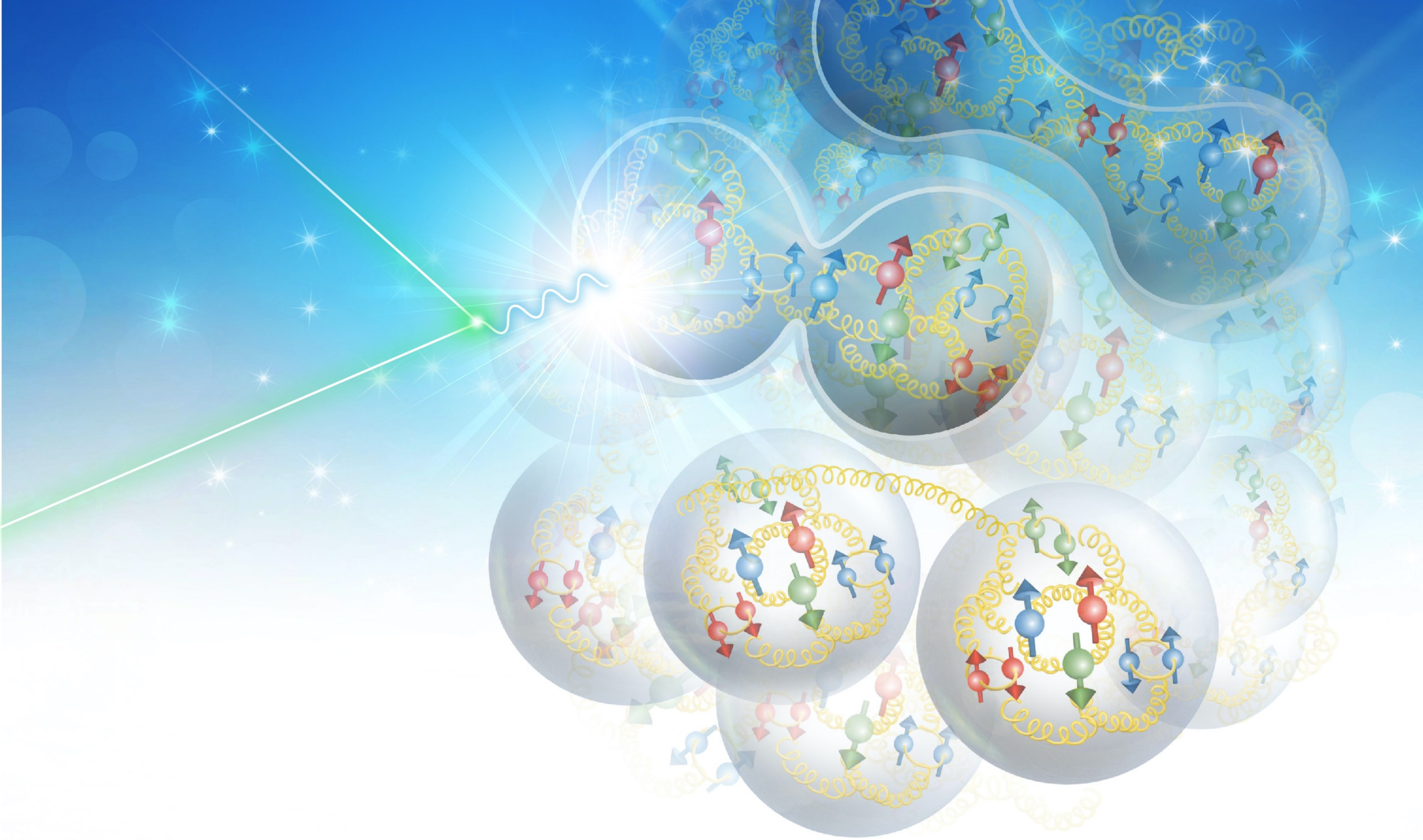


Hampton University Graduate School (HUGs)

June 2022, JLab, Newport News, VA.

HUGs Lecture notes:

Topic:

Nuclear Structure and Short-Range Correlations Via Electron Scattering Probes

Dien Nguyen
Nathan Isgur Fellow at JLab

Hampton University Graduate School (HUGs)
June 2022, JLab, Newport News, VA.

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Lectures format

- Cover the basics level for PhD students
  - Little formalism, more conception
  - Including Basic Experimental information
  - Experimental Results and their interpretations
- Style
  - Informal, encouraging the interaction
  - Interrupt any time for questions

Many slides are adapted from my collaborators.
Special Thanks to Prof. L. Weinstein, Prof. O. Hen, Prof. D. Day, Prof. A. Schmidt, Dr. R. Cruz Torres, Dr. F. Hauenstein and More

Lectures Outlines:

<u>Lecture1+2</u>:

- ❑ Overview of an electron scattering probe
- ❑ Elastic scattering
  - Charge distribution
  - Form factors
- ❑ Quasi-elastic scattering
  - Overview of nuclear structure
  - (e,e'), y-scaling
  - (e,e'p) Single nucleon and shell structure

<u>Lecture 3:</u>

- ❑ Introduction to Short Range Correlations
- ❑ Short-range Correlation Studies
  - (e,e') measurements
  - (e,e'NN) measurement
  - Neutron-rich nuclei

<u>Lecture4+5:</u>

- ❑ Nucleon-Nucleon (NN) interactions
  - (e,e'p) measurement on A=3
- ❑ Short Range Correlations and EMC effect
- ❑ Proton visualization

Lecture1 + 2:

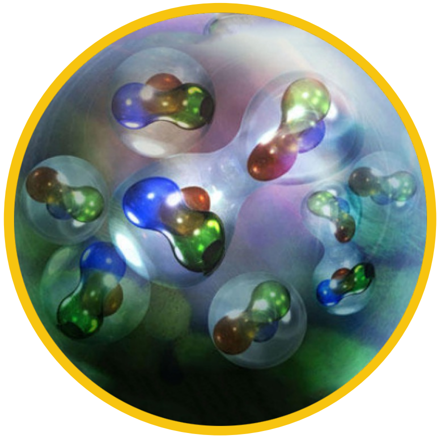
- Overview of an electron scattering probe

- Elastic scattering
  - Charge distribution
  - Form Factors

- Quasi-elastic scattering
  - Overview of nuclear structure
  - Single nucleon and shell structure

Electron Scattering: Nuclear Microscope

Goal: Study the internal structure (and dynamics) of complex objects

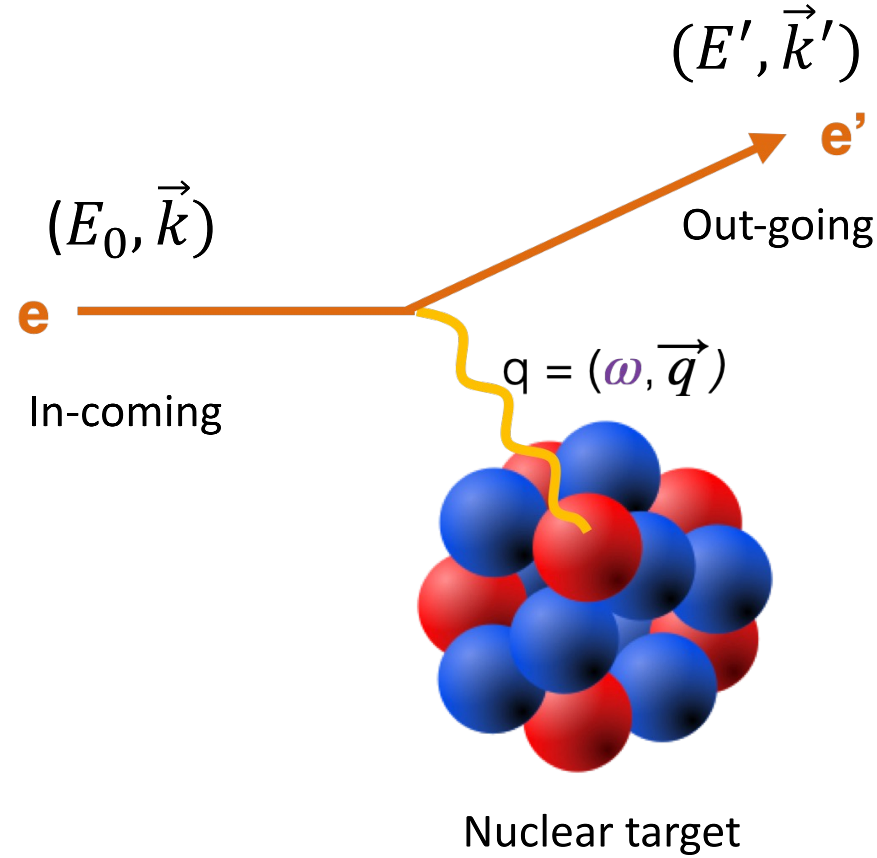


Electron Scattering: Nuclear Microscope

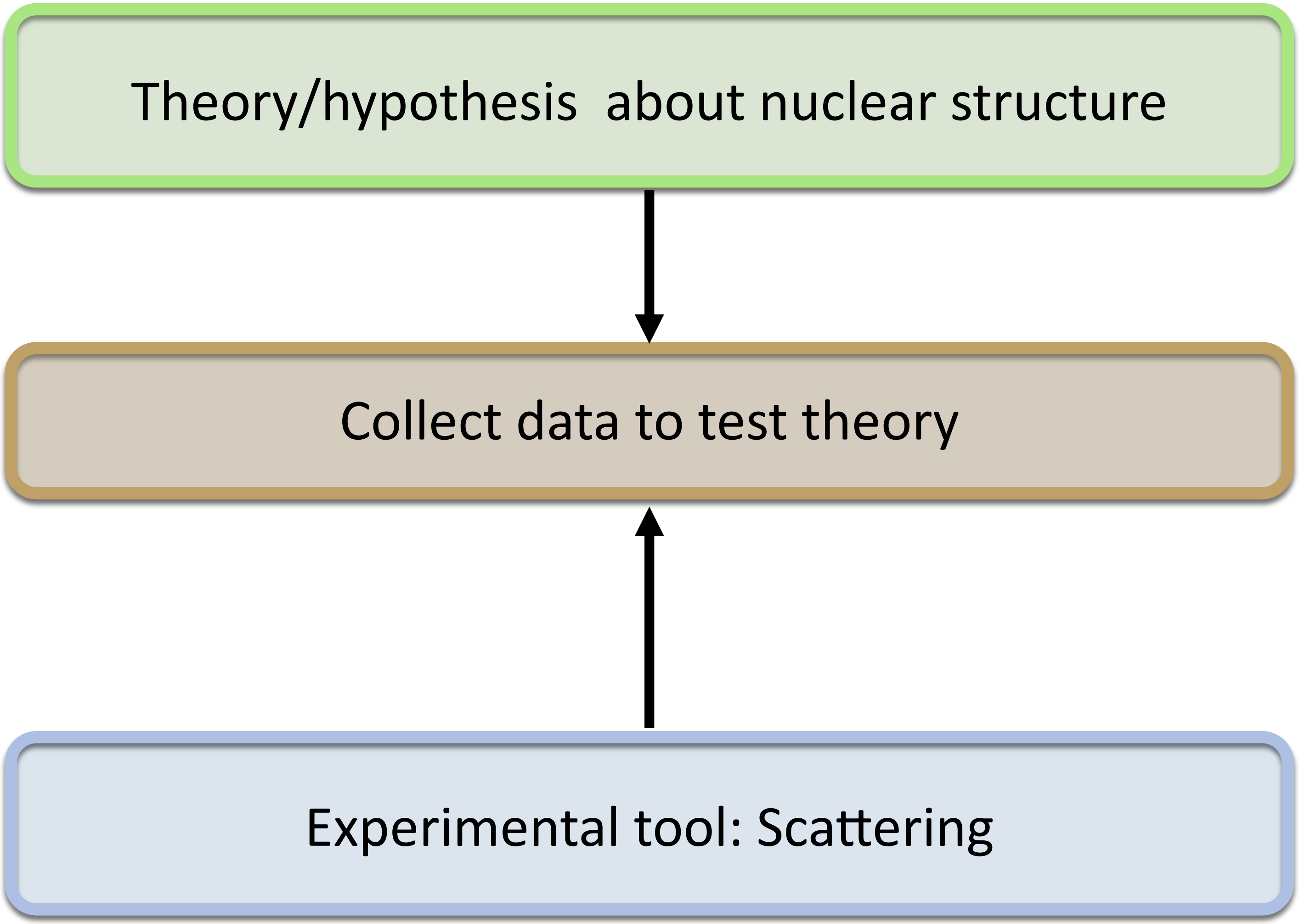
Goal: Study the internal structure (and dynamics) of complex objects

Means:

- Using high energy electron scattering off nuclear target
- Detecting final states particles
- Using detected particle's information to infer the nuclear structure



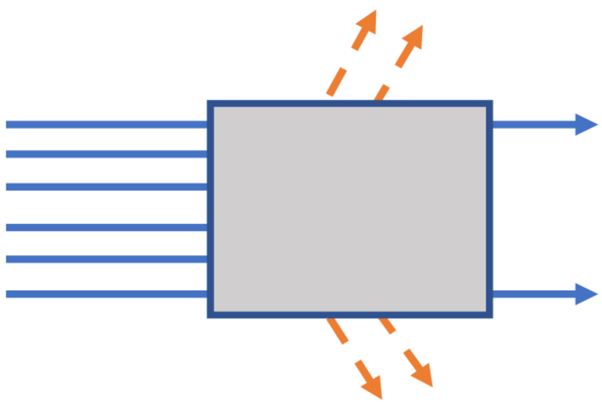
Scientific Method

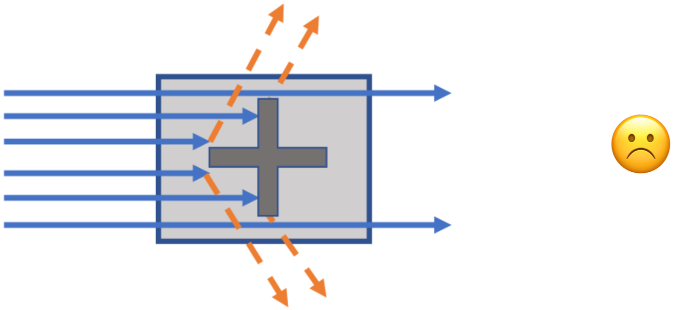


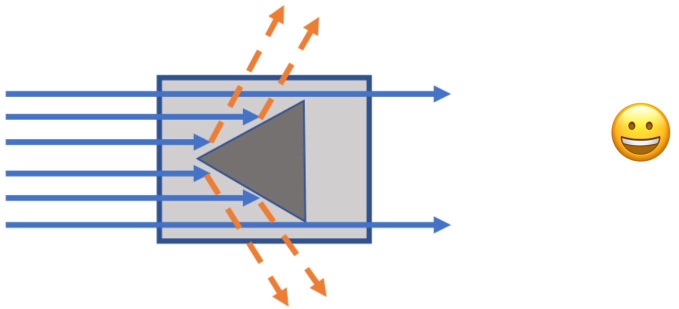
Determine Internal Structure with Scattering

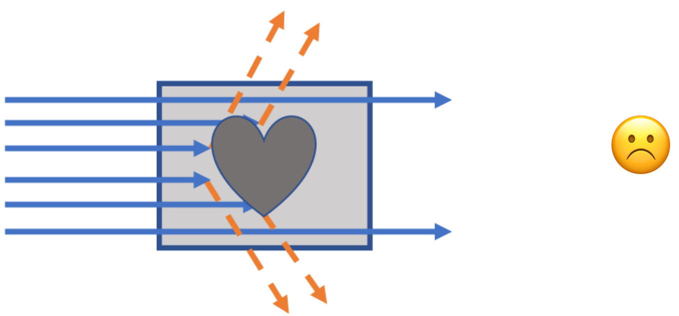
Hypotheses

Measured

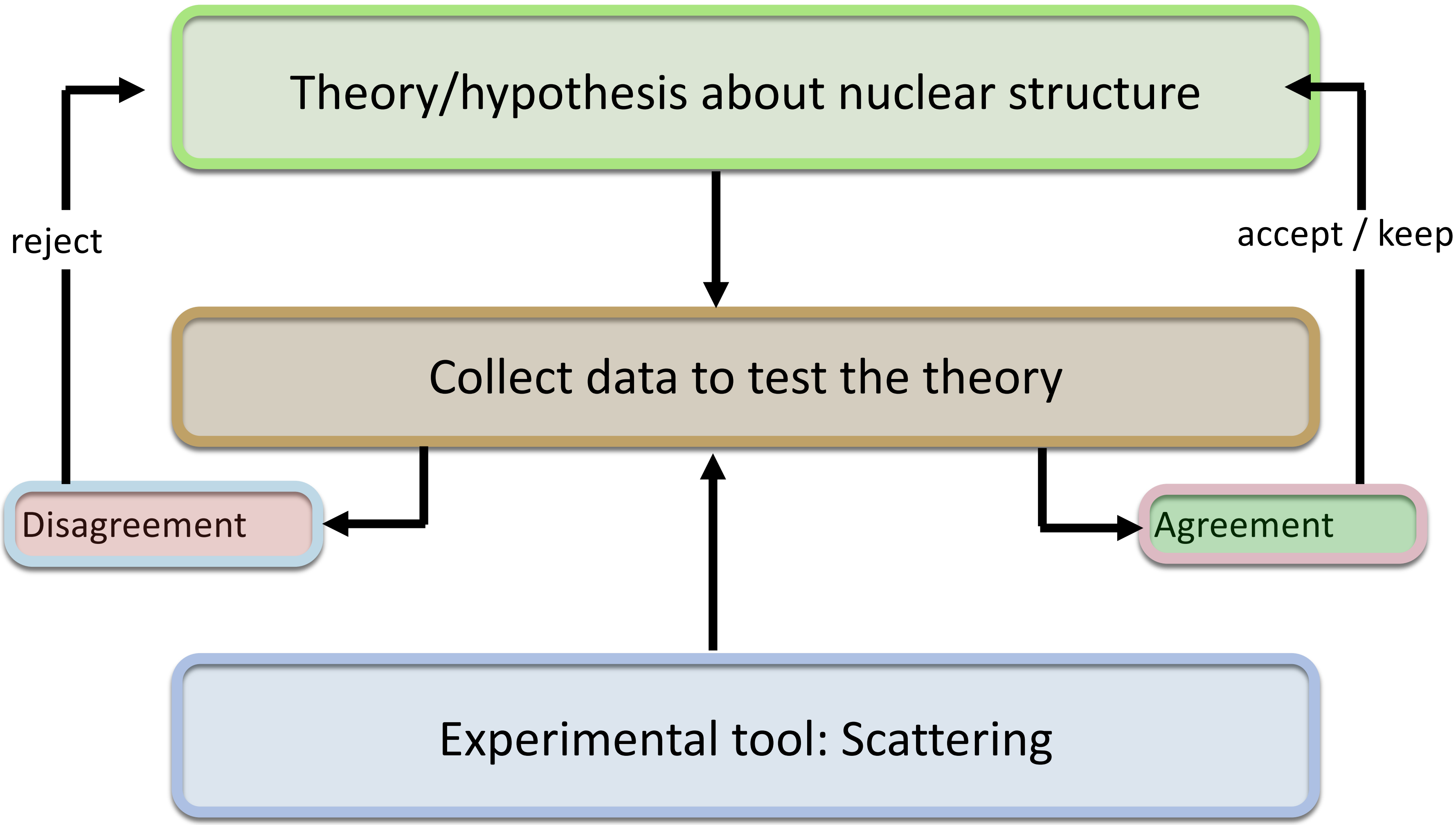








Scientific Method



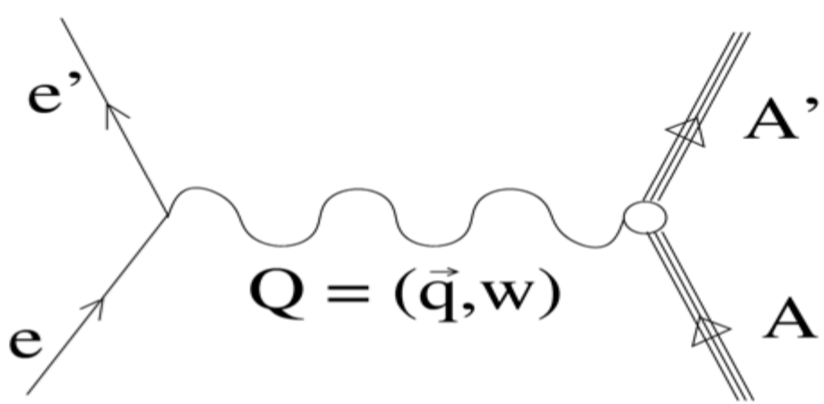
Electron Scattering: Nuclear Microscope

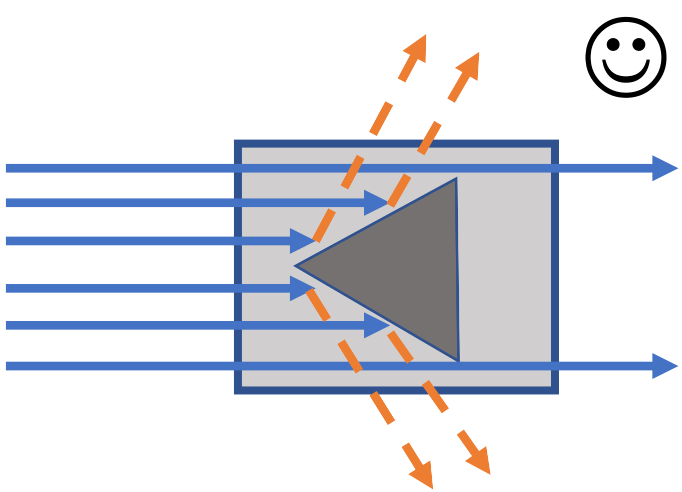
Goal: Study the internal structure (and dynamics) of complex objects

Means: Using high energy electron scattering

Reaction determined by kinematic variables:

- $Q^2 = -q^2$ Interaction-Scale
- $x_B = Q^2/(2m_p\nu)$ Dynamics
- $\omega(\upsilon) = E - E'$ Energy transfer



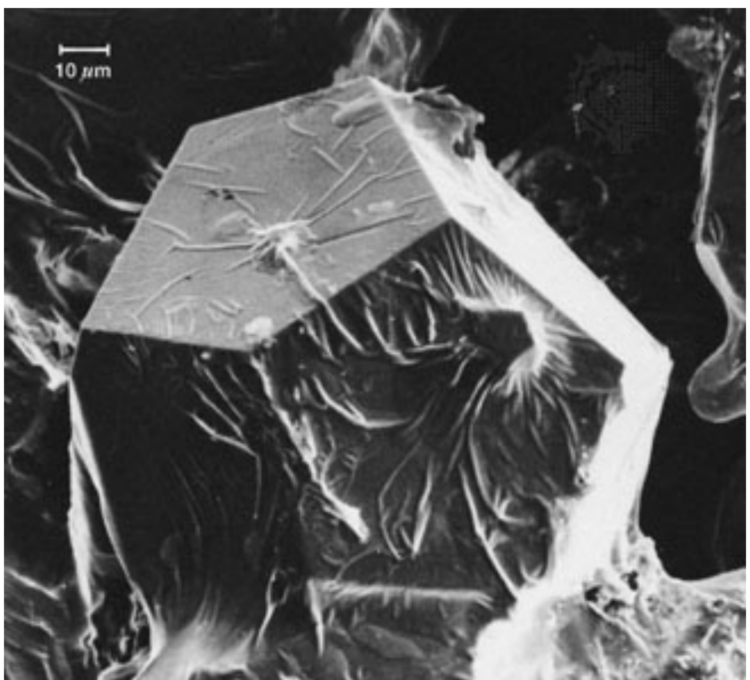


Electron Scattering: Nuclear Microscope

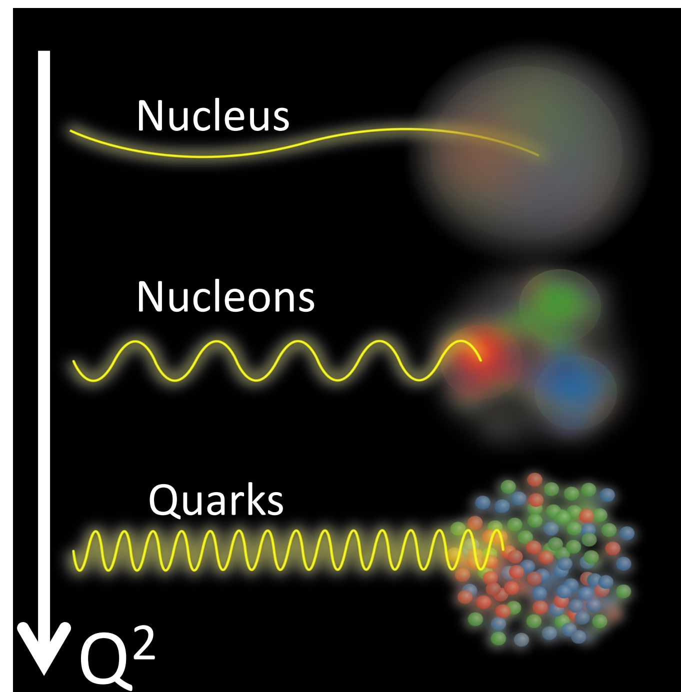
Goal: Study the internal structure (and dynamics) of complex objects

Means: Using high energy electron scattering

100s eV – 100s keV: Material structure



100s MeV – 10s GeV: Nuclear structure

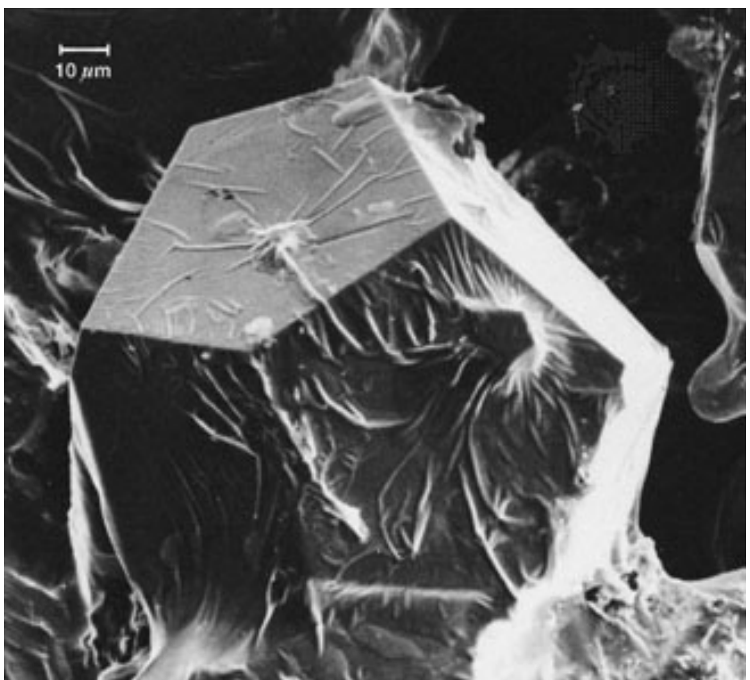


Electron Scattering: Nuclear Microscope

Goal: Study the internal structure (and dynamics) of complex objects

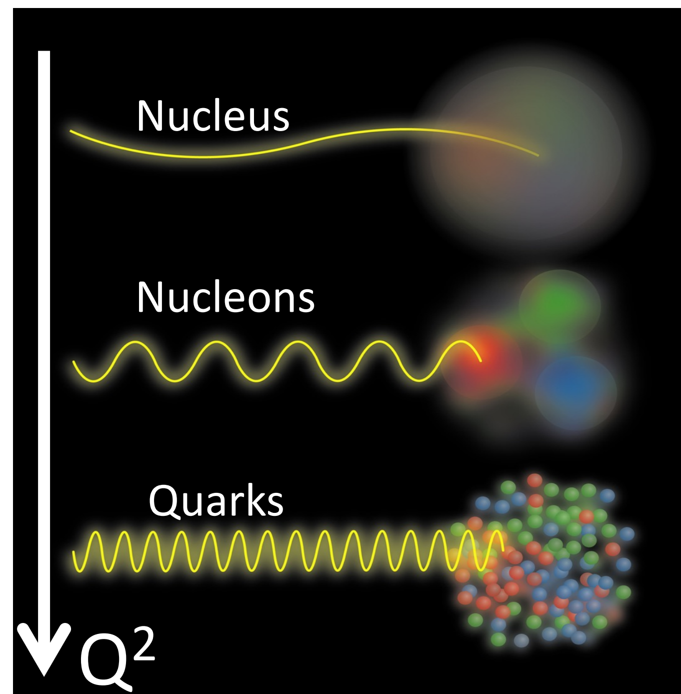
Means: Using high energy electron scattering

100s eV – 100s keV:
Material structure



Energy
=
Resolution !

100s MeV – 10s GeV:
Nuclear structure



Energy vs length

Select spatial resolution and excitation energy independently

- Photon energy ν determines excitation energy
- Photon momentum q determines spatial resolution: $\lambda \approx \frac{\hbar}{q}$

Three cases:

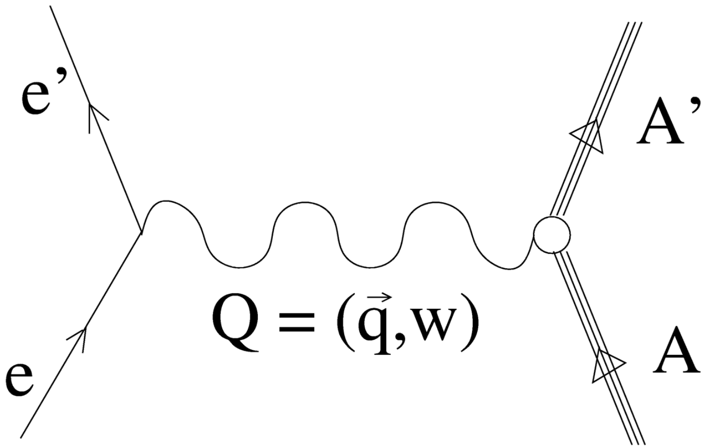
- Low q
  - Photon wavelength λ larger than the nucleon size (R_p)
- Medium q: $0.2 < q < 1$ GeV/c
  - $\lambda \sim R_p$
  - Nucleons resolvable
- High q: $q > 1$ GeV/c
  - $\lambda < R_p$
  - Nucleon structure resolvable

Why use electrons?

- ❑Probe structure understood (point particles)
- ❑Electromagnetic interaction understood (QED)
- ❑Interaction is weak (α = 1/137)
  - ❑Theory works!
    - ❑First Born Approx / one photon exchange
  - ❑Probe interacts only once
  - ❑Study the entire nuclear volume

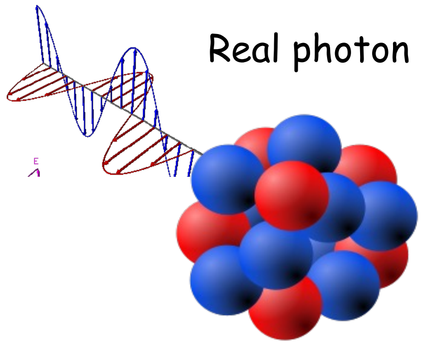
BUT:

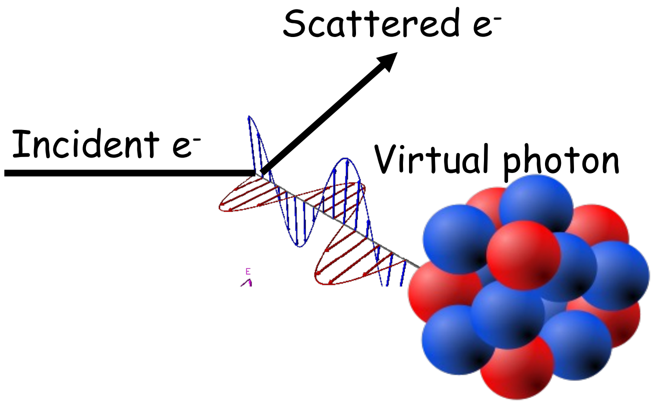
- ❑Cross sections are small
- ❑Electrons radiate



It's all photons!

- An electron interacts with a nucleus by exchanging a single virtual photon.





Real photon:

Momentum q = energy ν

Mass = $Q^2 = |\boldsymbol{q}|^2 - \nu^2 = 0$

Virtual photon:

Momentum q > energy ν

$Q^2 = -q_\mu q^\mu = |\boldsymbol{q}|^2 - \nu^2 > 0$

Virtual photon "has mass"!

(ν and ω are both used for energy transfer)

Electron beams need …

- High energy
  - $q \sim 2E \sin(\theta_e/2)$
  - $\Delta x < 0.2$ fm ➔ $q > 1$ GeV/c

- High duty cycle (no large beam current variation)
  - Reduces accidental coincidences for multiparticle detection
  - Reduces detector rates, multiple hits, …

- High intensity (since cross sections are small)

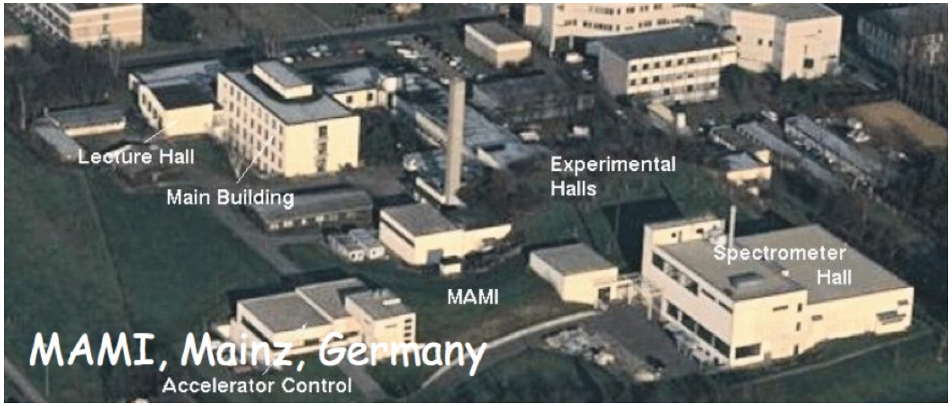
- High resolution to separate nuclear levels

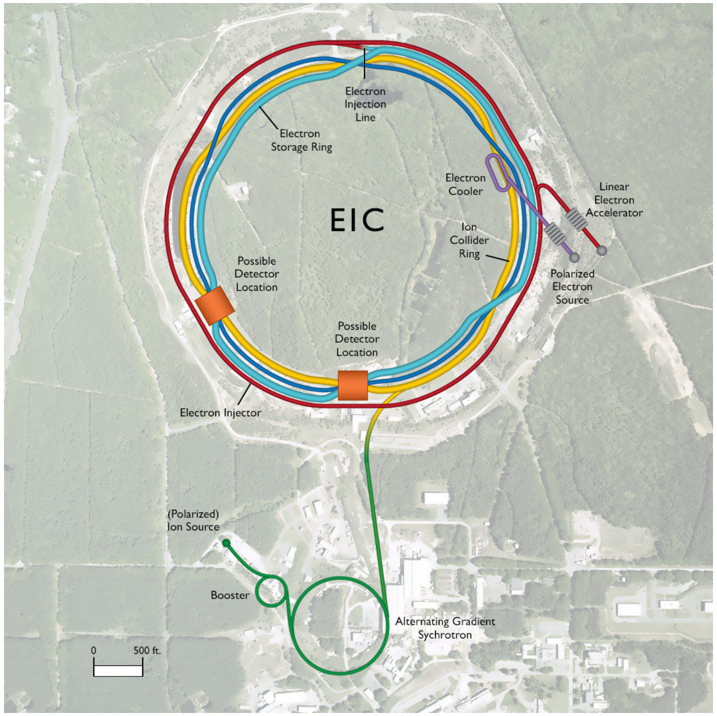
- High polarization (for spin asymmetry measurements)

Luminosities

- Electron beam luminosity:
  - Number of electrons per unit of time (s)
  - $\mathcal{L}_B$ [s^{-1}]$= \frac{I_B}{q_e} = \frac{N_e}{s}$
- Target Luminosity (Thickness):
  - Number of particles (N = Nucleon/Nuclear) in a unit of area
  - $\mathcal{L}_T[\mathrm{cm}^{-2}] = \rho_v[\frac{g}{\mathrm{cm}^{-3}}]\times \frac{L[\mathrm{cm}]}{A} \times N_{Av} = \frac{N_N}{\mathrm{cm}^2}$
- Total (integrated) luminosity:
  - Number of eN interactions per unit of time, per unit of area
  - $\mathcal{L}[s^{-1}\mathrm{cm}^{-2}] = \mathcal{L}_B \times \mathcal{L}_T$
- Event rate: $N_{evt} = \mathcal{L} \times \sigma$
  - Determines how much time you need to measure a reaction with a given cross-section σ $[\mathrm{cm}^2]$

Electron Accelerators - Worldwide

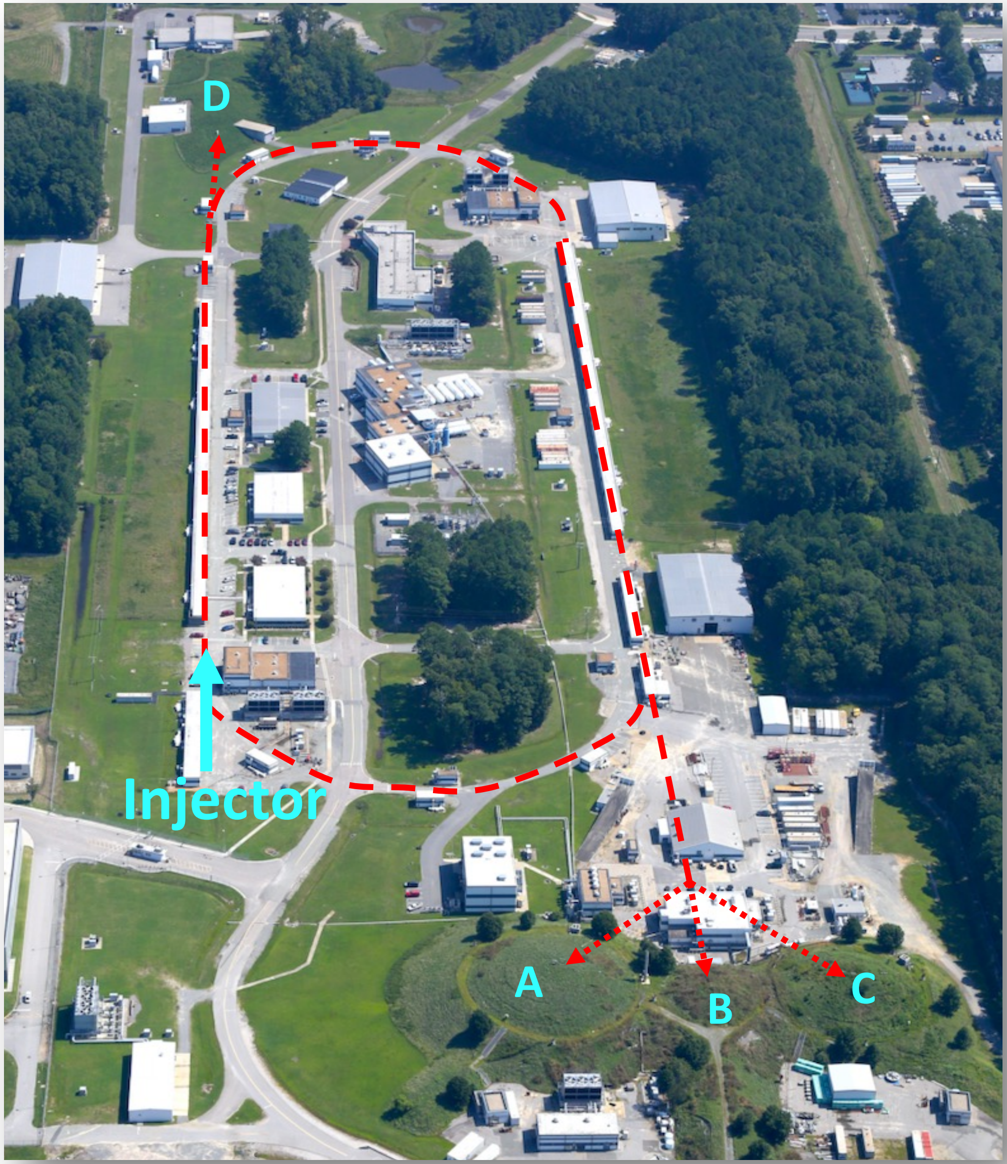




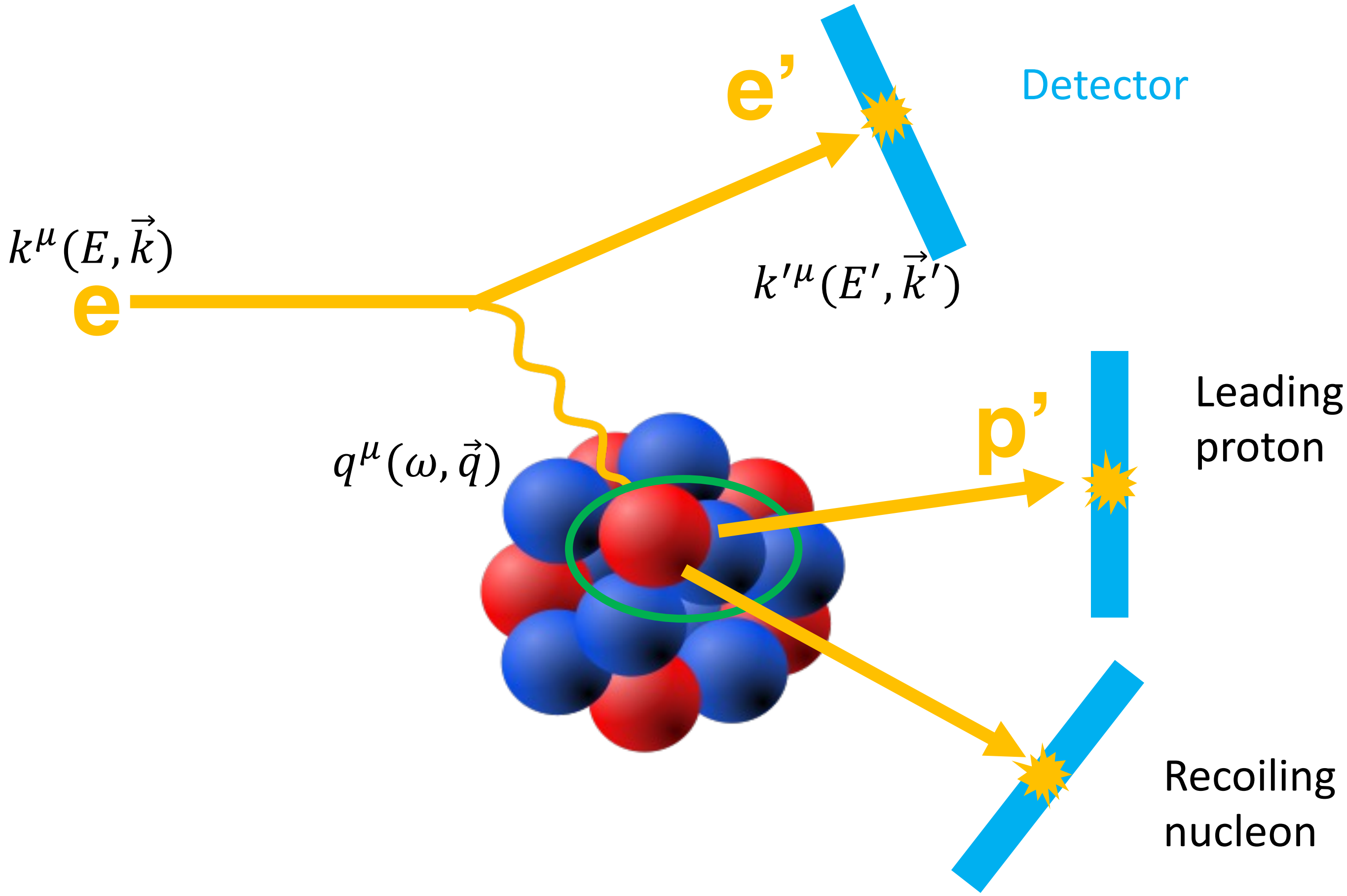
+ many others (past and present)

Jefferson Lab

- ❑ Virginia, USA
- ❑ 1- 11 GeV Electron beam
- ❑ Polarized beams and targets (spin study)
- ❑ 4 experimental halls

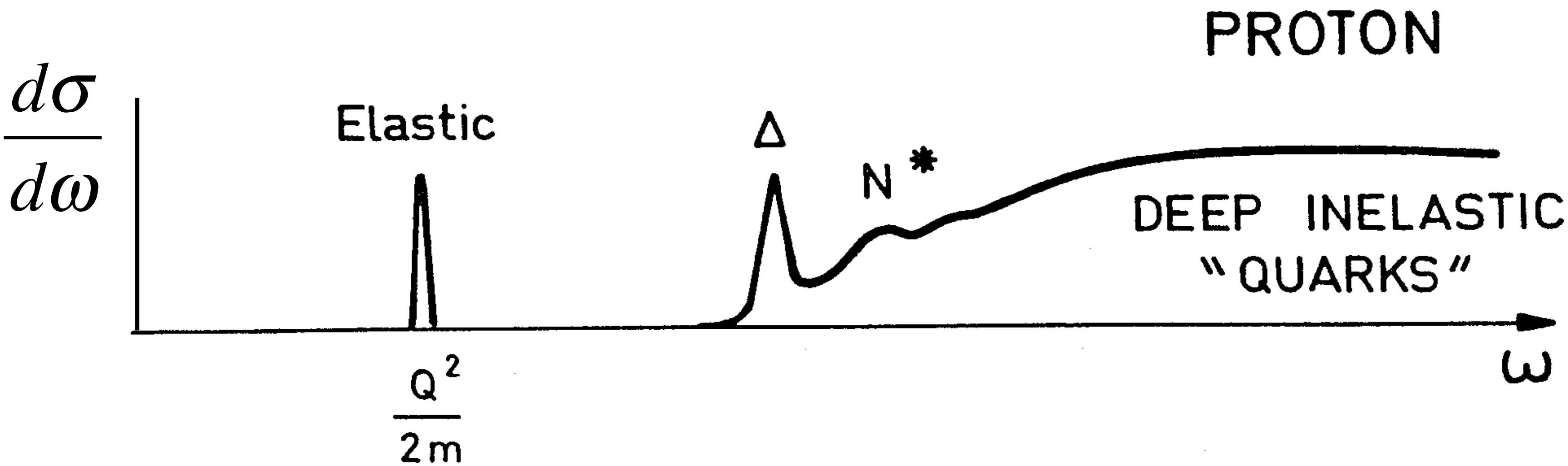


Different electron scattering channels



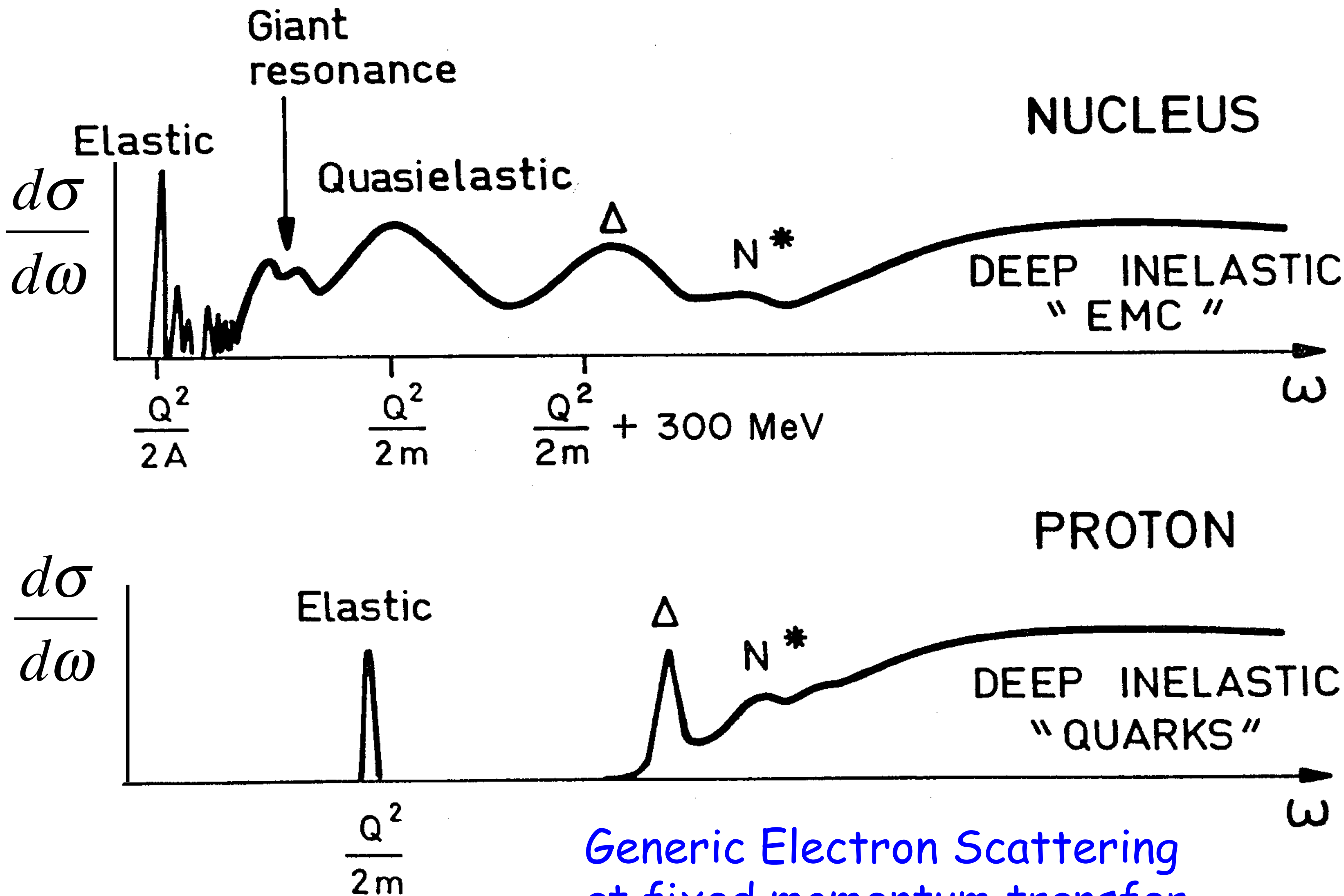
- ❑ (e, e'): Detect only scattering electron (e')
- ❑ (e, e'P): Detect e' and knock-out proton
- ❑ (e, e'NN): Detect e' and two knock-out nucleon

(e,e’): Energy transfer defines physics



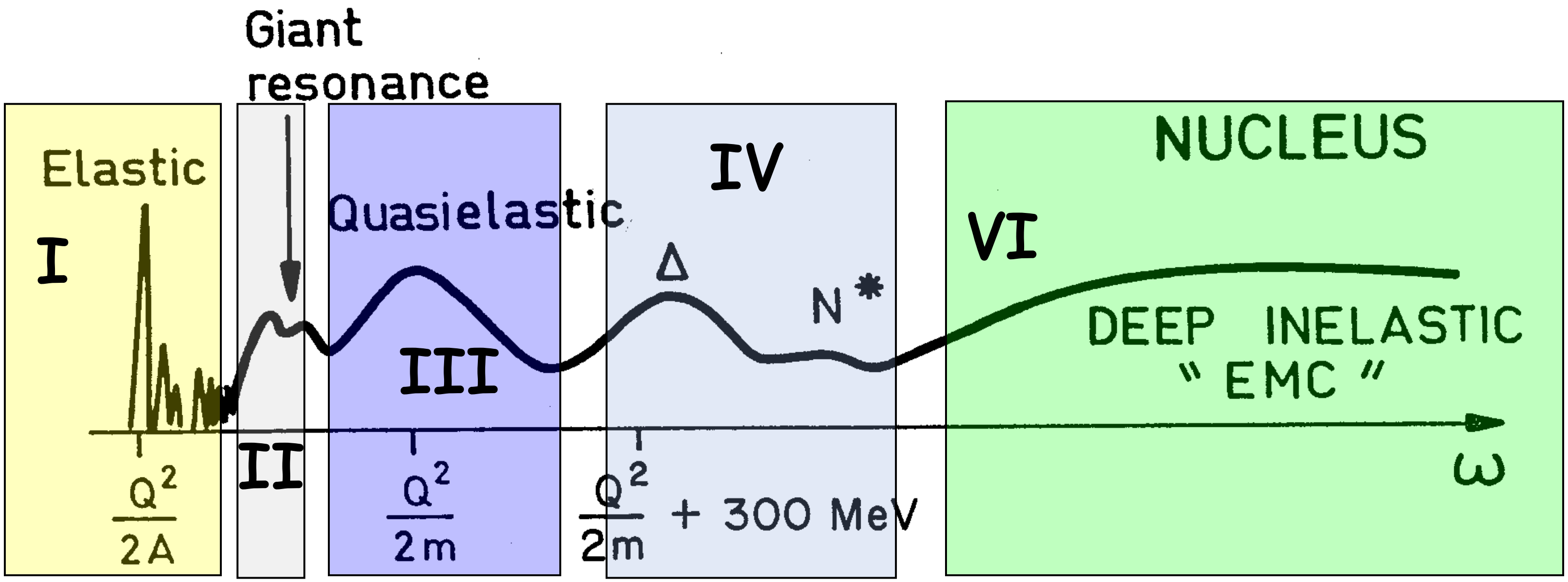
Generic Electron Scattering
at fixed momentum transfer

(e,e'): Energy transfer defines physics

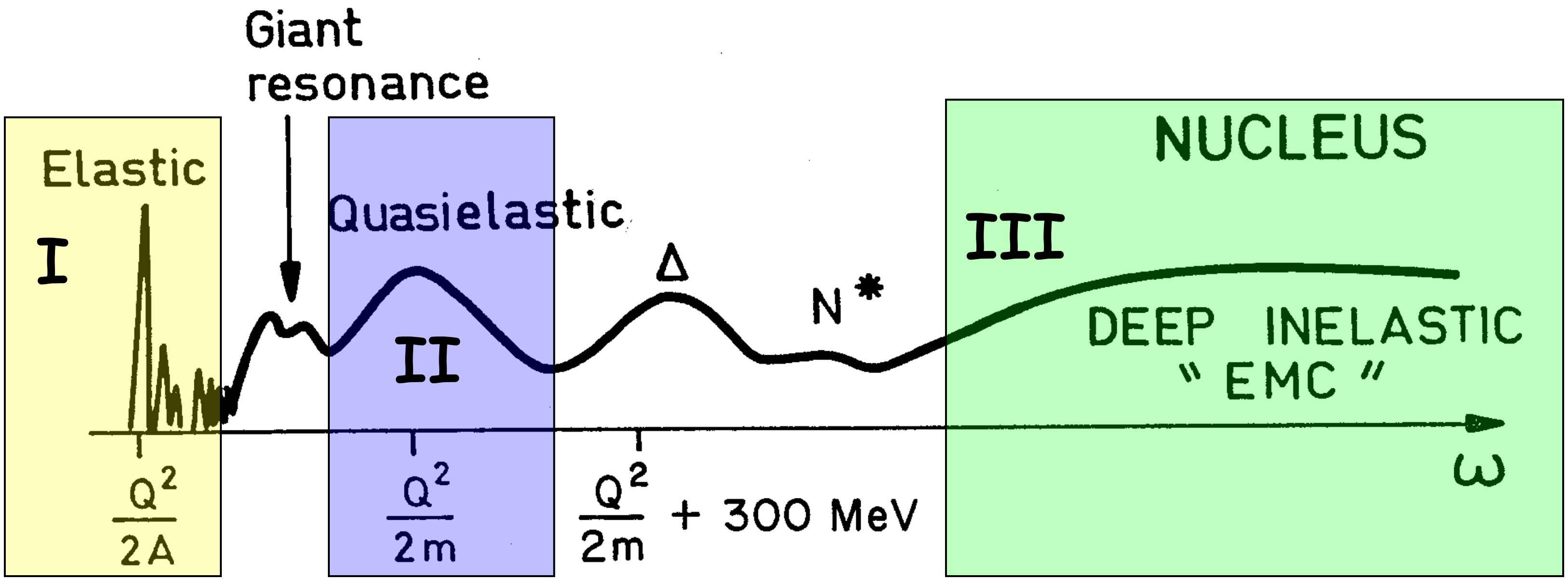


Generic Electron Scattering
at fixed momentum transfer

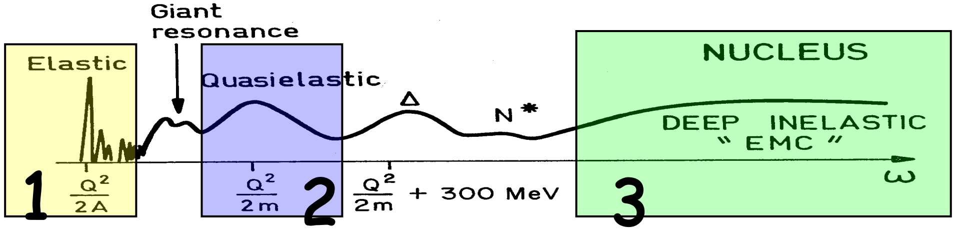
Everything is interesting…



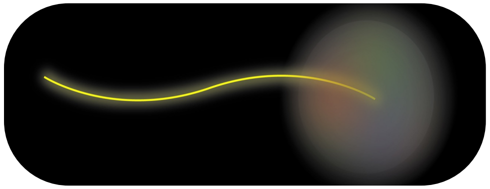
...But we will focus on 3 regions



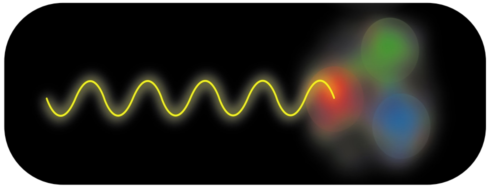
Experimental Goals



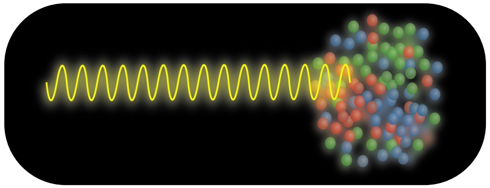
1. Elastic
   - structure of the nucleon/nucleus
     - Form factors, charge distributions



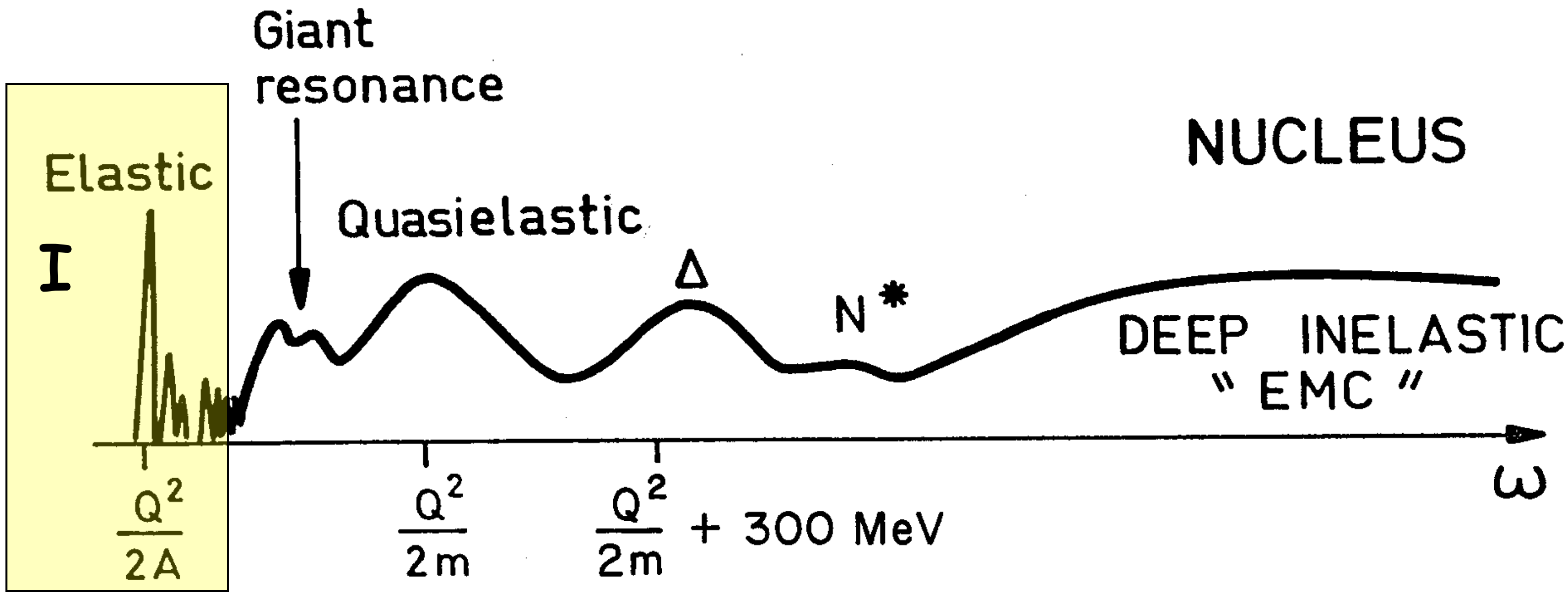
2. Quasi-elastic (QE)
   - Shell structure
     - Momentum distributions
     - Occupancies
   - Short Range Correlated nucleon pairs



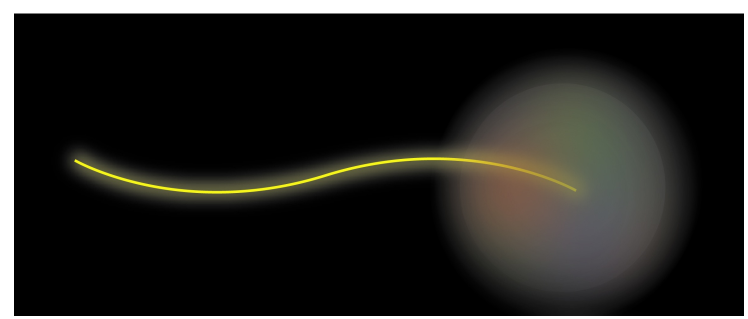
3. Deep Inelastic Scattering (DIS)
   - The EMC Effect and Nucleon modification
   - Quark Hadronization in nuclei



Quick Overview: Elastic



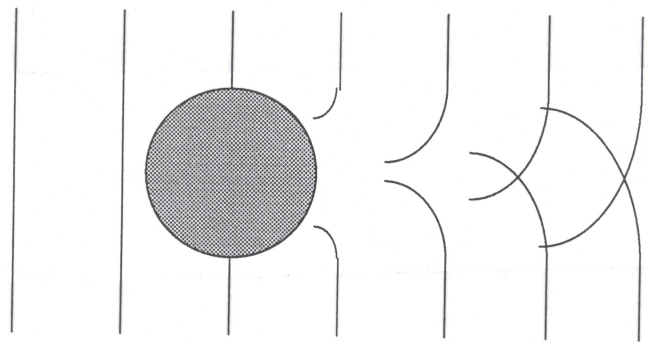
- Elastic scattering
  - Charge distribution
  - Form Factors



Electrons as Waves

Scattering process is quantum mechanical

De broglie wavelength: $\lambda = \dfrac{h}{p}$



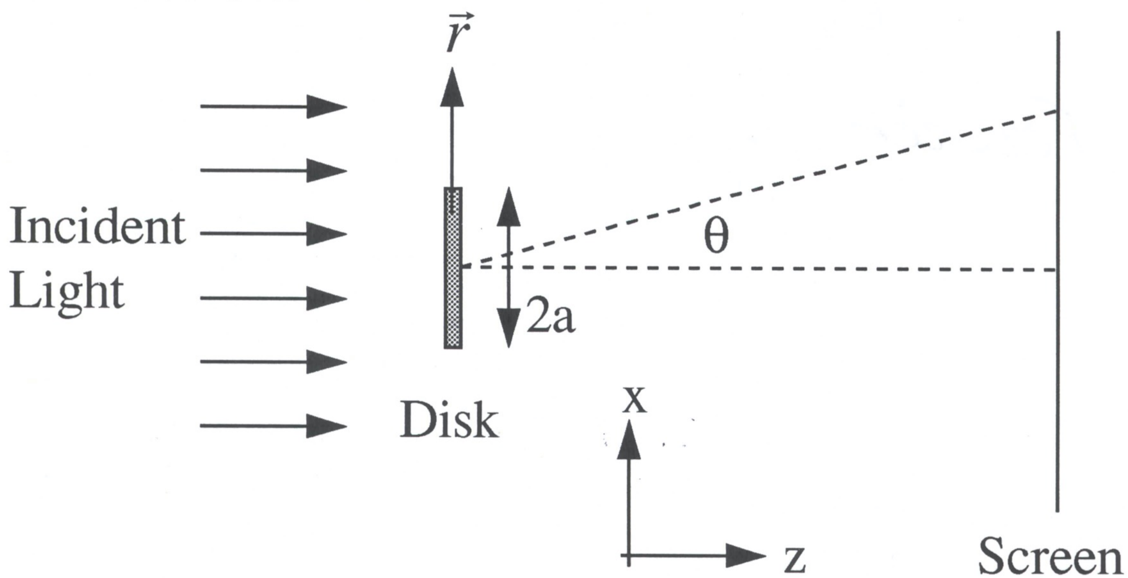
Electron energy: $E_e \approx pc$

$\hbar c = 197$ MeV-fm

λ resolving "scale": $$\lambda = \frac{2\pi(197\ \mathrm{MeV \cdot fm})}{E_e}$$

Simple analogy for elastic electron scattering….

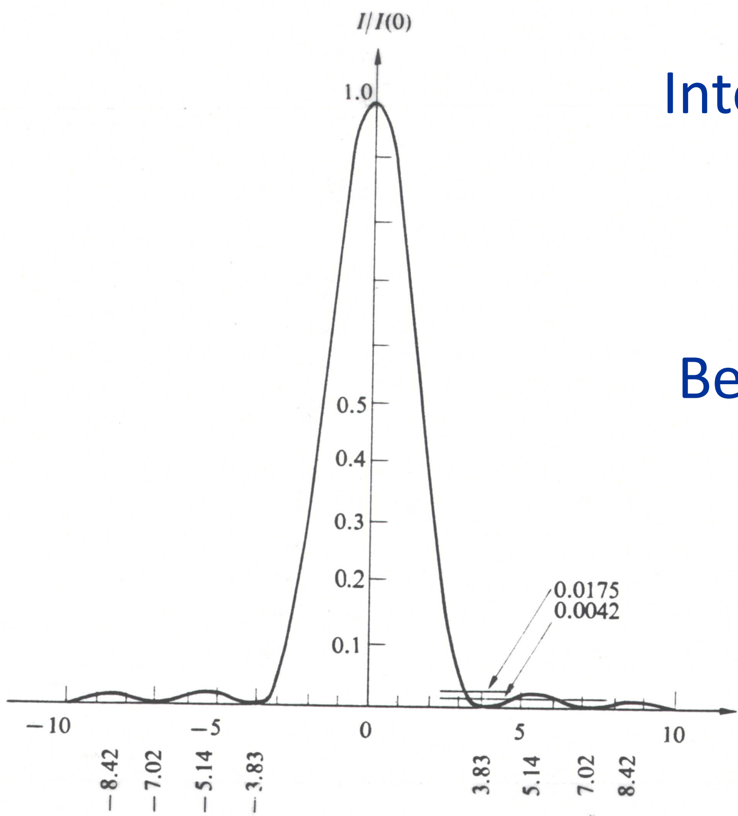
Classical Fraunhofer Diffraction



Amplitude of wave at screen:

$$\Phi \propto \int_0^a \int_0^{2\pi} \exp(ibr\cos\phi)\, r\, d\phi\, dr$$

Classical Fraunhofer Diffraction



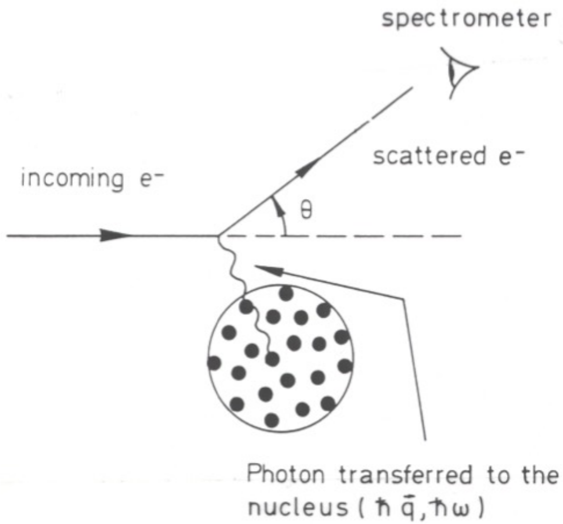
Intensity: $\Phi^2 \propto \left(\frac{J_1((2\pi a/\lambda)\sin\theta)}{\sin\theta} \right)^2$

Minima occur at zeroes of Bessel function. 1st zero: x = 3.8317

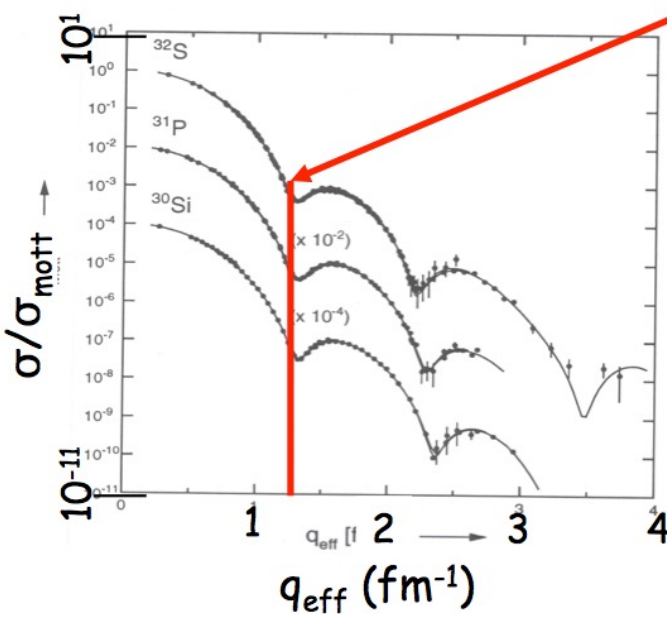
…some algebra…

Hence $2a \approx \frac{1.22\lambda}{\sin\theta_{min}}$

Example: $^{30}Si(e,e')$



Cross Section ⇔ Charge Form Factor



1st minimum = 1.3 fm^{-1}

➔ $\theta = 32.8^{o}$

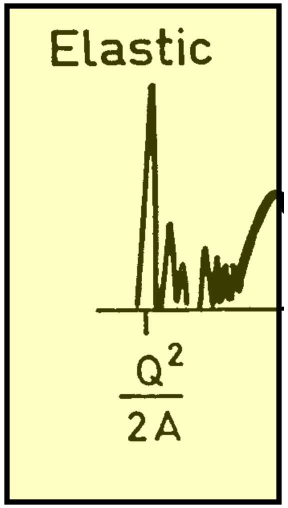
Electron energy = 454.3 MeV

➔ $\lambda = 2.73$ fm

Calculated radius = 3.07 fm

Measured rms radius = 3.19 fm

Elastic Electron Scattering from Nuclei (done formally)

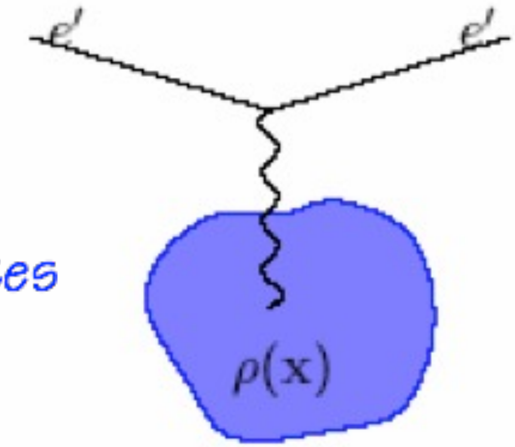


Fermi's Golden Rule

$$\frac{d\sigma}{d\Omega} = \frac{2\pi}{\hbar} \,|\, M_{fi} \,|^2 D_f$$

M_{fi}: scattering amplitude

D_f: density of the final states (or phase factor)



$$M_{fi} = \int \Psi_f^* V(x) \Psi_i d^3x$$

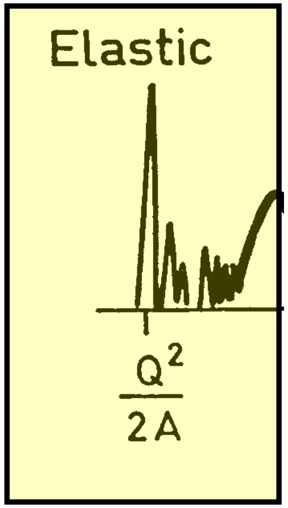
$$= \int e^{-k_f \cdot x} V(x) e^{-k_i \cdot x} d^3x$$

$$= \int e^{iq \cdot x} V(x) d^3x$$

Plane wave approximation for incoming and outgoing electrons

Born approximation (interact only once)

Elastic Electron Scattering from (spin-0) Nuclei



Form Factor and Charge Distribution

Using Coulomb potential from a charge distribution, $\rho(x)$,

$$V(x) = -\frac{Ze^2}{4\pi\epsilon_0}\int \frac{\rho(x')}{|x-x'|}d^3x'$$

$$M_{fi} = -\frac{Ze^2}{4\pi\epsilon_0}\int e^{iq\cdot x}\int \frac{\rho(x')}{|x-x'|}d^3x'd^3x$$

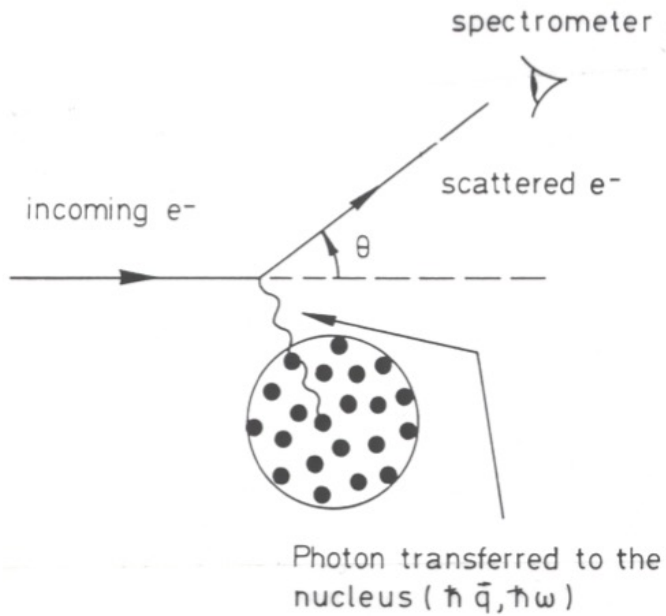
$$= -\frac{Ze^2}{4\pi\epsilon_0}\int e^{iqR}\left[\int \frac{e^{iq\cdot x'}\rho(x')}{|R|}d^3x'\right]d^3R$$

$$= -\frac{Ze^2}{4\pi\epsilon_0}\int \frac{e^{iqR}}{R}d^3R\int e^{iq\cdot x'}\rho(x')d^3x'$$

$$F(q) = \int e^{iq\cdot x'}\rho(x')d^3x'$$

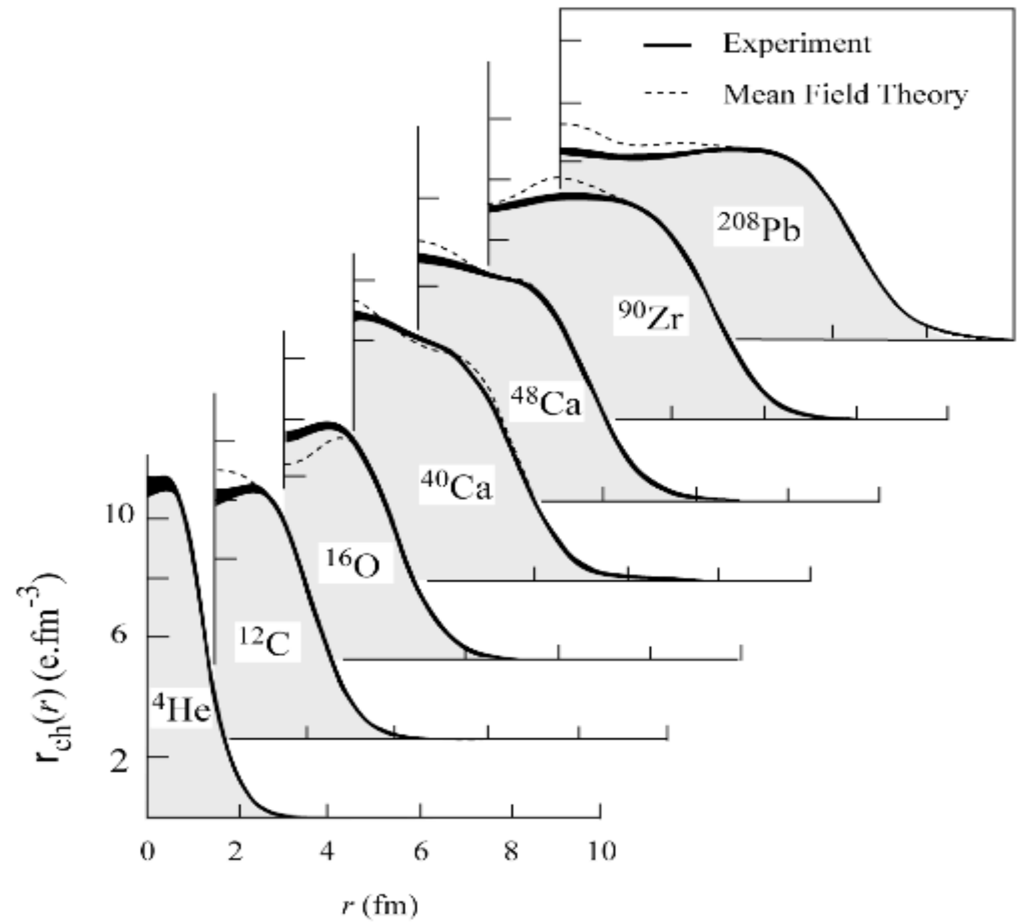
Charge form factor F(q) is the Fourrier transform of the charge distribution $\rho(x)$

Elastic (e,e') Scattering
Cross-section ⇒ Charge distributions

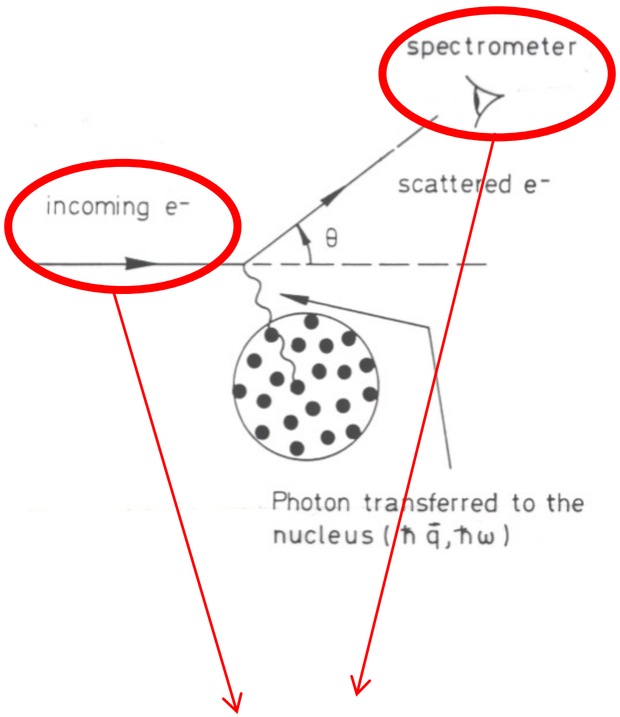


$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{mott} |F(q)|^2$$

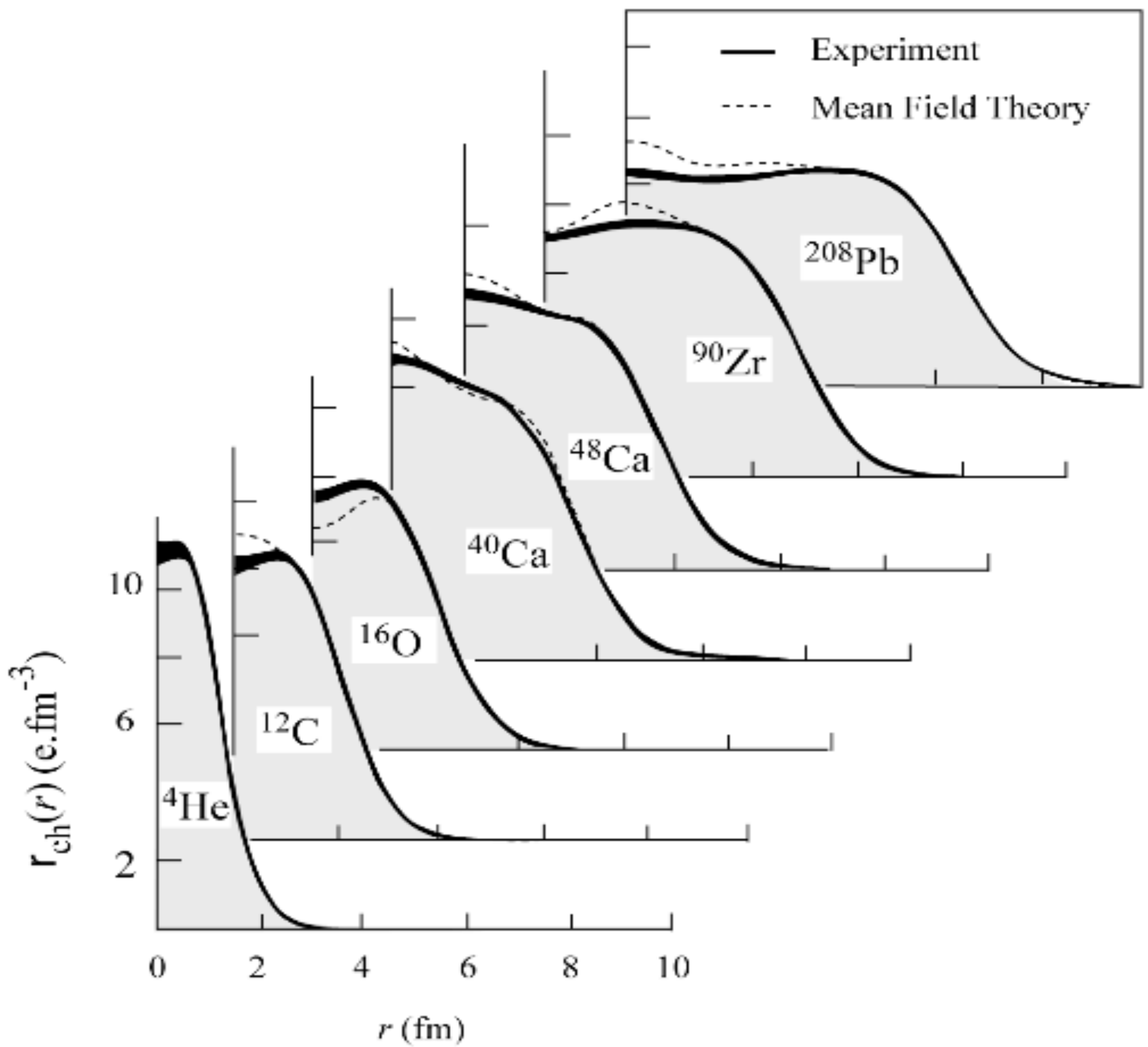
Charge Distribution, $r_{CH}(r)$, is a Fourier Transform of the Charge Form Factor, F(q)



Diffraction Measurements of Small Radii



10s – 100s Million Dollar Machines



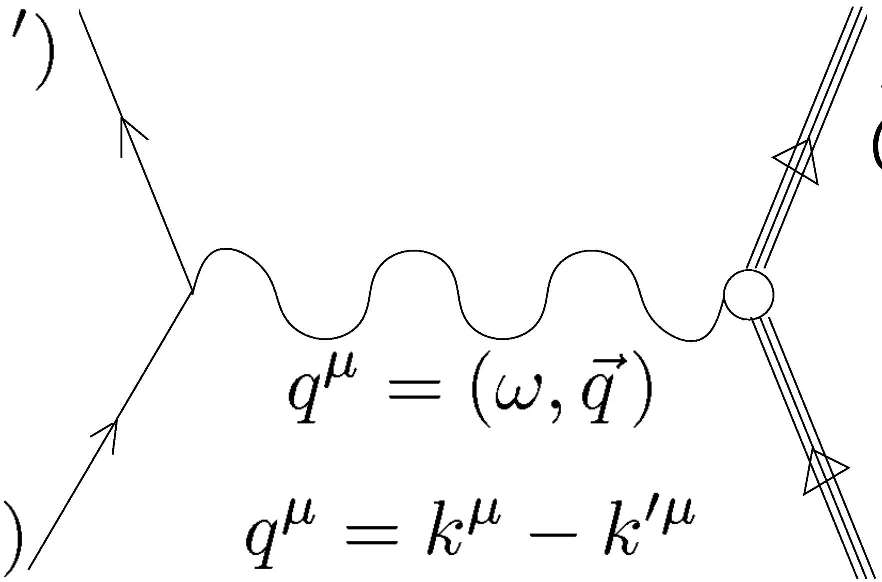
From Intuition to Formalism

Lab frame kinematics

$$k'^{\mu} = (E', \vec{k}\,')$$

$$p'^{\mu} = (E_p, \vec{p}_p)$$

(not always detected)



$$q^{\mu} = (\omega, \vec{q}\,)$$

$$k^{\mu} = (E, \vec{k}\,)$$

$$q^{\mu} = k^{\mu} - k'^{\mu}$$

$$p^{\mu} = (M, \vec{0}\,)$$

Invariants:

$$p^{\mu} p_{\mu} = M^2$$

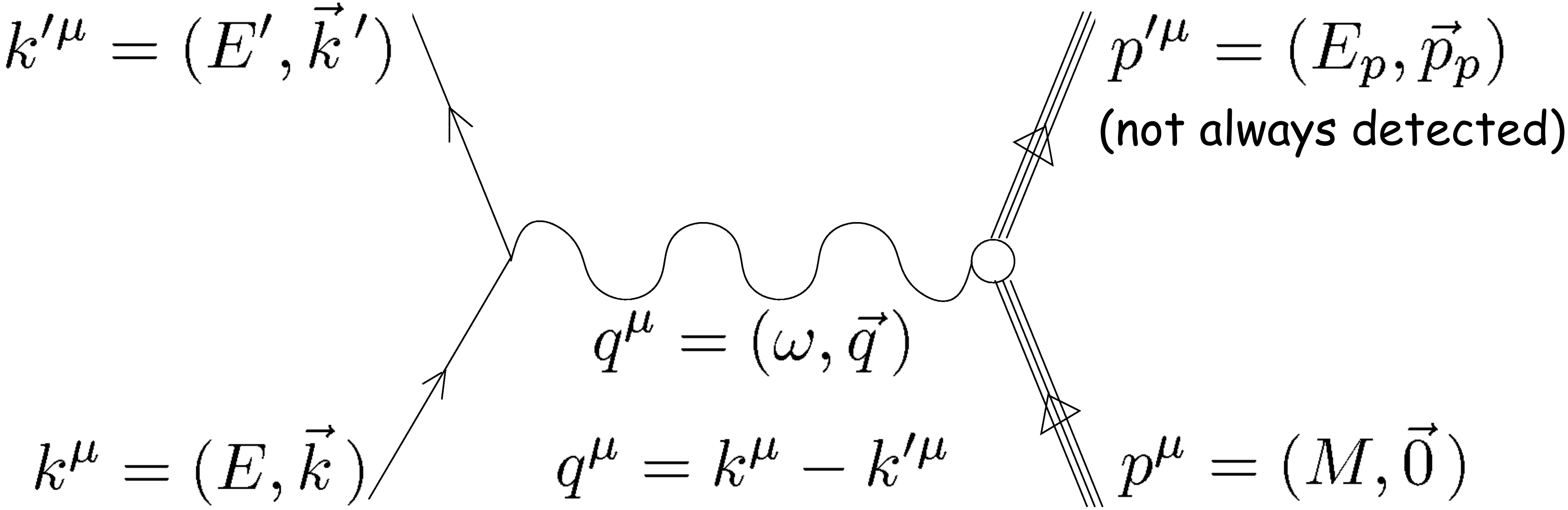
$$p_{\mu} q^{\mu} = M\omega$$

$$Q^2 = -q^{\mu} q_{\mu} = |\vec{q}\,|^2 - \omega^2$$

$$W^2 = (q^{\mu} + p^{\mu})^2 = p'_{\mu} p'^{\mu}$$

From Intuition to Formalism

Lab frame kinematics



Invariants:

$$p^{\mu} p_{\mu} = M^2 \qquad\qquad p_{\mu} q^{\mu} = M\omega$$

$$Q^2 = -q^{\mu} q_{\mu} = |\vec{q}\,|^2 - \omega^2 \qquad W^2 = (q^{\mu} + p^{\mu})^2 = p'_{\mu} p'^{\mu}$$

From Intuition to Formalism (Elastic)

Mott cross-section: $$\sigma_M = \frac{\alpha^2 \cos^2\left(\frac{\theta_e}{2}\right)}{4E^2 \sin^4\left(\frac{\theta_e}{2}\right)}$$

A. Minten, CERN report 1967

From Intuition to Formalism (Elastic)

Recoil factor

Form factors

$$\frac{d\sigma}{d\Omega} = \sigma_M \frac{E'}{E} \left\{ \left[F_1^2(Q^2) + \frac{Q^2}{4M^2}\kappa^2 F_2^2(Q^2) \right] + \frac{Q^2}{2M^2}[F_1(Q^2) + \kappa F_2(Q^2)]^2 \tan^2\frac{\theta}{2} \right\}$$

Mott cross section: $\sigma_M = \frac{\alpha^2 \cos^2\left(\frac{\theta_e}{2}\right)}{4E^2 \sin^4\left(\frac{\theta_e}{2}\right)}$

From Intuition to Formalism (Elastic)

Recoil factor

Form factors

$$\frac{d\sigma}{d\Omega} = \sigma_M \frac{E'}{E}\left\{\left[F_1^2(Q^2) + \frac{Q^2}{4M^2}\kappa^2 F_2^2(Q^2)\right] + \frac{Q^2}{2M^2}[F_1(Q^2) + \kappa F_2(Q^2)]^2 \tan^2\frac{\theta}{2}\right\}$$

$$= \sigma_M \frac{E'}{E}\left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau \tan^2\frac{\theta}{2} G_M^2(Q^2)\right]$$

From Intuition to Formalism (Elastic)

Recoil factor Form factors

$$\frac{d\sigma}{d\Omega} = \sigma_M \frac{E'}{E}\left\{\left[F_1^2(Q^2) + \frac{Q^2}{4M^2}\kappa^2 F_2^2(Q^2)\right] + \frac{Q^2}{2M^2}[F_1(Q^2) + \kappa F_2(Q^2)]^2 \tan^2\frac{\theta}{2}\right\}$$

$$= \sigma_M \frac{E'}{E}\left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau \tan^2\frac{\theta}{2} G_M^2(Q^2)\right]$$

nucleons

- F_1, F_2: Dirac and Pauli form factors
- G_E, G_M: Sachs form factors (electric and magnetic)
  - $G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2)$
  - $G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$

$\tau = Q^2/4M^2$

(more standard definition of F_1 and F_2)

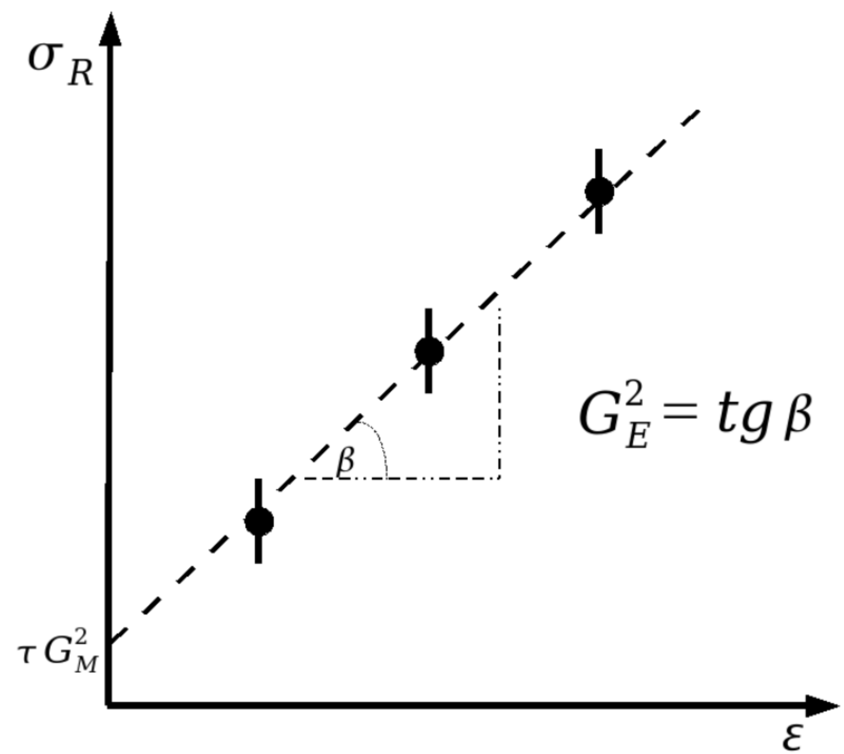
Form Factors: Unpolarized Cross-Sections

$$\frac{\varepsilon}{\tau} G_E^2 + G_M^2 = \frac{\varepsilon(1+\tau)}{\tau} \left[\frac{d\sigma}{d\Omega} / \left(\frac{d\sigma}{d\Omega} \right)_{Mott+recoil} \right]$$

At a fixed Q2

$$\varepsilon = \left[1 + 2(1+\ \tau) tan^2 \left(\frac{\theta_e}{2} \right) \right]^{-1}$$

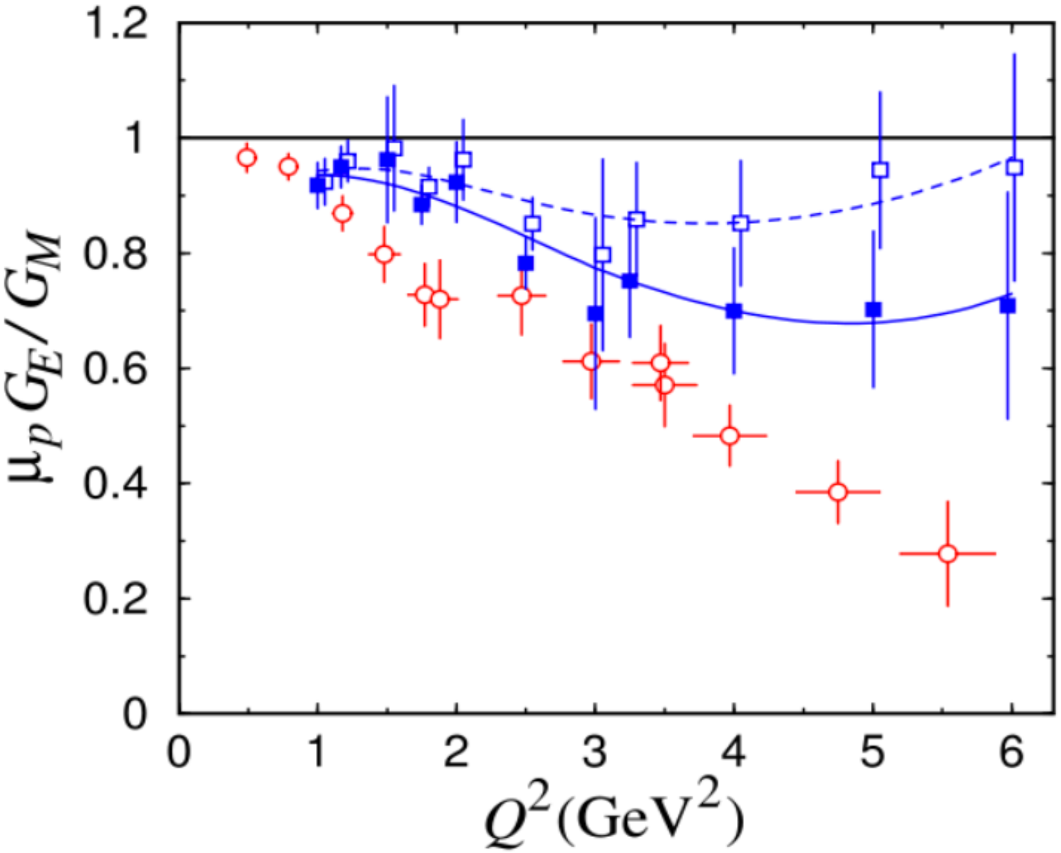
Rosenbluth Separation method



M.N Rosenbluth, Physical Review (1950)

Form Factors: Recoil polarization method

$$\frac{G_E^2}{G_M^2} = \frac{-P_x}{P_z}\frac{E+E'}{2M}\tan(\theta/2)$$



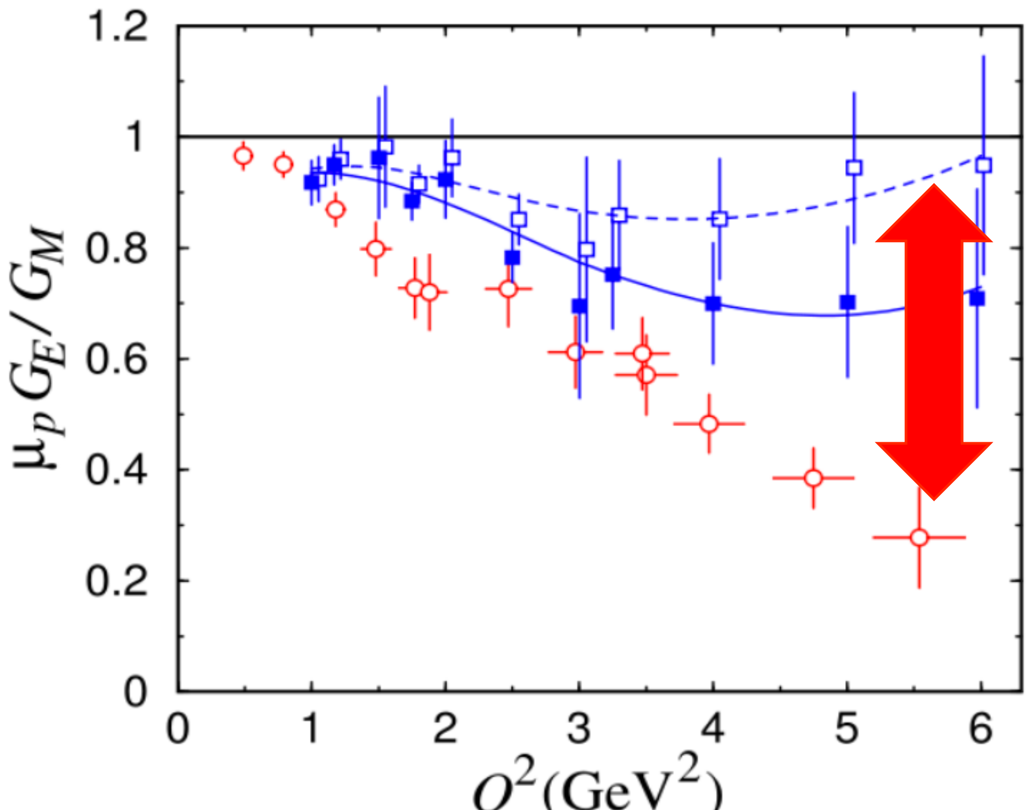
Rosenbluth method

Recoil Polarization method

O. Gayou, Phys. Rev. Lett (2002)

Form Factors: Polarization Transfer

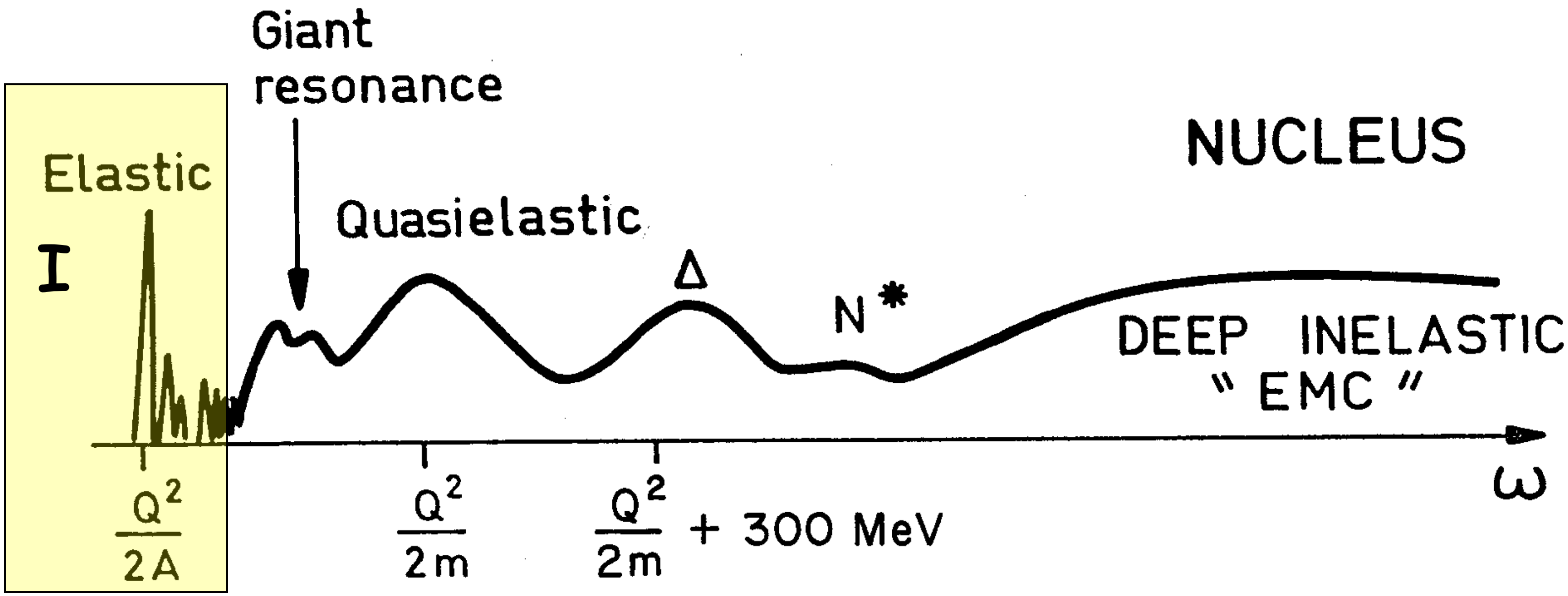
$$\frac{G_E^2}{G_M^2} = \frac{-P_x}{P_z} \frac{E+E'}{2M} \tan(\theta/2)$$



LARGE Discrepancy!

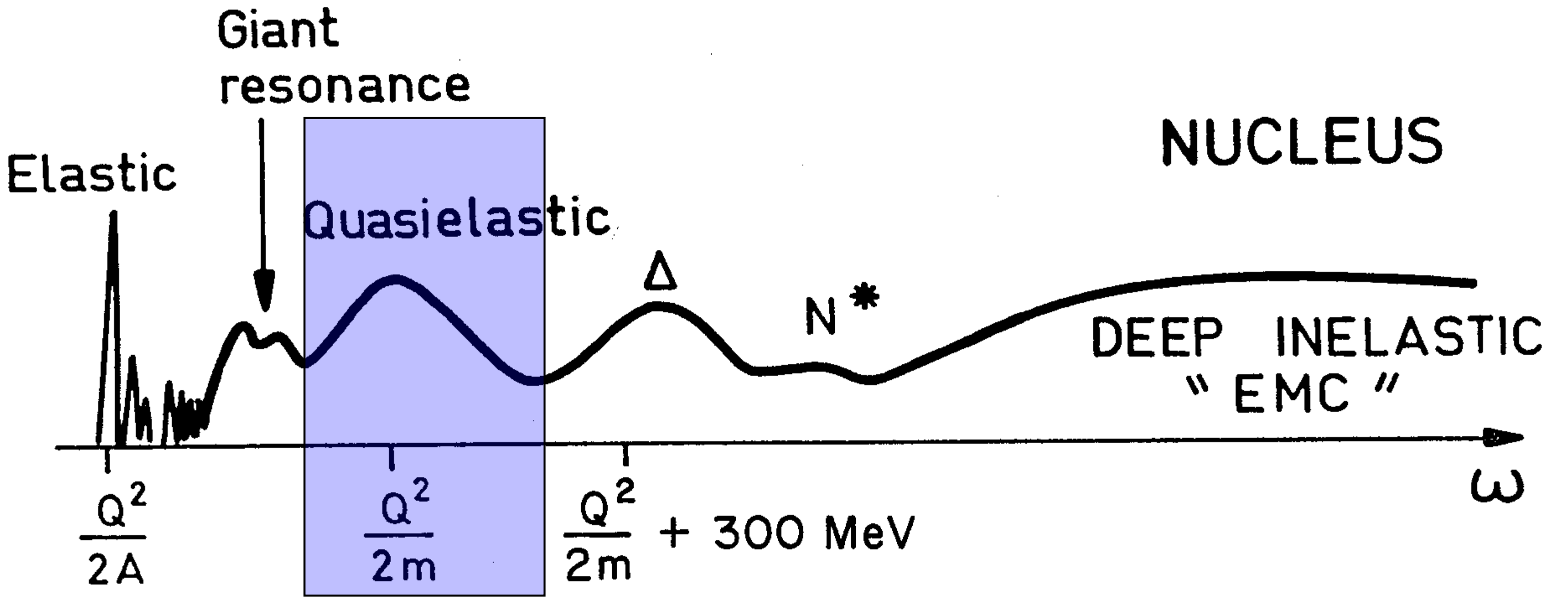
(2 photon exchange?)

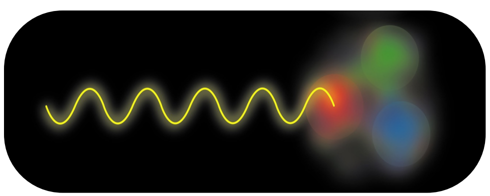
Elastic scattering summary



- ❑Measurements of charger distribution for nucleon and nucleus
- ❑Measurement for the electromagnetic form factor of Nucleon.

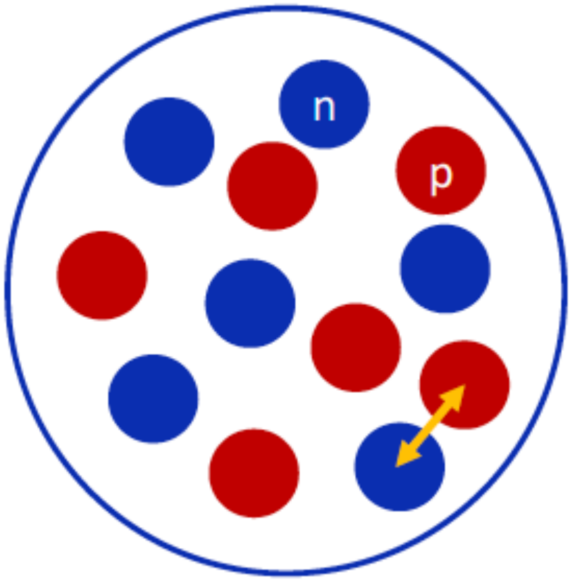
Quick overview: Quasi-elastic scattering



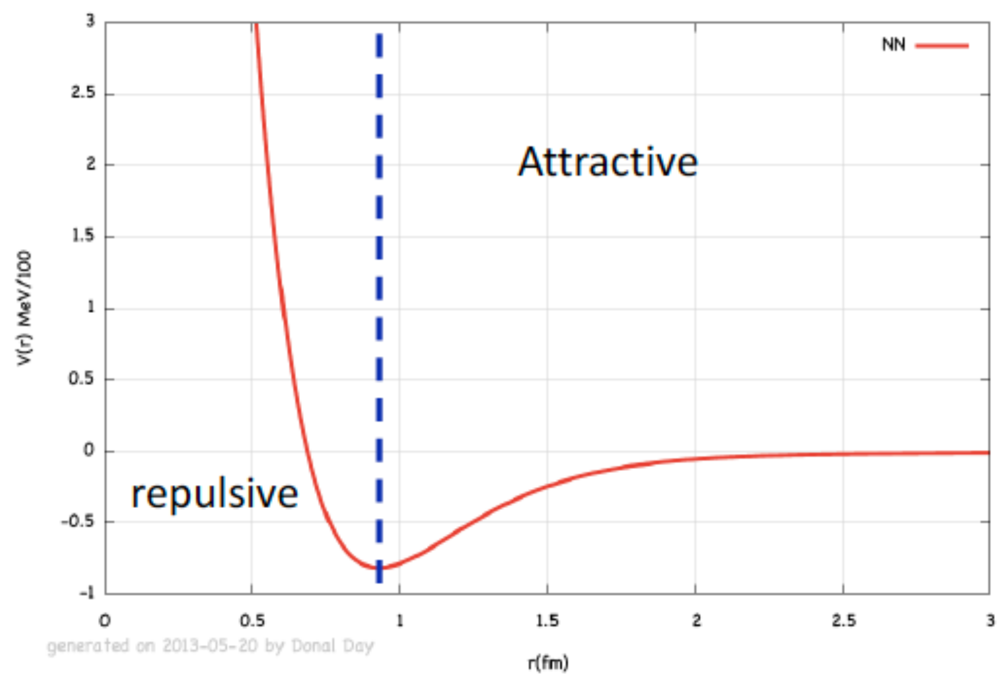


- ❑ Shell structure
  - Momentum distributions
  - Occupancies
- ❑ Short Range Correlated nucleon pairs

Nuclear structure and NN potential

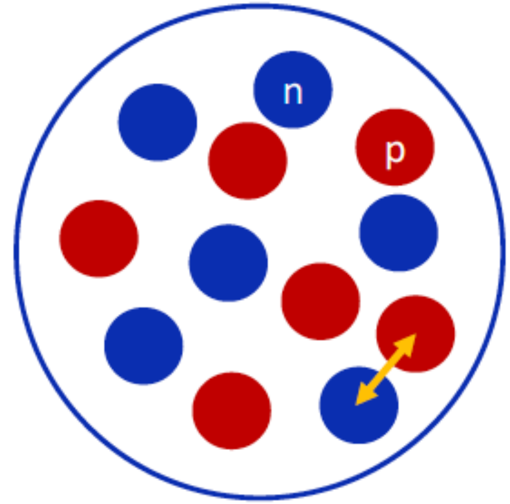


Nucleon-Nucleon (NN) potential



- ❑ Attractive force: Moderate distance
- ❑ Repulsive force: Short distance

… In Principle



- Nucleons are bound: Energy distribution, n(E)
- Nucleons are not static: Momentum distribution, n(k)
- Spectral function: Probability of finding a nucleon inside nuclei with a given energy and momentum, S(E, k)

Many-Body Hamiltonian:

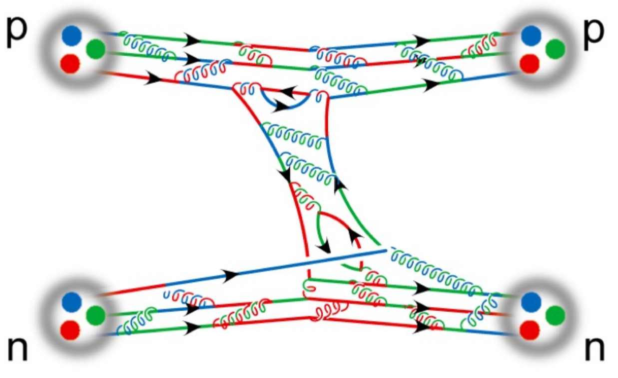
$$H = \sum_{i=1}^{A} T + \sum_{i<j}^{A} V_{2N}(i,j) + \sum_{i<j<k}^{A} V_{3N(i,j,k)} + \dots$$

Challenging Many-Body Problem

1. Many-body Schrödinger equation

$$\sum_i \left\{-\frac{\hbar^2}{2m_i}\nabla_i^2\Psi(\vec{r}_1, \dots, \vec{r}_N, t)\right\} + U(\vec{r}_1, \dots, \vec{r}_N)\Psi(\vec{r}_1, \dots, \vec{r}_N, t) = i\hbar\frac{\partial}{\partial t}\Psi(\vec{r}_1, \dots, \vec{r}_N, t)$$

2. Complex interaction



Challenging Many-Body Problem

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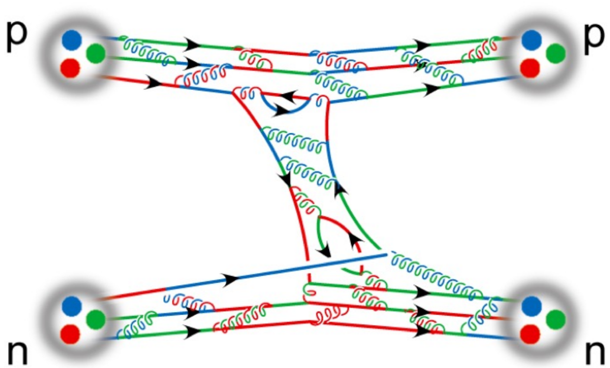
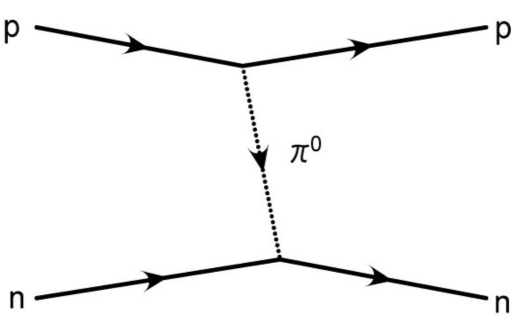
2. ~~Complex interaction~~ —> **Effective Interaction**





Challenging Many-Body Problem

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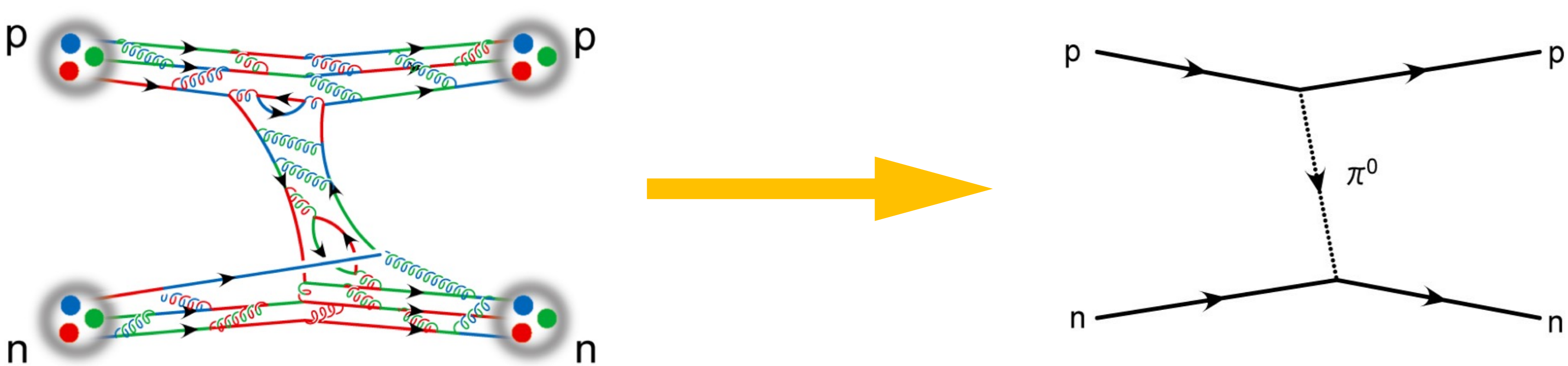
$$\sum_i \left(-\frac{\hbar^2}{2m_i}\nabla_i^2\Psi(\vec{r}_1,\dots,\vec{r}_N,t)\right) + U(\vec{r}_1,\dots,\vec{r}_N)\Psi(\vec{r}_1,\dots,\vec{r}_N,t) = i\hbar\frac{\partial}{\partial t}\Psi(\vec{r}_1,\dots,\vec{r}_N,t)$$

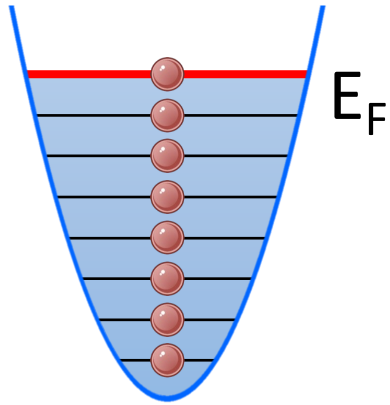
—> Effective Models

~~2. Complex interaction~~ —> **Effective Interaction**

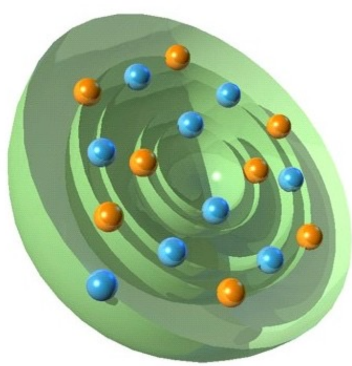


What is a Nucleus ?

Fermi Gas Model

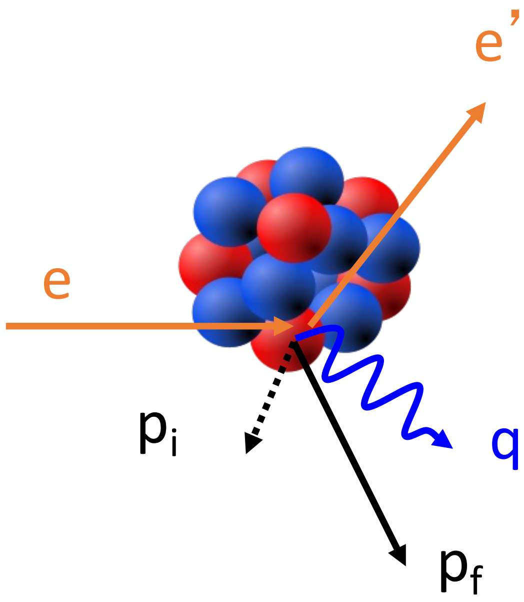


Shell Model



Fermi gas model:

how simple a model can you make?

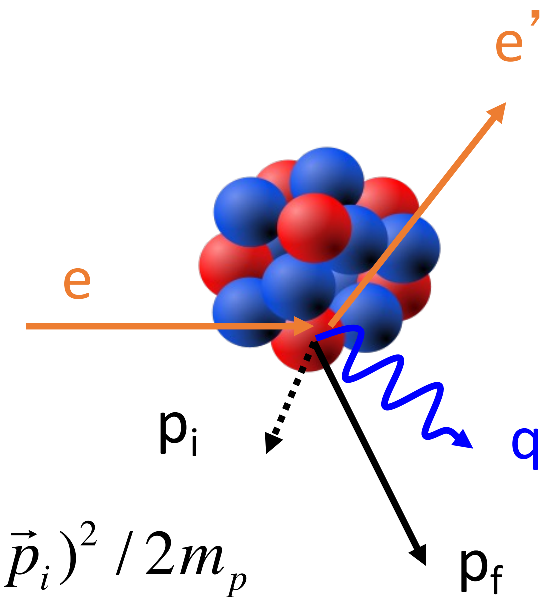


Initial nucleon energy: $KE_i = p_i^2 / 2m_p$

Final nucleon energy: $KE_f = p_f^2 / 2m_p = (\vec{q} + \vec{p}_i)^2 / 2m_p$

Energy transfer: $$\nu = KE_f - KE_i = \frac{\vec{q}^{\,2}}{2m_p} + \frac{\vec{q} \cdot \vec{p}_i}{m_p}$$

Fermi gas model:



how simple a model can you make?

Initial nucleon energy: $KE_i = p_i^2 / 2m_p$

Final nucleon energy: $KE_f = p_f^2 / 2m_p = (\vec{q} + \vec{p}_i)^2 / 2m_p$

Energy transfer: $\nu = KE_f - KE_i = \dfrac{\vec{q}^{\,2}}{2m_p} + \dfrac{\vec{q} \cdot \vec{p}_i}{m_p}$

Expect:

- Peak centroid at $\nu = q^2/2m_p + \varepsilon$
- Peak width $2qp_{fermi}/m_p$
- Total peak cross section = $Z\sigma_{ep} + N\sigma_{en}$

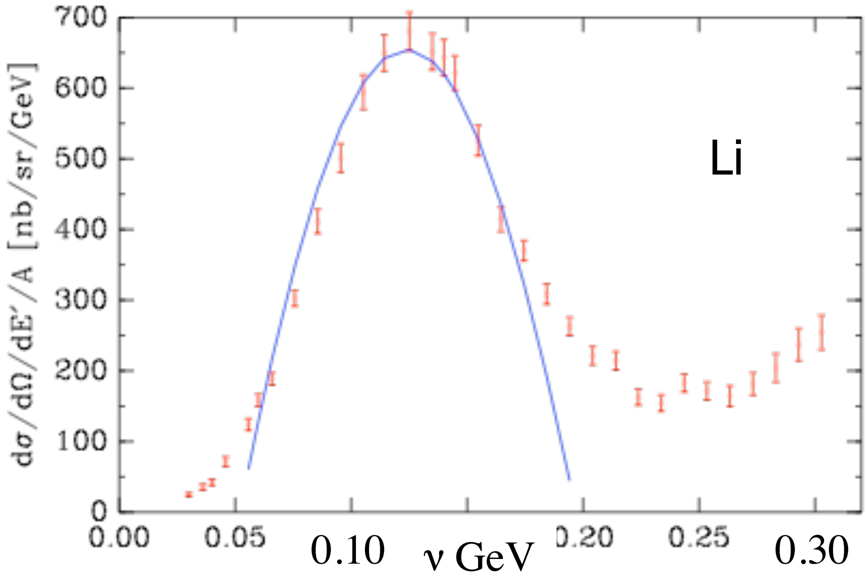
Early 1970s Quasi-elastic Data

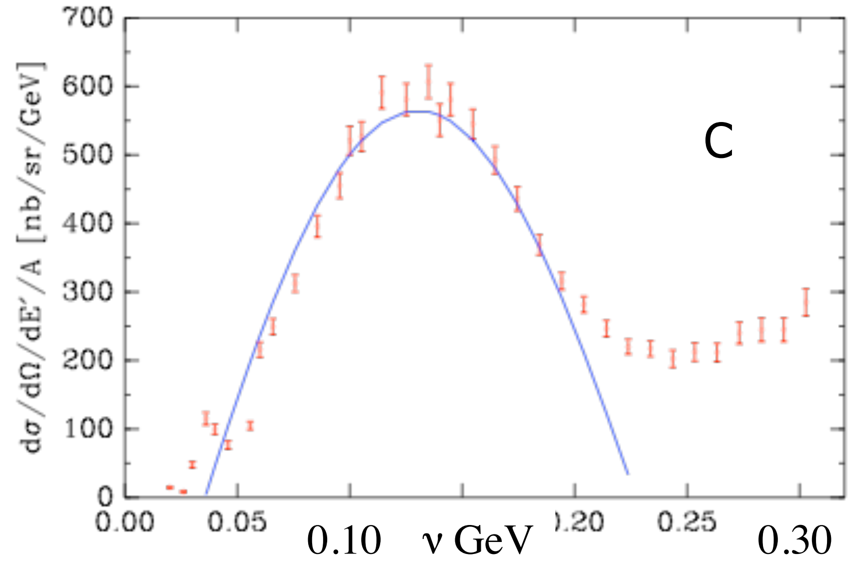
-> getting the bulk features

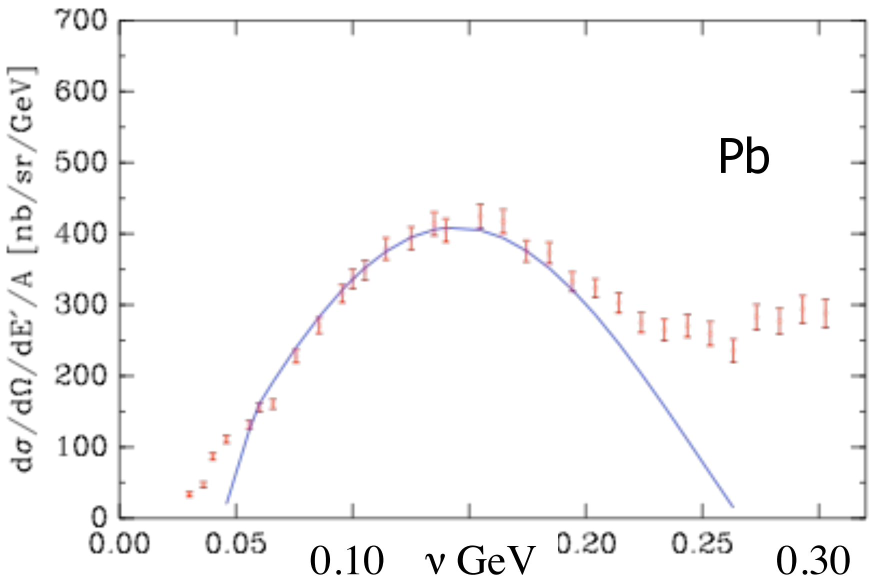
500 MeV, 60 degrees

$\vec{q} \simeq 500 MeV/c$

R.R. Whitney et al., PRC 9, 2230 (1974).



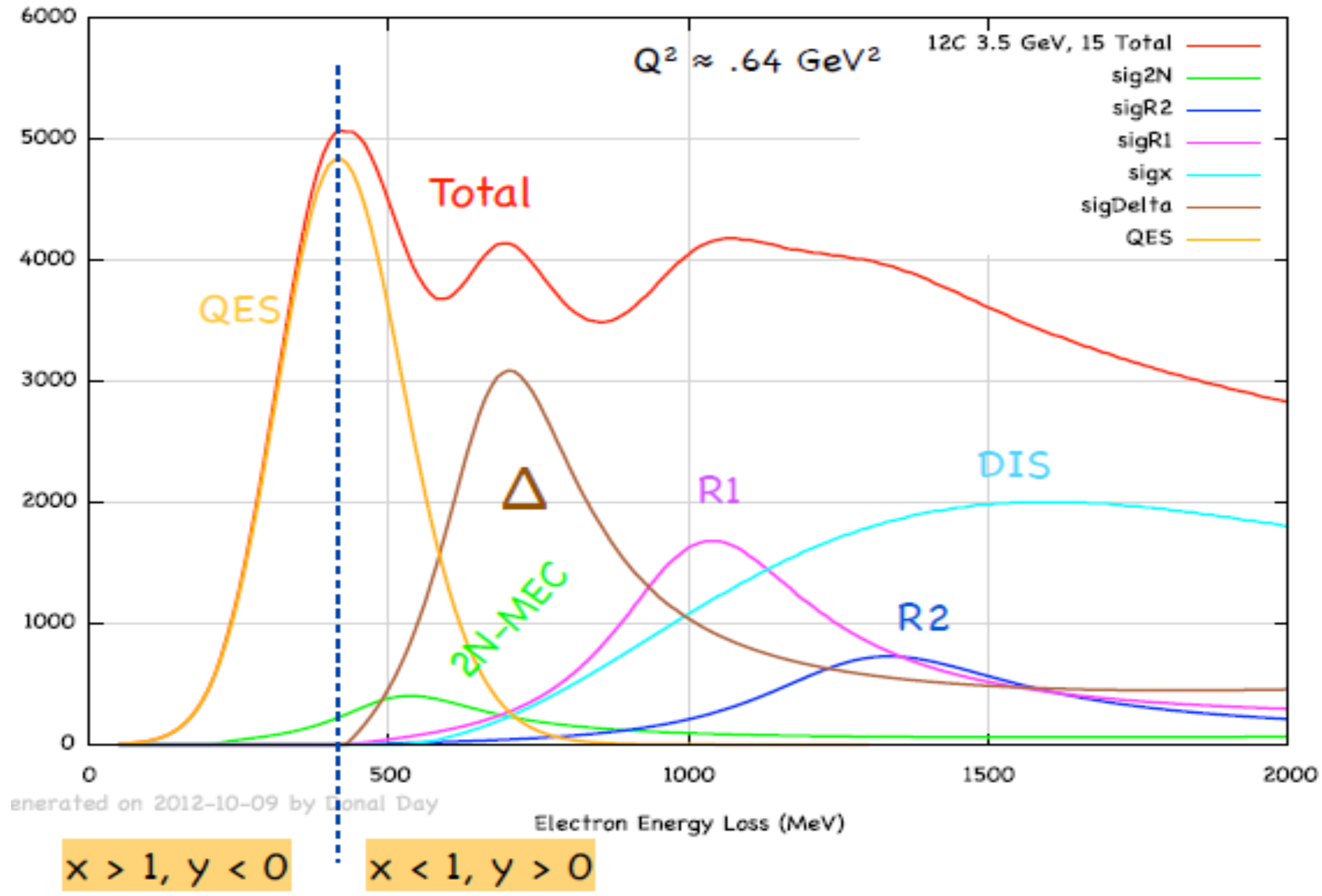




Nucleus	k_F MeV/c	$\bar{\epsilon}$ MeV
^{6}Li	169	17
^{12}C	221	25
^{24}Mg	235	32
^{40}Ca	251	28
^{nat}Ni	260	36
^{89}Y	254	39
^{nat}Sn	260	42
^{181}Ta	265	42
^{208}Pb	265	44

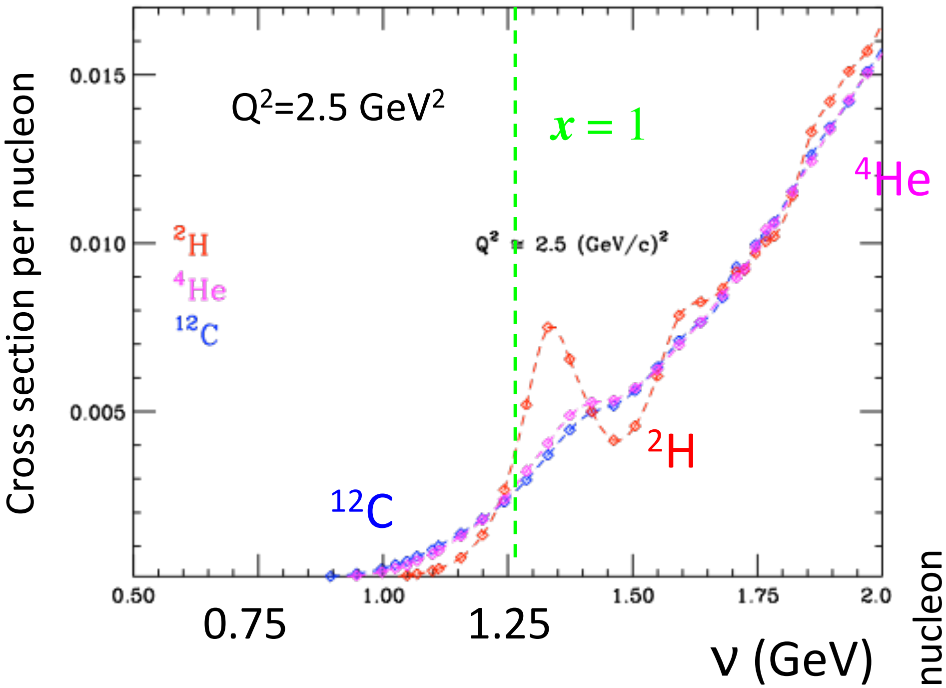
compared to Fermi model: fit parameter k_F and ε

Inclusive (e.e’) Quasi-elastic scattering



O. Benhar, D. Day, Rev. Mod. Phys (2008)

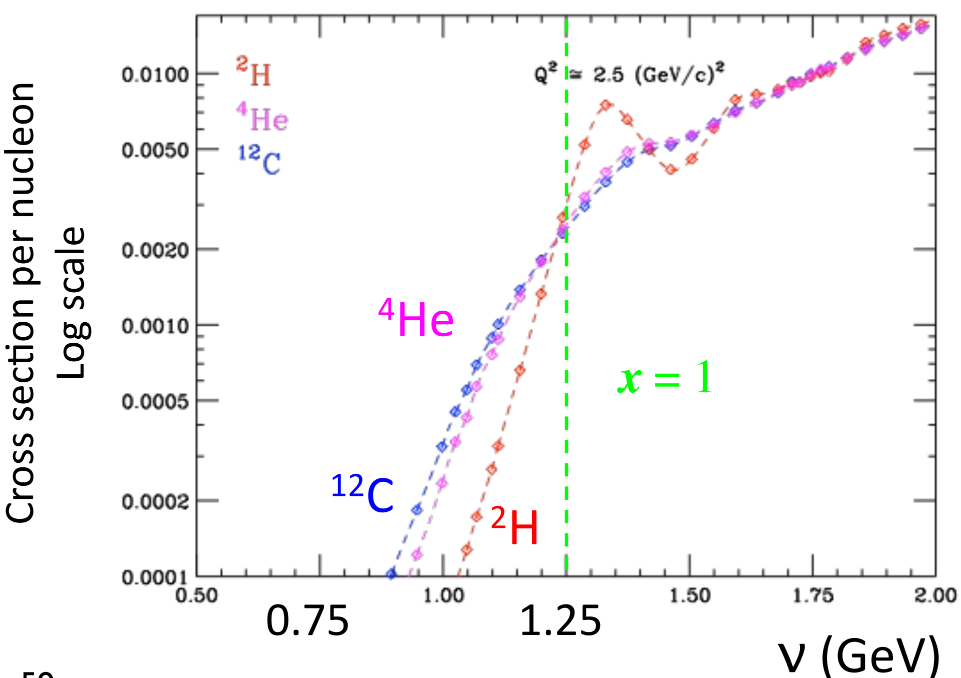
Nuclear mass (A) dependence



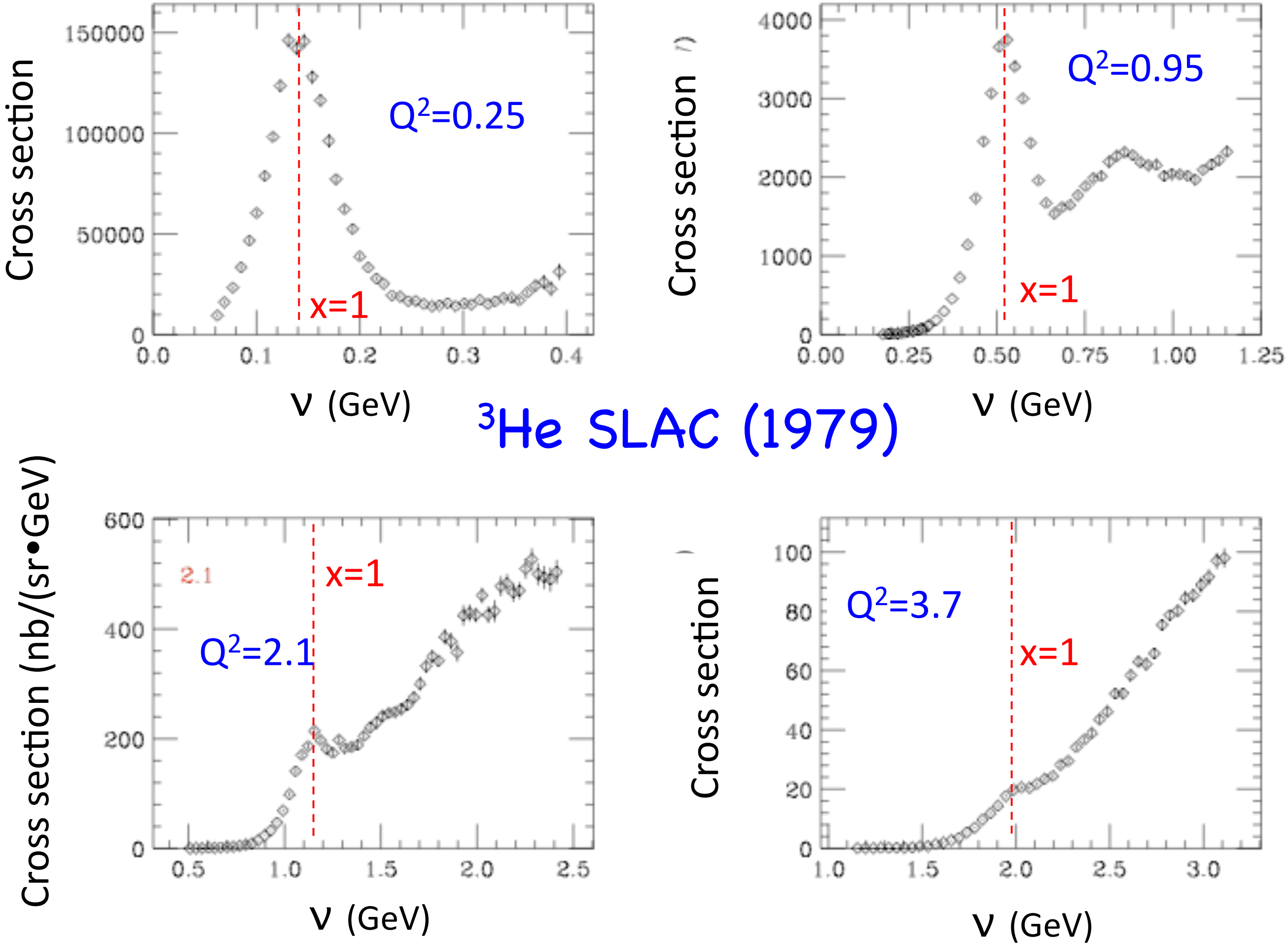
Heavier nucleus

- ➢ higher nucleon momenta
- ➢ broadened peak

(same plot, log scale)



Q^2 dependence



- As $Q^2 >> 1$ inelastic scattering from the nucleons begins to dominate
- Quasi Elastic scattering is still dominant at low energy transfer, even at high Q^2

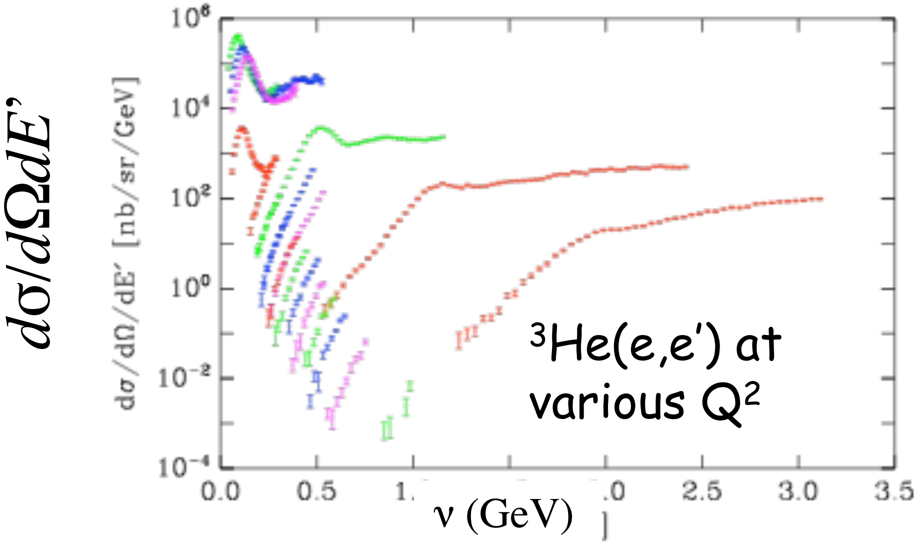
Scaling

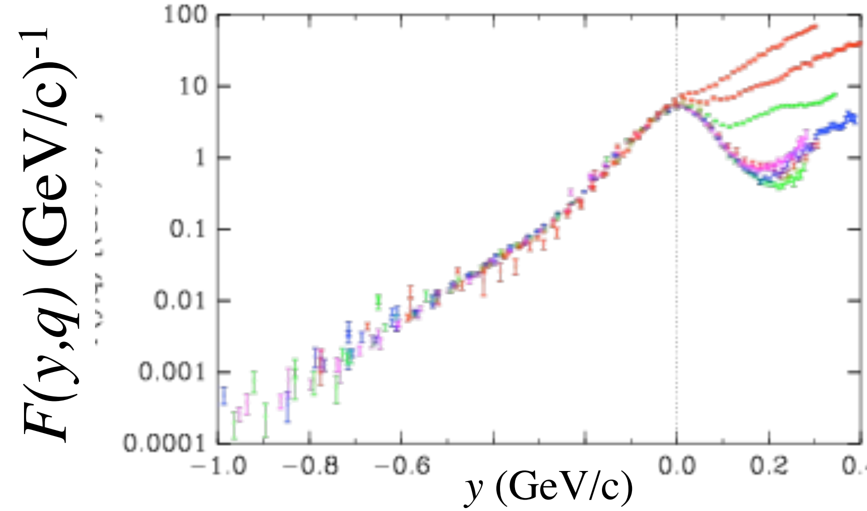
- The dependence of a cross-section, in certain kinematic regions, on a single variable.
  - scaling validates the scaling assumption.
  - Scale-breaking indicates new physics.

- At moderate Q^2 and $x>1$ we expect to see evidence for y-scaling, indicating that the electrons are scattering from quasifree nucleons
  - y = minimum momentum of struck nucleon

- At high Q^2 we expect to see evidence for x-scaling, indicating that the electrons are scattering from quarks.
  - $x = Q^2/2m\nu$ = fraction of nucleon momentum carried by struck quark (in infinite momentum frame)

y-scaling in inclusive electron scattering from ^{3}He





$$F(y) = \frac{\sigma^{\exp}}{(Z\tilde{\sigma}_p + N\tilde{\sigma}_n)} \cdot K$$

$$n(k) = -\frac{1}{2\pi y}\frac{dF(y)}{dy}$$

- Assumption: scattering takes place from a quasi-free proton or neutron in the nucleus.
- y is the momentum of the struck nucleon parallel to the momentum transfer:

$y \approx -q/2 + m\nu/q$ (nonrelativistically)

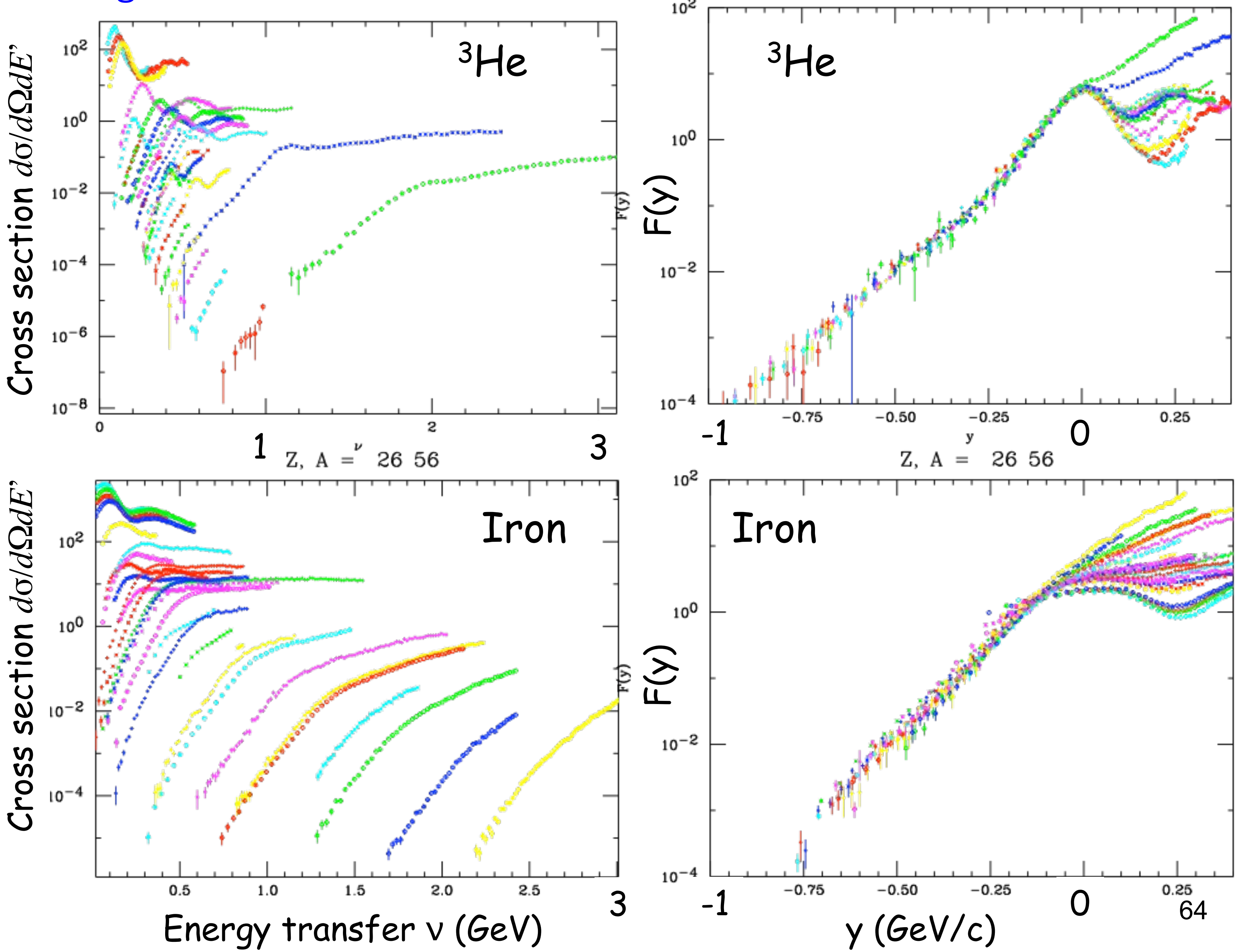
IF the scattering is quasifree, then $F(y)$ is the integral over all perpendicular nucleon momenta (nonrelativistically).

Goal: extract the momentum distribution $n(k)$ from $F(y)$.

Assumptions & Potential Scale Breaking Mechanisms

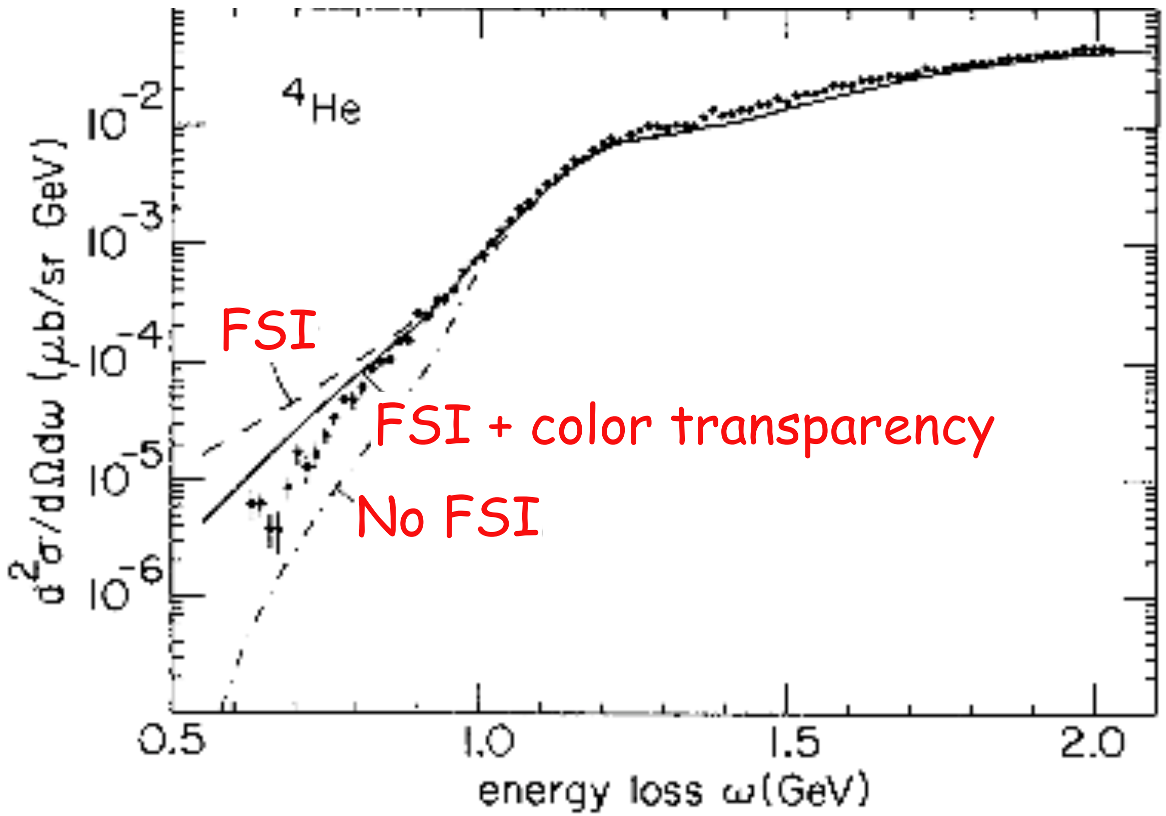
- No Final State Interactions (FSI)
- No internal excitation of (A-1)
- Full strength of Spectral function can be integrated over at finite *q*
- No inelastic processes (choose $y<0$)
- No medium modifications (discussed later)

Y-scaling works!



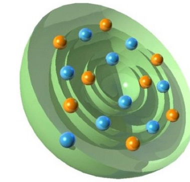
Final State Interactions (FSI) complicate this simple picture

^{4}He(e,e') at 3.595 GeV, 30°



Benhar et al. PRC 44, 2328
Benhar, Pandharipande, PRC 47, 2218
Benhar et al. PLB 3443, 47

Independent particle shell model

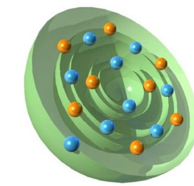


$$H = \underbrace{[T + V_M]}_{\text{IPSM}} + \underbrace{[V_{2-body} + V_{3-body} + ... - V_M]}_{\text{neglected in IPSM}}.$$

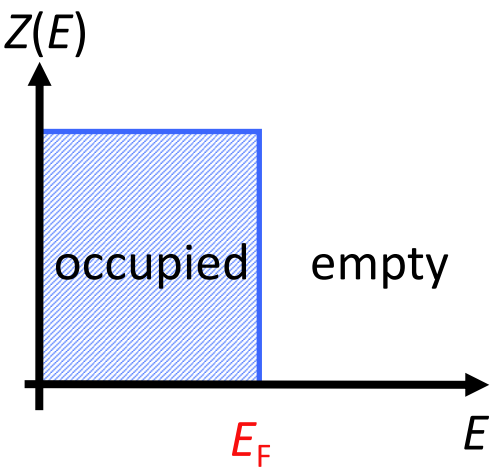
<u>Assumptions:</u>

- ❑ Nucleon moves in a mean-field created by surrounding nucleons
- ❑ No interaction at a short distance
- ❑ Nucleons fill up distinct energy level defined by quantum numbers, highest energy level is called Fermi-energy, corresponding to Fermi-momentum

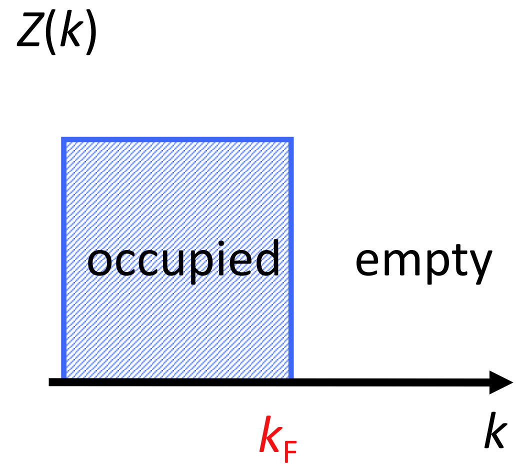
Independent particle shell model



$$H = \underbrace{[T + V_M]}_{\text{IPSM}} + \underbrace{[V_{2-body} + V_{3-body} + \ldots - V_M]}_{\text{neglected in IPSM}} .$$



$$E_F = \frac{k_F^2}{2m_p}$$

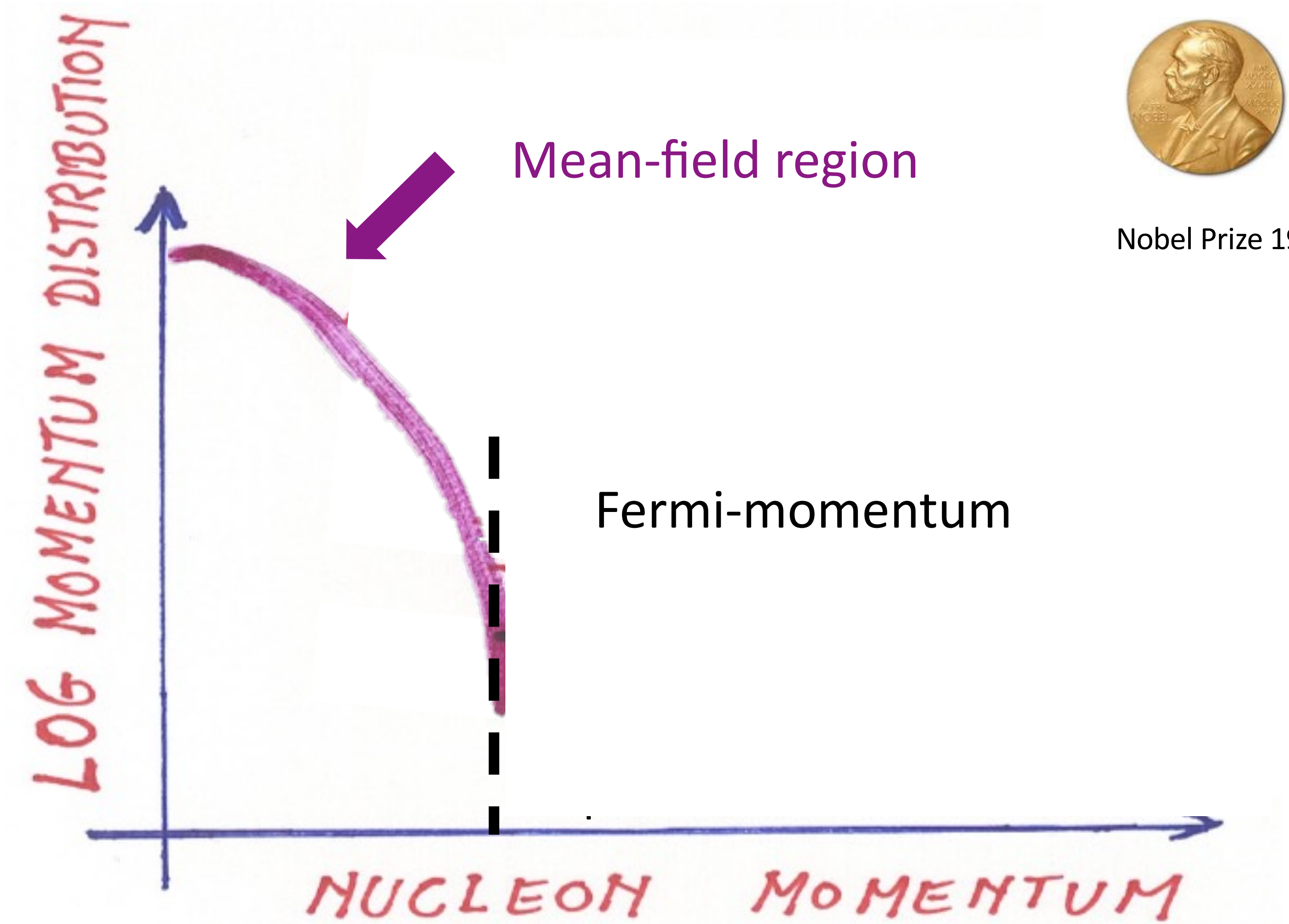


<u>Pauli's principle:</u>

- ❑ Forbids nucleon scattering to occupied shell: Suppressed the nucleon interaction

- Ground state energies
- Excitation Spectrum
- Spins
- Parities
- …

Momentum distribution:



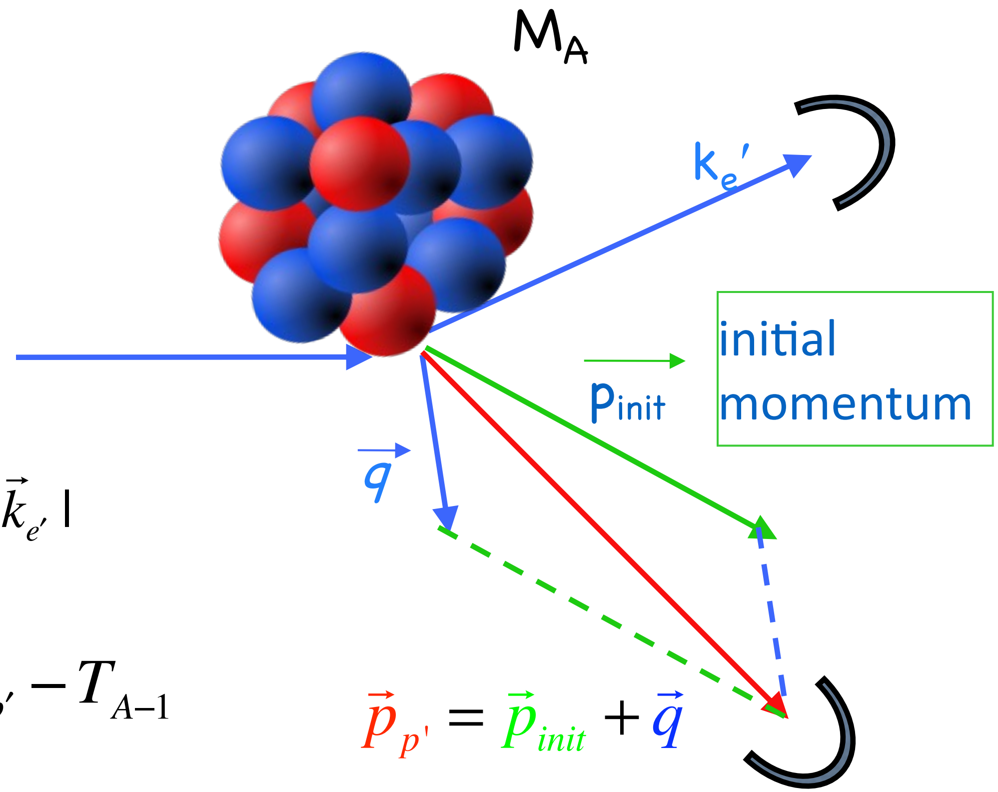
Nobel Prize 1963

Detect the knocked out nucleon (e,e'p)

coincidence experiment

measure: momentum, angles

electron energy: E_e
proton: $\vec{p}_{p'}$
scattered electron: $\vec{k}_{e'}$ $E_{e'} = |\vec{k}_{e'}|$



$$\vec{p}_{p'} = \vec{p}_{init} + \vec{q}$$

reconstructed quantities:
missing energy: $E_m = \nu - T_{p'} - T_{A-1}$

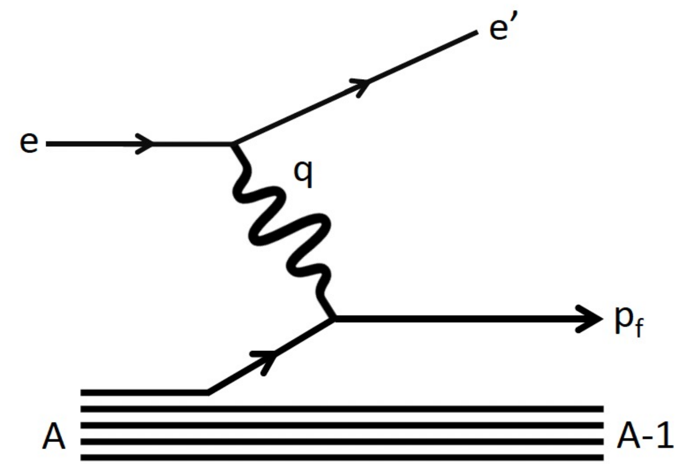
missing momentum: $\vec{p}_m = \vec{q} - \vec{p}_{p'}$

in Plane Wave Impulse Approximation (PWIA):
direct relation between measured quantities and theory:

$$|E| = E_m \quad \vec{p}_{init} = -\vec{p}_m$$

(e,e’p) Plane Wave Impulse Approximation (PWIA)

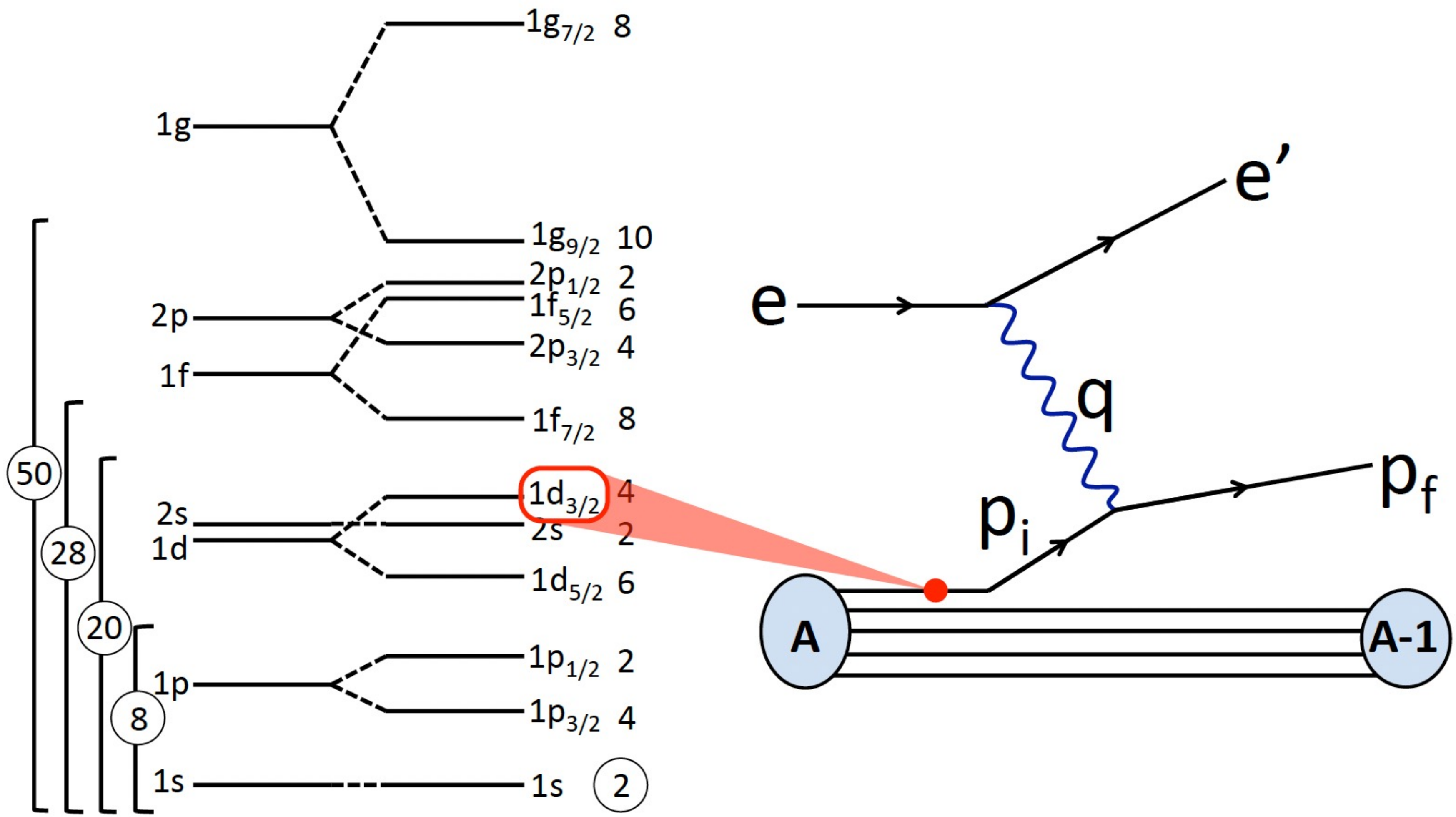
1. Only one nucleon absorbs the virtual photon
2. That nucleon does not interact further
3. That nucleon is detected



Cross-section factorization

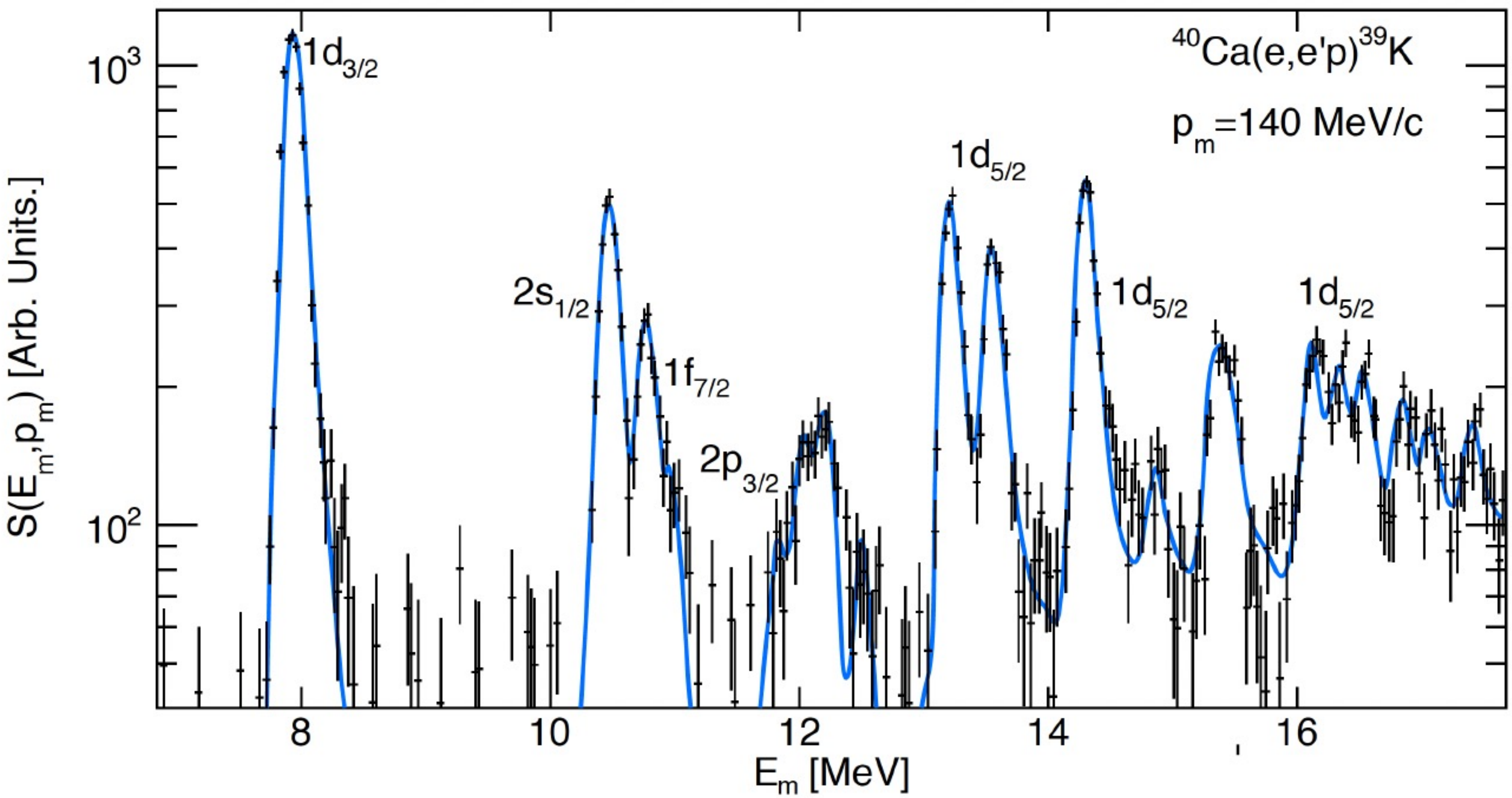
$$\sigma = K\,\sigma_{ep}\,S(|\overrightarrow{P_i}|, E_i)$$

(e,e'p) scattering off shell orbitals



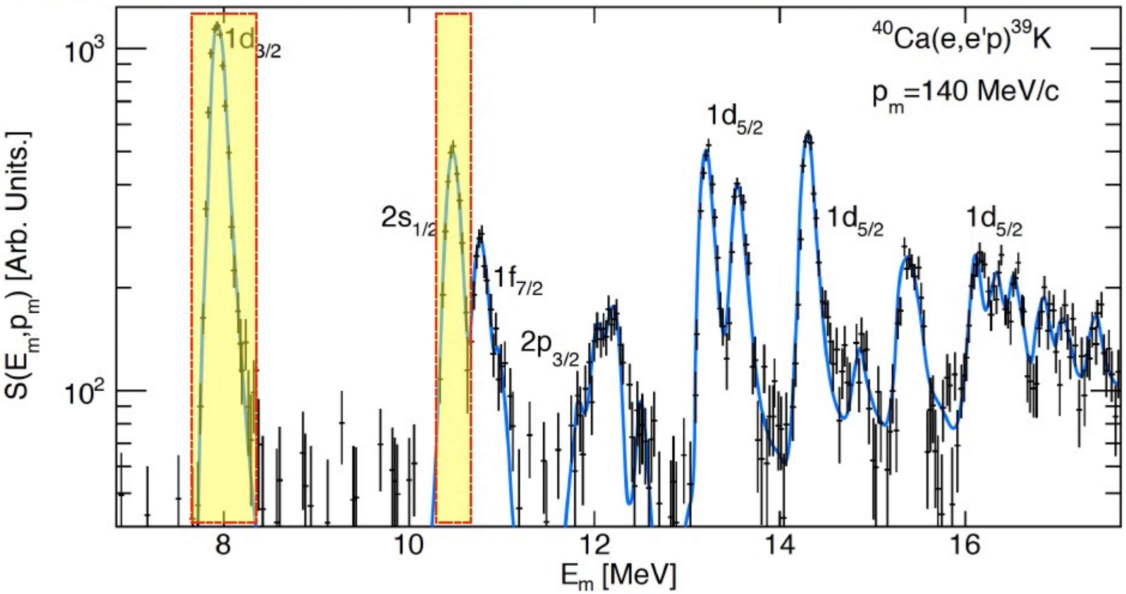
(e,e'p) scattering off shell orbitals

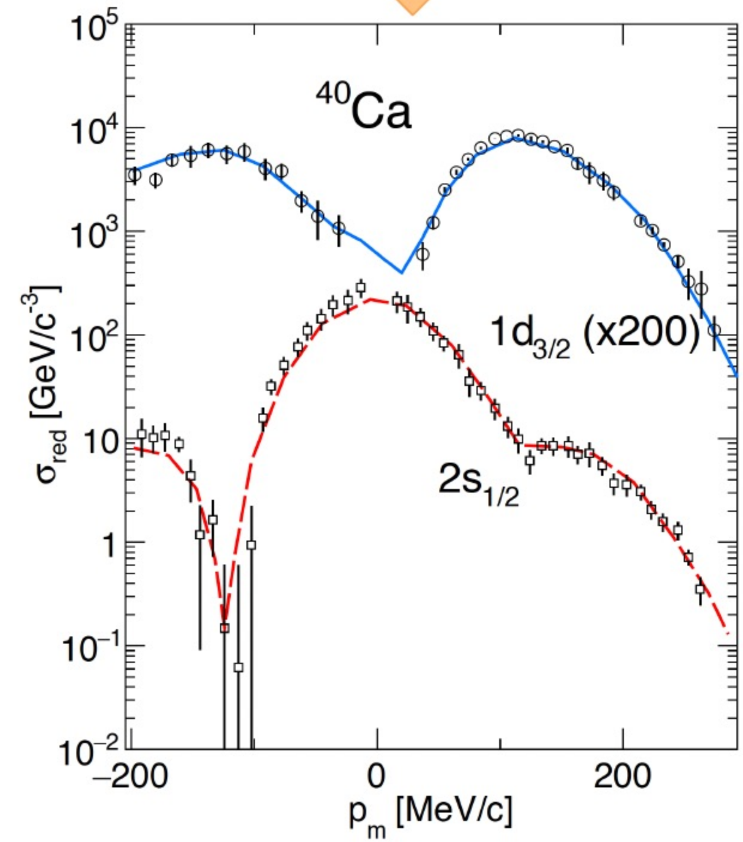
The missing energy spectrum shows shells occupancy



L. Lapikas, Nuclear Phys. A553, 297c (1993)

(e,e'p) scattering off shell orbitals



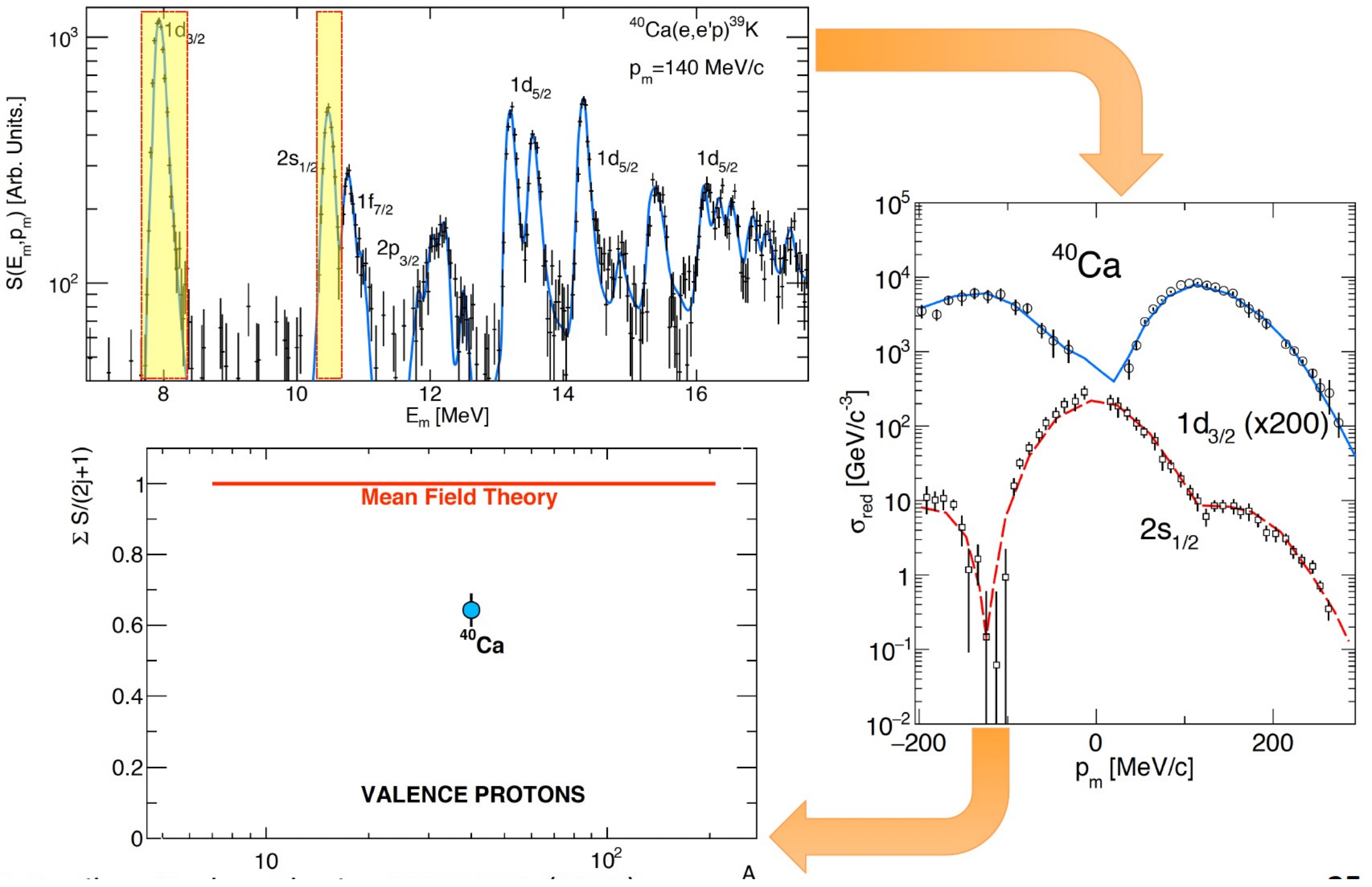


Compare to Shell Model predictions:

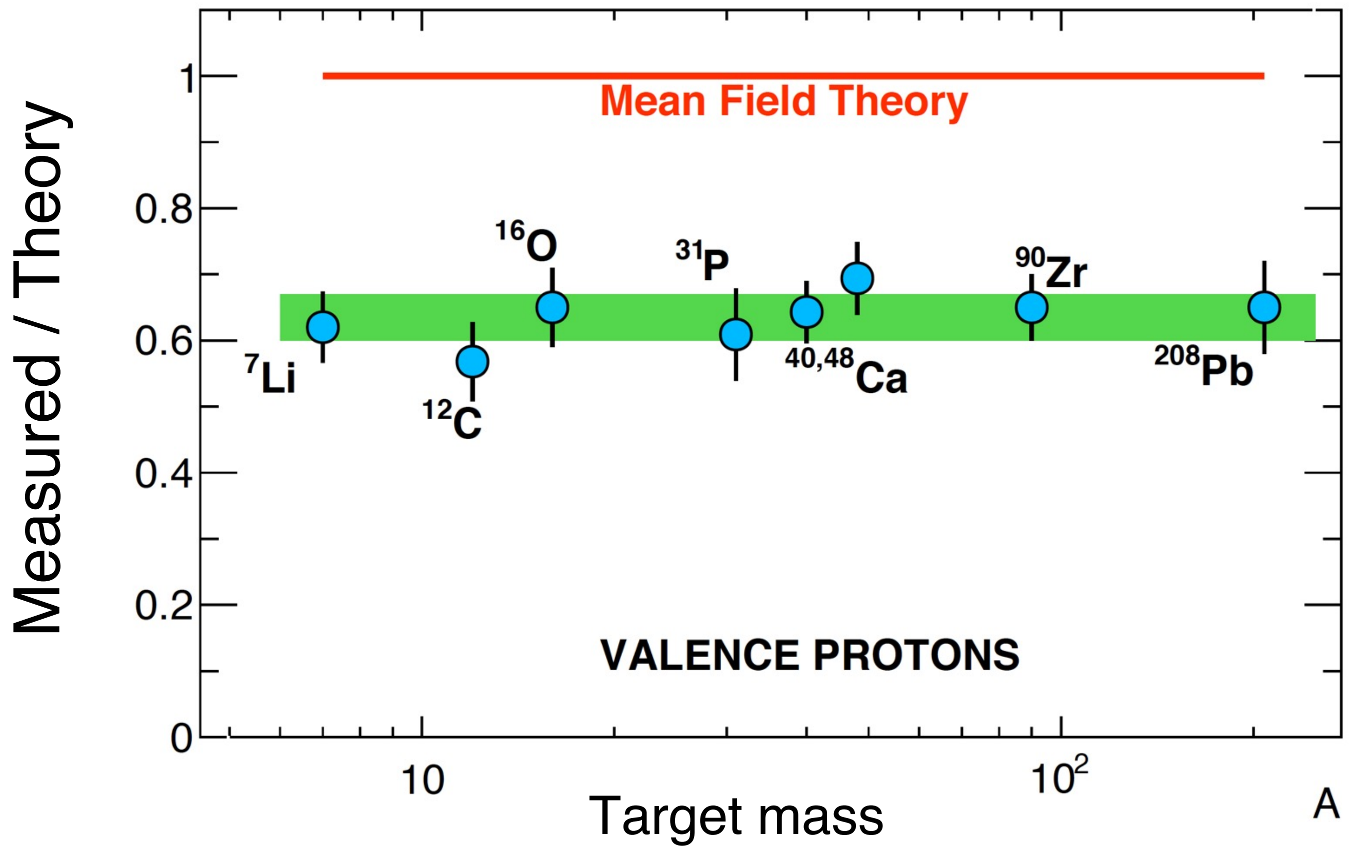
- Shapes well described
    - Normalization…

L. Lapikas, Nuclear Phys. A553, 297c (1993)

(e,e'p) scattering off shell orbitals



Nucleon went missing??



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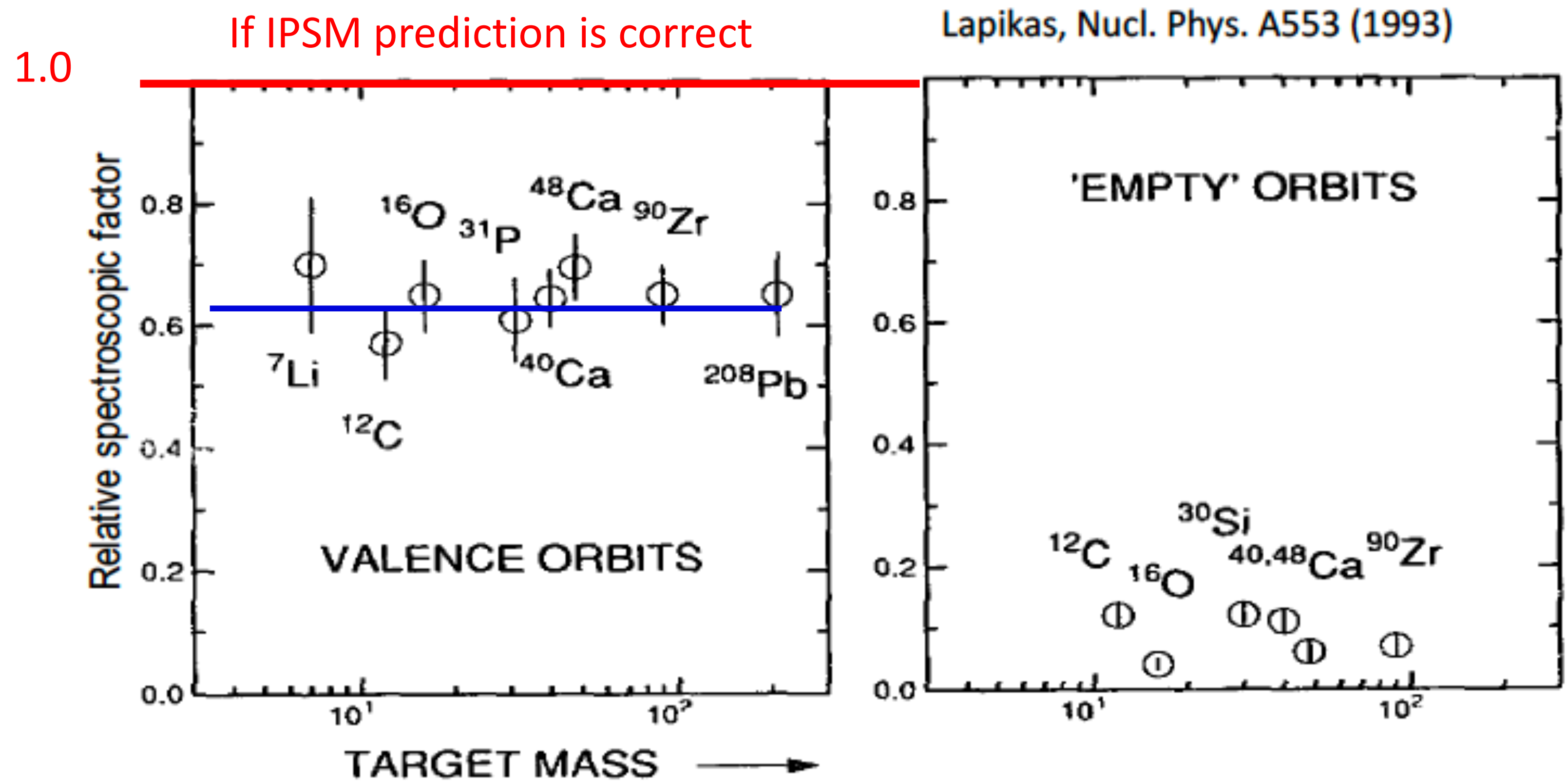


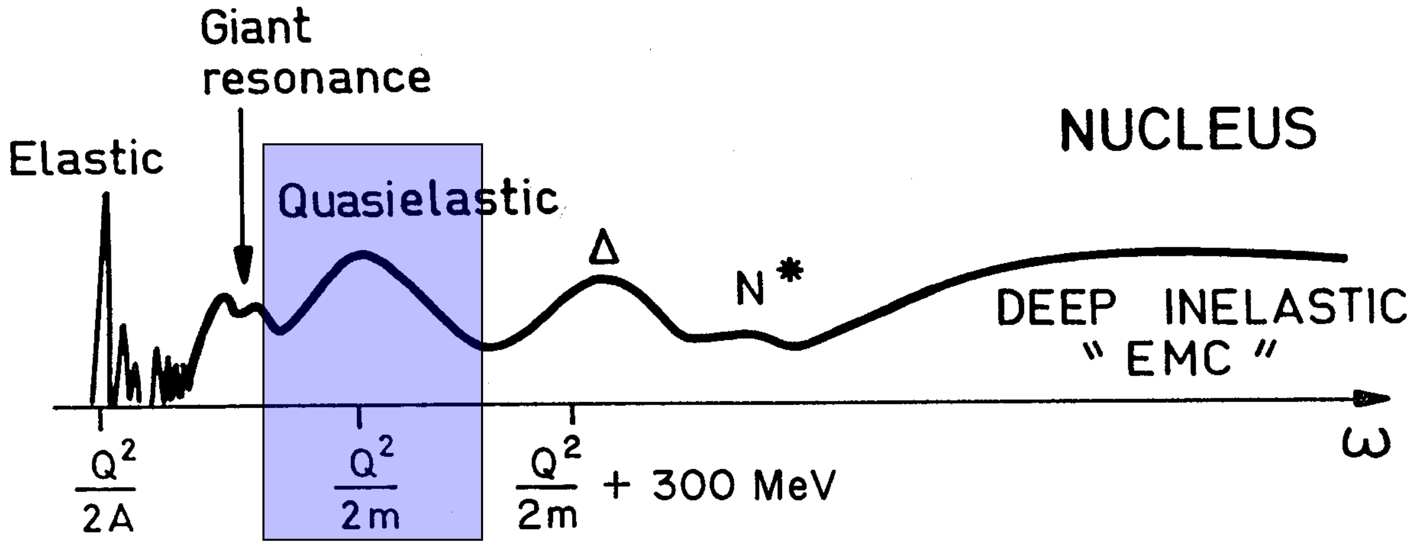
- Some strength was detected in the shell above the fermi edge which is predicted to be empty In IPSM

$$H = \underbrace{[T + V_M]}_{\text{IPSM}} + \underbrace{[V_{2-body} + V_{3-body} + \ldots - V_M]}_{\text{neglected in IPSM}}.$$

- ❑Long range correlations can not account for the spectroscopic factor difference
- ❑Short Range Correlations (SRCs) is possible solution

Welcome to SRCs

Quasi-elastic Summary



- ❑Measures shell structure directly
- ❑Provide information on nucleon momentum distribution
- ❑Nucleon went missing, provide the hint to SRCs