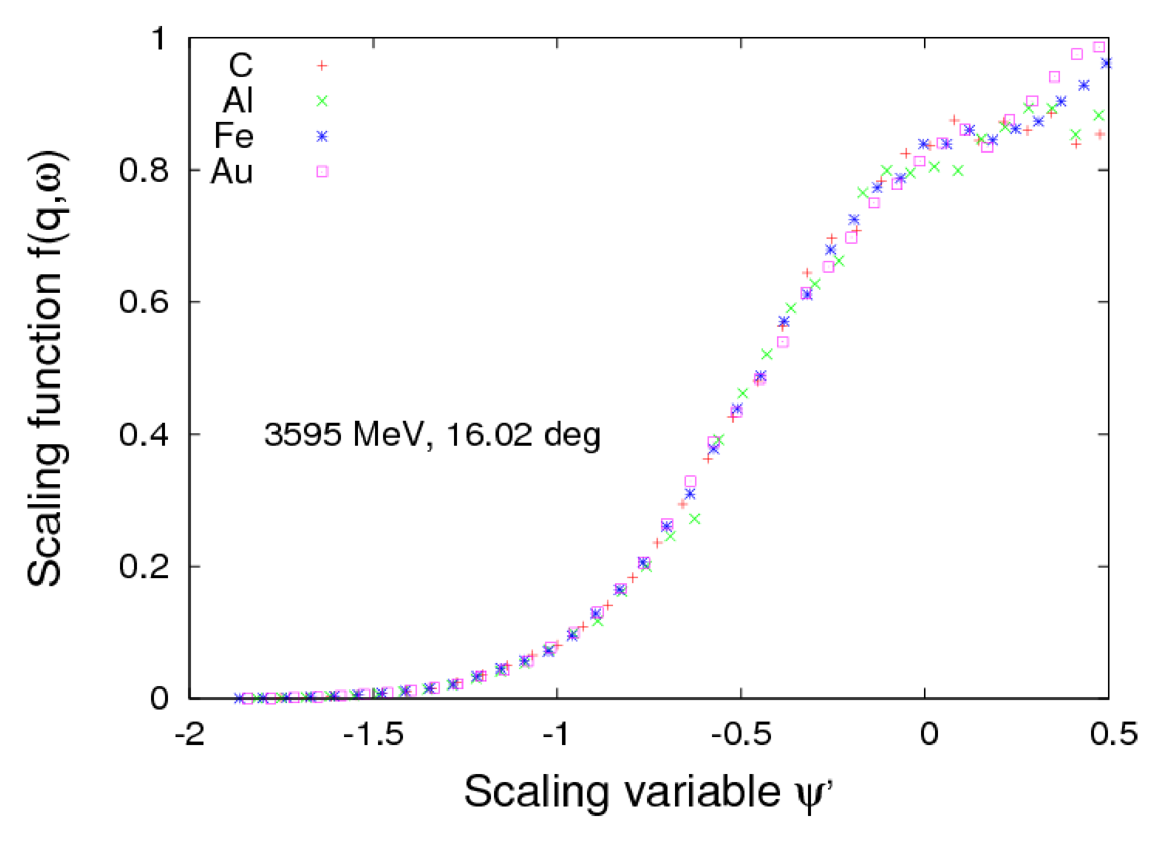


Day *et al*, PRC48(1993)1849

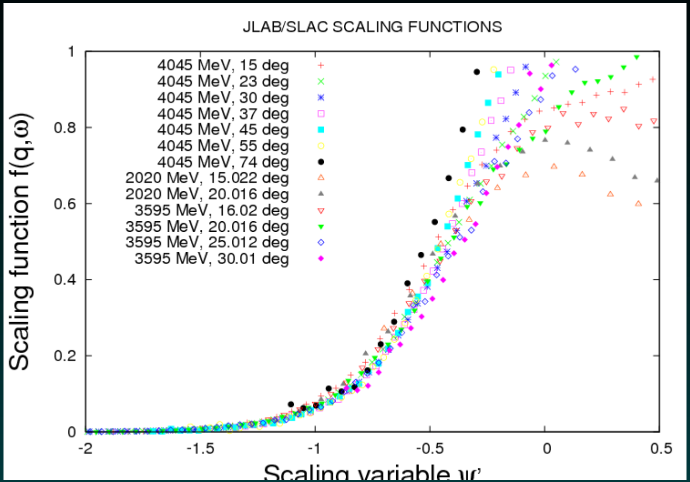
$q \approx 1$ GeV/c
$E_e = 3{,}6$ GeV,
$\theta_e = 16^o$

Inclusive quasielastic electron data at $q \approx 1$ GeV/c

SCALING BEHAVIOR

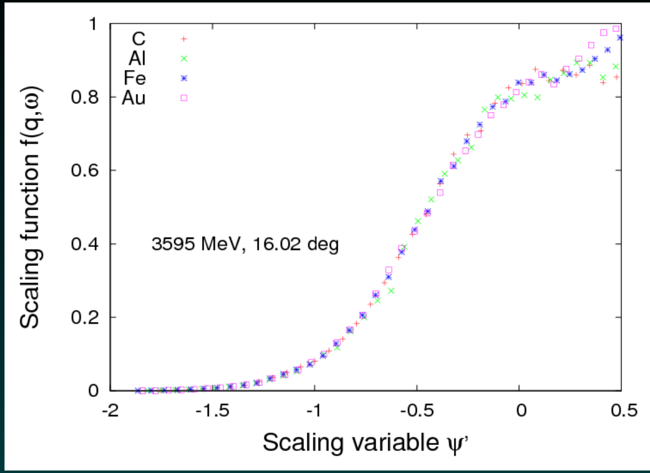


Same target (^{12}C), different transferred momenta



FIRST KIND SCALING

Same transferred momenta, different targets (C, Al, Fe, Au)



SECOND KIND SCALING

FIRST (y-scaling) + SECOND = SUPERSCALING

Day *et al*, Ann. Rev. Nucl. Part. Sci. **40** (1990) 357,
Donnelly and Sick, Phys. Rev. C **60** (1999) 065502,
Donnelly and Sick, Phys. Rev. Lett. **82** (1999) 3212

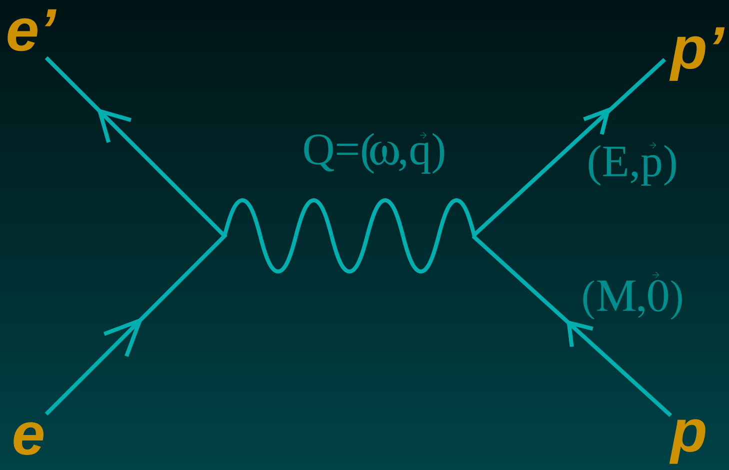
Superscaling, although not perfect, is exhibited by Nature:

- **Why does it happen?**
- **What is the scaling function?**
- **What can we learn studying Superscaling (and its violations)?**
- **How can we use it?**

ELASTIC ELECTRON SCATTERING OFF A FREE NUCLEON AT REST

Conservation of energy and momentum makes that:

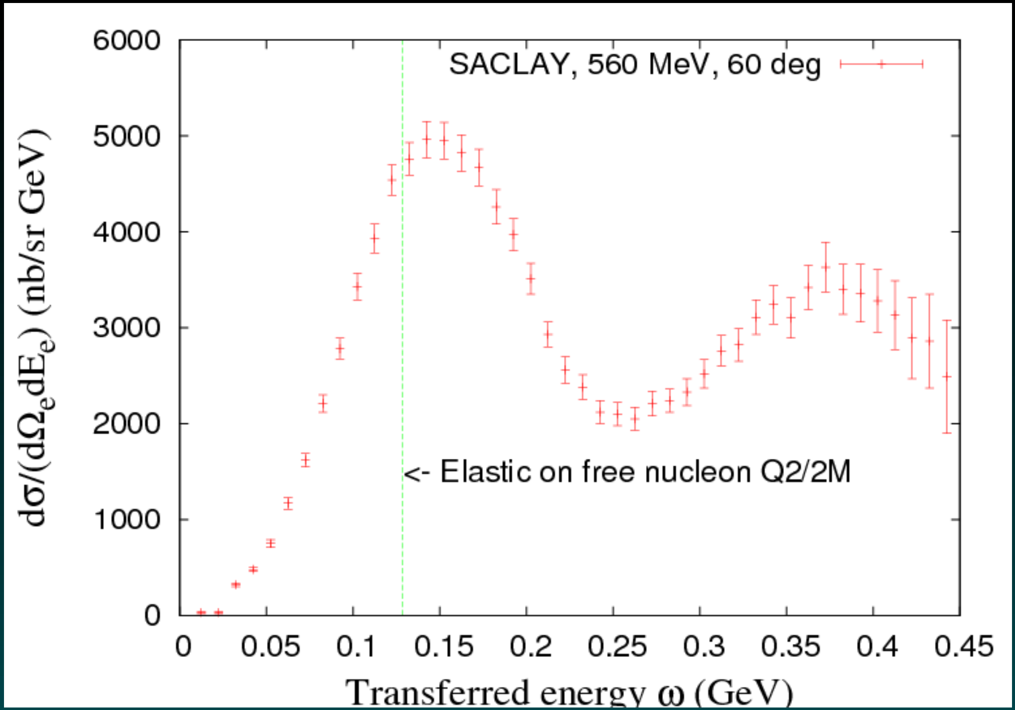
$$\omega + M = \sqrt{p^2 + M^2} \Rightarrow$$
$$\omega + M = \sqrt{q^2 + M^2} \Rightarrow$$
$$\omega = |Q^2|/2M$$



The transferred energy ω and momentum q are related to each other:

ω and q are not independent degrees of freedom

Quasielastic (e, e') experimental data...



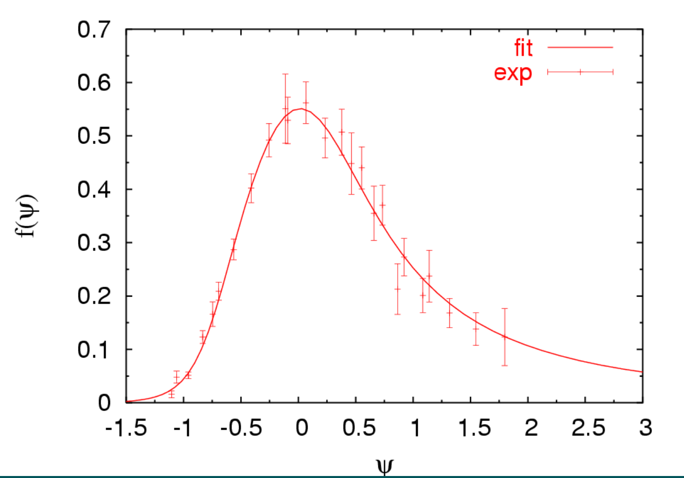
Dominant process in the QE peak: 'elastic' scattering on individual nucleons

Width ($\approx 2qk_F/M_N$): momentum of nucleons in the nucleus
Maximum shifted: binding energy and FSI effects

But there is a relationship between ω and q, similar to the elastic one, but corrected for the dynamics of nucleons in the nucleus $\Rightarrow$ SCALING

What is the scaled response?

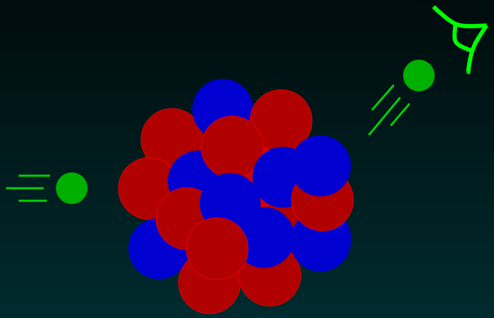
- **Scaling function: relevant information about the initial and final nuclear dynamics explored by the probe (in a very COMPACT form!).**
- In a very very simple model, it would be the integral of the spectral function of the nucleus, but the scaling of the data tells us that this idea, although a good approach, is not the full answer...



Maieron, Donnelly and Sick,
Phys. Rev. C **65**, 025502 (2002)

QE long. (e,e') **DATA** $\Longleftrightarrow$ **SCALING FUNCTION**

Some general ideas about scaling in inclusive scattering



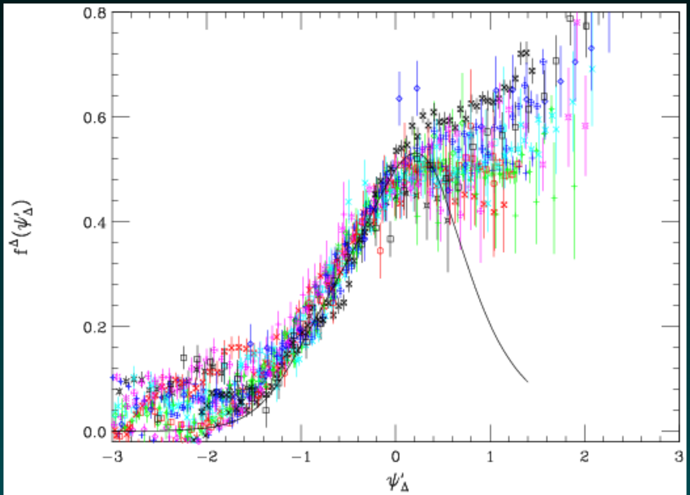
- Requires a **weakly interacting probe** and a **composite target**
- The probe must scatter from **one of the bound constituents** of the target

$$F(q,\omega) = \frac{\left[\frac{d\sigma}{d\Omega_{probe} dE_{probe}}\right]}{\overline{\sigma}_{probe-constituent}}$$

At high q this function depends on a combination of q and $\omega \Rightarrow$ **SCALING**

Scaling ideas have been extended into the Δ region...

In that region, the main contribution is impulsive, inelastic *e*-N scattering, mainly N-Δ transition:



Amaro *et al*,
Phys. Rev. C 71, 015501(2005)

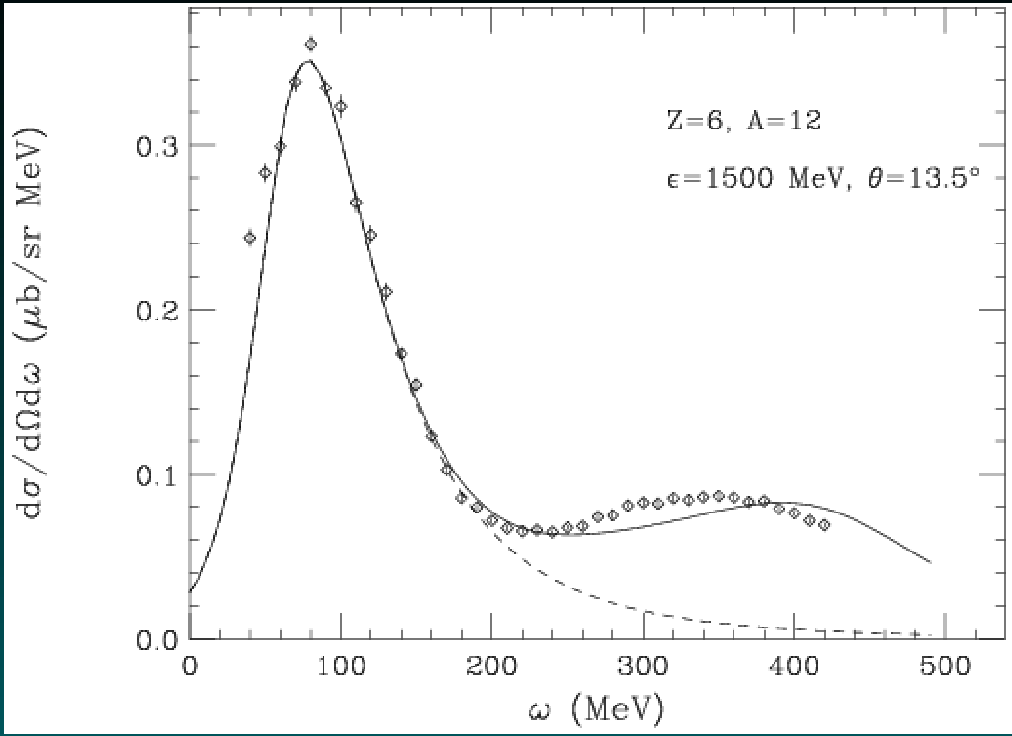
Δ DATA ⟺ Δ SCALING FUNCTION

What can be learnt studying SCALING?

- **Reaction mechanism: Strong and economic TEST OF MODELS of inclusive scattering.**
- **Nuclear dynamics: role of correlations, final state interactions...**
- **It can be used to PREDICT inclusive cross sections without the need of any model**

$$\text{QE, } \Delta \ \frac{d\sigma}{d\varepsilon_e d\Omega_e} \text{ data} \Longleftrightarrow \text{QE and } \Delta \text{ scaling functions}$$

An example of these predictions based on (QE + Δ) scaling ideas...



Advantage: very simple to implement!

NEUTRINO-NUCLEUS SCATTERING

One problem of neutrino experiments:

Neutrino detectors are filled with “nuclei” to increase the chances of detecting these elusive particles

$\Longrightarrow$ **Reliable neutrino-nucleus cross sections are needed to analyze data and to extract unambiguous results.**

One option is to rely on neutrino-nucleus models:

How to constrain these models?

Neutrino data are really scarce...

Most neutrino event generators use a Relativistic Fermi Gas to model the neutrino-nucleus interaction:

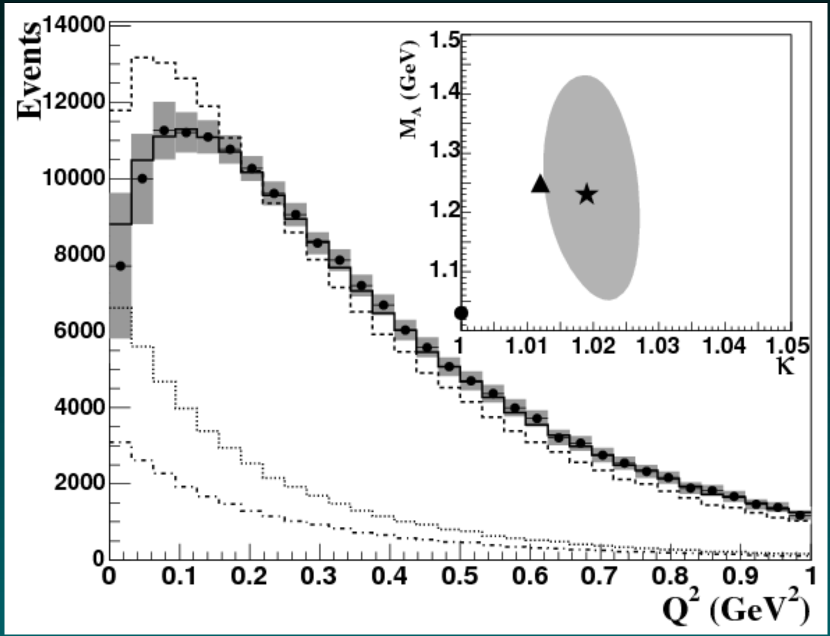
Example: Miniboone oscillation experiment@Fermilab

Measurement of Muon Neutrino Quasielastic Scattering on Carbon

(Aguilar-Arevalo *et al*, Phys. Rev. Lett. 100, 032301 (2008))

The CC QE ν_μ sample is used to constrain the expected ν_e rate...

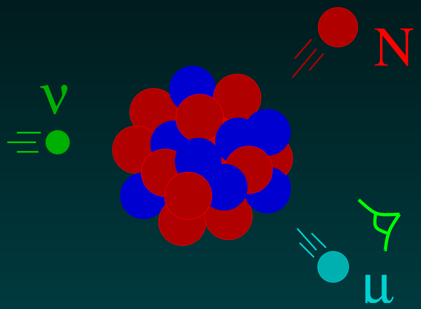
But the usual Relativistic Fermi Gas cannot reproduce their Q^2 event distribution... what is easy to understand...



Quasielastic (e,e') versus (ν,μ) (Charged-Current neutrino reactions)

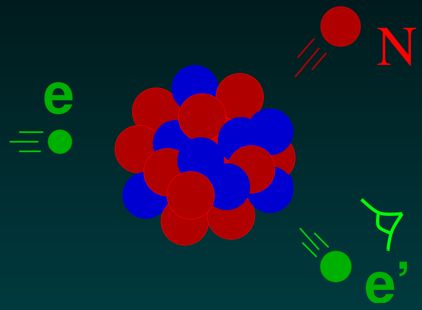
Neutrinos

$$\nu + A \Rightarrow \mu + N + B$$



Electrons

$$e + A \Rightarrow e' + N + B$$



Electron and neutrino INCLUSIVE scattering are very related, one should check models of neutrino scattering against the large amount of inclusive electron data...

How well compares the Relativistic Fermi Gas to QE inclusive electron data?

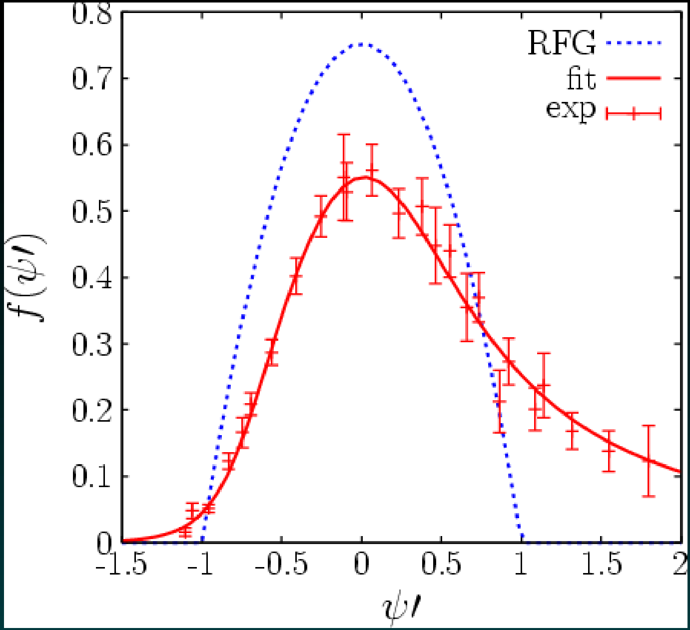
Relativistic Fermi Gas:

Perfect superscaling behaviour

(Alberico *et al*, Phys. Rev. C 38, 1801 (1988))

Experimental data:

Good superscaling behaviour, although not perfect



The RFG superscales, and data also superscale, but the scaling functions of data and of RFG disagree ⇒

The RFG lacks important initial and final state nuclear dynamics effects, even at high energies!

In Miniboone, the nucleon axial mass and Pauli blocking are modified to fit their event distribution, rather than using a better model...

Instead of employing direct neutrino-nucleus modeling,

why not USE SCALING TO PREDICT CHARGE-CHANGING NEUTRINO-NUCLEUS CROSS SECTIONS?

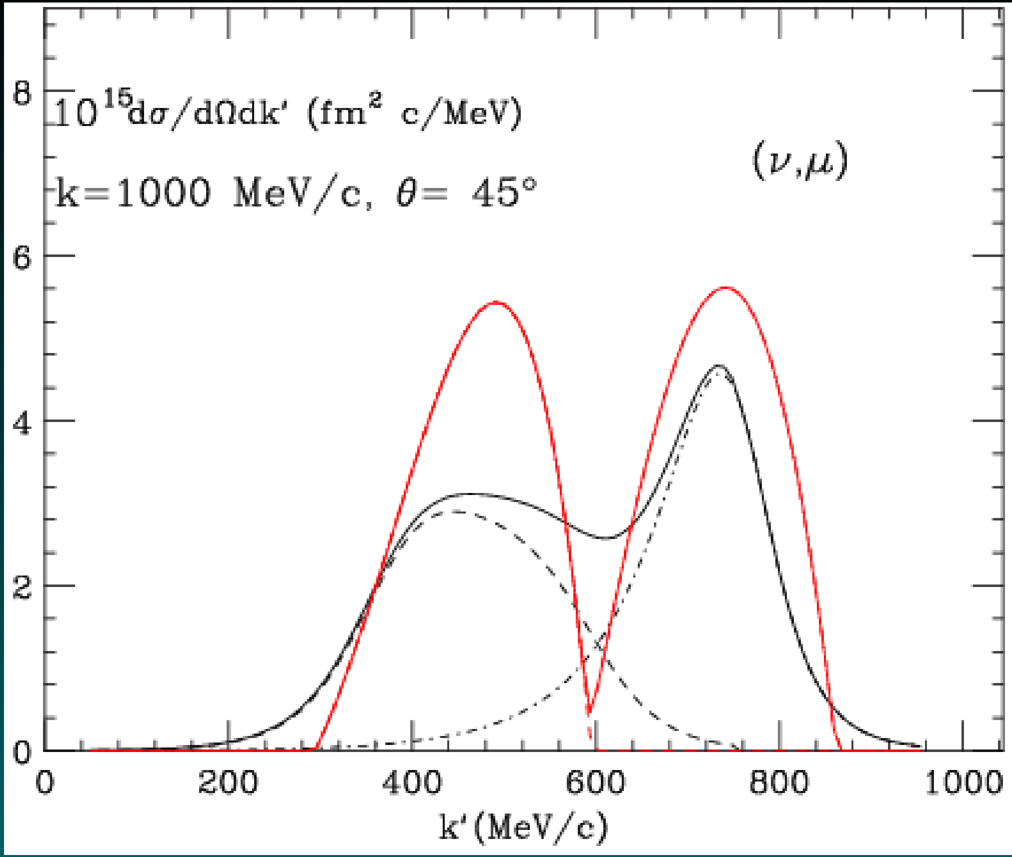
(Amaro *et al*, Phys. Rev. C71, 015501(2005))

Starting point of this SuperScaling approach: both electron and neutrino scattering share the **same universal scaling function** *under similar kinematics*:

$$\text{Scaling function} \propto \frac{\left[\frac{d\sigma}{d\Omega_e dE_e}\right]}{\overline{\sigma}_{eN}} \Rightarrow \frac{d\sigma}{d\varepsilon_\mu d\Omega_\mu} \propto \overline{\sigma}_{\nu N}\ \text{Scaling f.}$$

electron data ⇒ (CC) neutrino predictions

An example of these *neutrino* predictions based on nuclear information from the experimental electron data...



Advantage: very simple to implement!

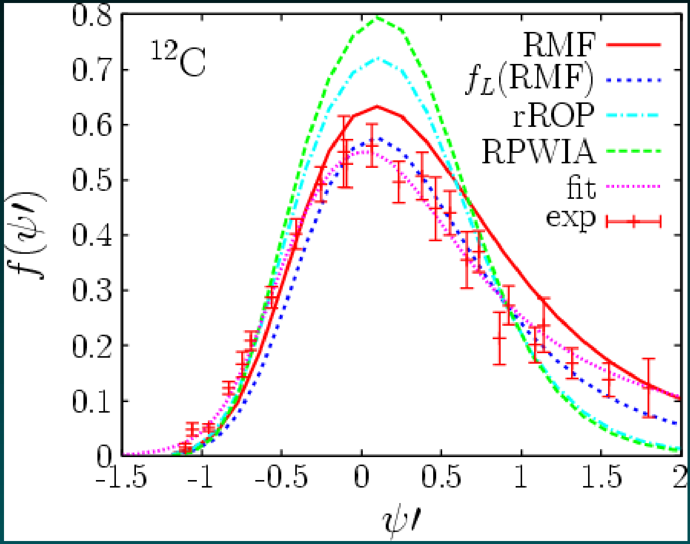
Summary

- **Whenever you need to check a model for inclusive scattering in QE (and Δ?) regions, try first to compare it to the experimental scaling function**
- **Scaling also serves as a predictive tool for lepton-nucleus scattering, and up to date, it probably introduces smaller uncertainties than modeling...**
- **We should try to avoid using a simple RFG to evaluate nuclear effects even at relatively high energies**
- **Scaling comes from a very simple idea, but the answer from Nature is not yet fully understood. Indeed...**

...not many models have been able to reproduce the experimental scaling function...

The **RELATIVISTIC IMPULSE APPROXIMATION + RELATIVISTIC MEAN FIELD (RIA-RMF)** for describing the bound and ejected nucleon does, both in magnitude and shape

(Caballero et al,
Phys. Rev. Lett. **95**, 252502 (2005),
Phys. Rev. C **74**, 015502 (2006)...)



Oooops...by now I will be running out of time, so thanks for your attention, and if you are interested...:

- Using electron scattering superscaling to predict charge-changing neutrino cross sections in nuclei
  Amaro et al, Phys. Rev. C **71**, 065501 (2005)
- Superscaling in Charged Current Neutrino Quasielastic Scattering
  Caballero et al, Phys. Rev. Lett. **95**, 252502 (2005)
- Scaling and isospin effects in QE lepton-nucleus scattering
  Caballero et al, Phys. Lett. B **653**, 366 (2007)
- Superscaling Predictions for Neutral Current Quasielastic Neutrino-Nucleus Scattering
  Martinez et al, Phys. Rev. Lett. **100**, 052502 (2008); Phys. Rev. C **77**, 064604 (2008)

y-scaling variable?

y is the minimum initial momentum of the nucleon allowed by the kinematics.

$$y \approx \sqrt{\omega(2M_N + \omega)} - q$$

$$\text{If } y = 0 \Rightarrow$$

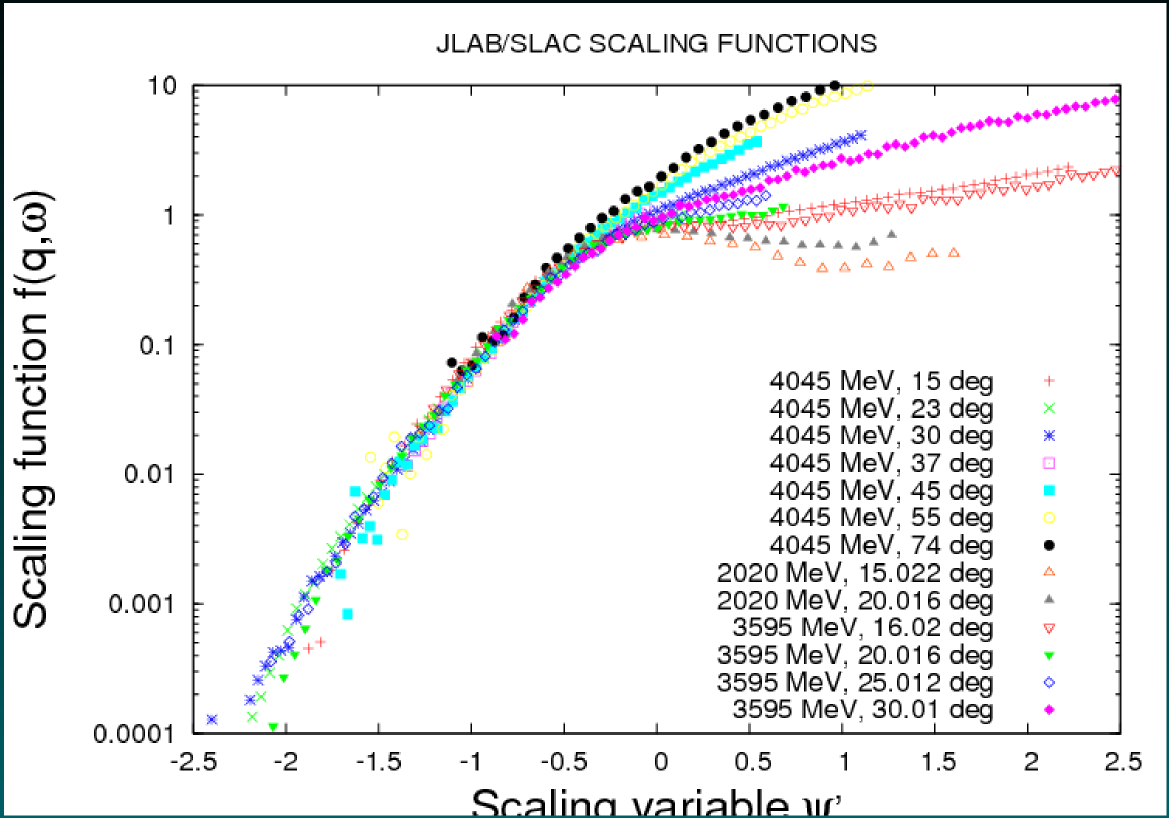
$$q^2 = \omega(2M_N + \omega) \Rightarrow$$

$$|Q^2| = 2M\omega$$

y and Bjorken x scaling variables are closely related to each other! One has binding energy and nucleus recoil corrections

Inclusive ^{12}C quasielastic electron data

SCALING BEHAVIOR IN LOG SCALE



Inclusive quasielastic electron data at $q \approx 1$ GeV/c

SCALING BEHAVIOR IN LOG SCALE