Nuclear Structure and Short-Range Correlations (Day 1)

Or Hen – MIT

Hampton University Graduate School (HUGS),
June 6th 2017, JLab, Newport-News VA.

Course Outline

Day I: Overview of Nuclear Systems and EM Probes.

Day II: Nuclear Structure.

(Short / Long Range)

(Experiment / Theory)

Day III: Cross Connections.

(QCD in Nuclei: Modification and Transparency)

(Contact Formalism and Short-Range Universality)

(Neutrino Physics)

(Neutron Stars)

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Day I: Overview of Nuclear Systems and EM Probes.

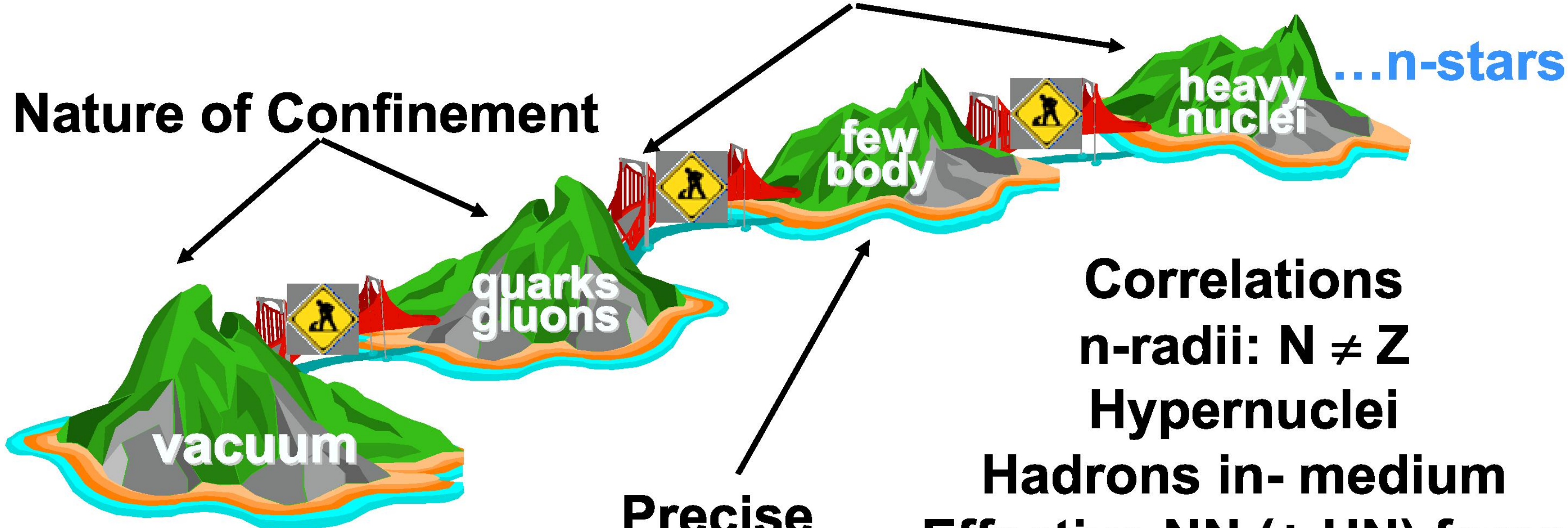
After today's overview, I want to hear from you what you want to learn!

Theory / Detectors / High energy / low energy

Modern nuclear physics: From nothing to everything

Quark-Gluon Structure Of Nucleons and Nuclei

Nature of Confinement



Correlations
n-radii: N ≠ Z
Hypernuclei
Hadrons in- medium
Effective NN (+ HN) force

Precise few-nucleon calculations

Exotic mesons and baryons

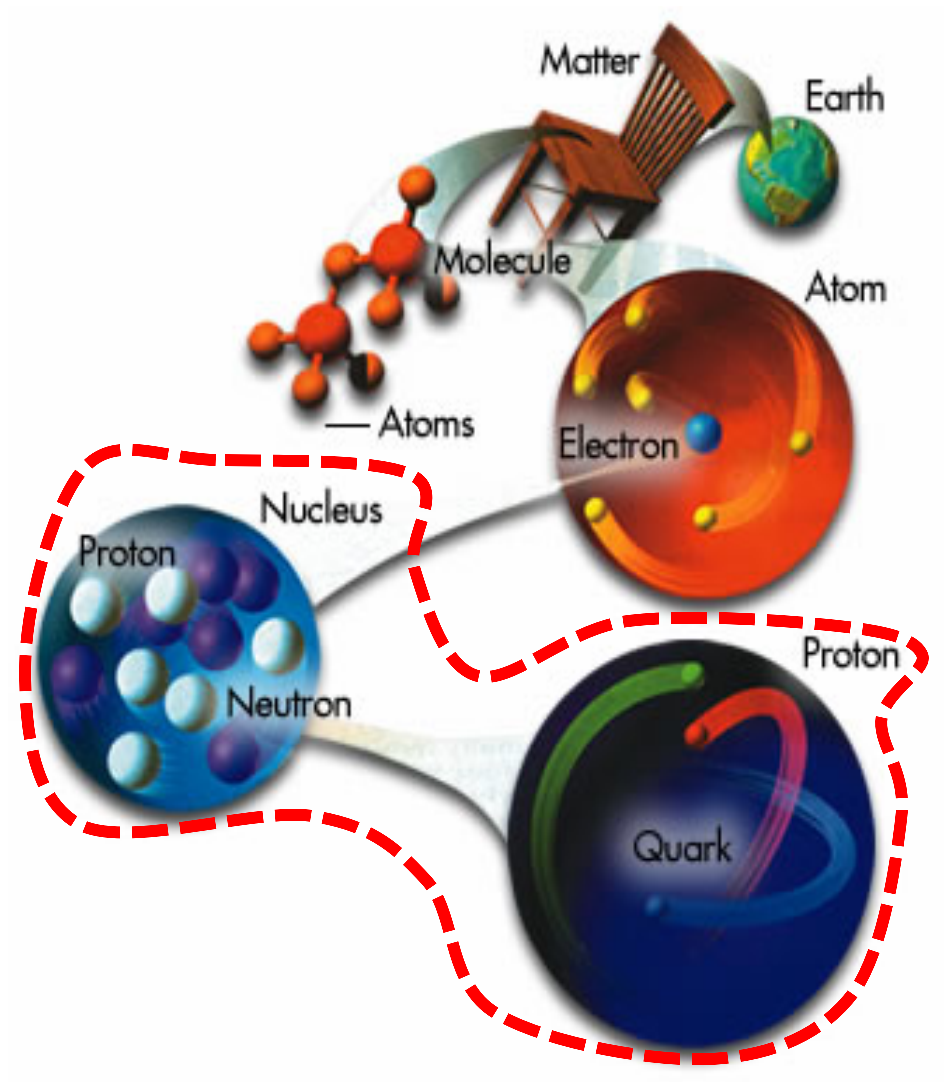
This Course: Two Systems and Their Interactions

Systems:

- *nucleus* as a collection of bound protons and neutrons,
- *nucleon* as a collection of bound quarks.

Interactions:

- Nuclear Interactions from quark interactions,
- Nuclear Medium Effects on quarks distributions.



(Some) Quantities of Interest

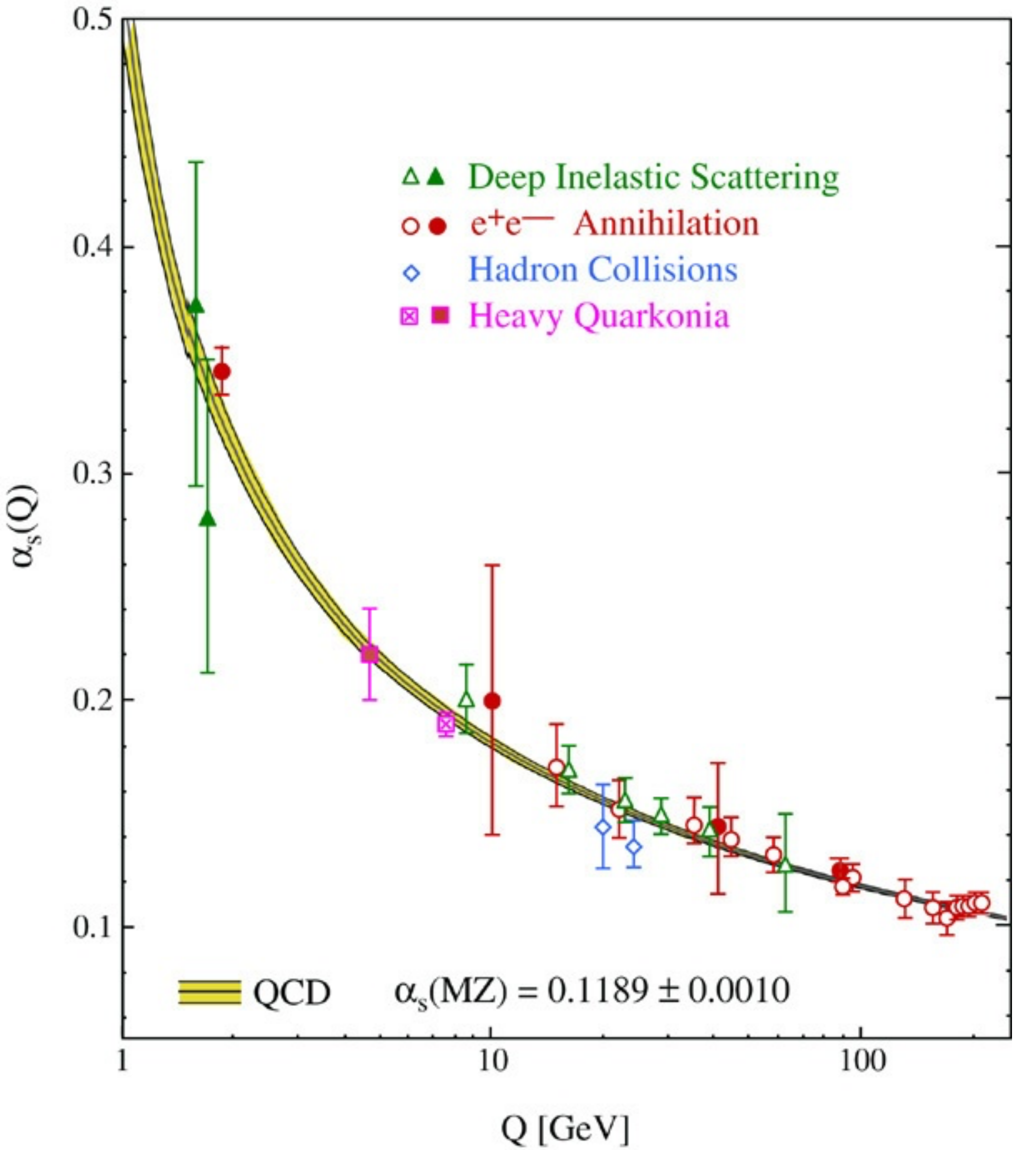
Nuclear structure:

- Shape (radii / deformation / …),
- Electro-magnetic charge distribution (form factor),
- Nucleon momentum distribution (wave function),
- Clustering and correlations,
- ….

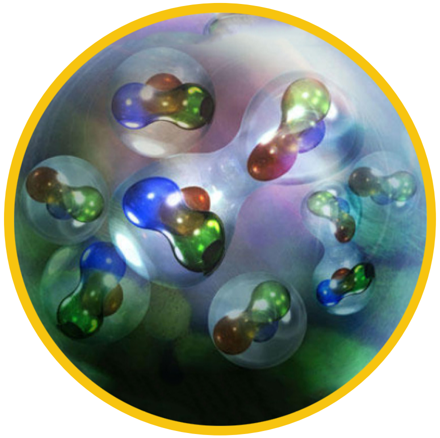
Nucleon Structure:

- Nuclear forces from quark interactions
- Quark structure of bound and free nucleons
- ….

Nuclear Challenge



Nuclei are a low energy phenomena, => QCD is non perturbative!



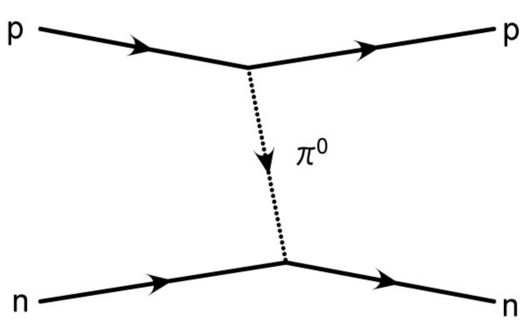
Nuclear *Many-Body* Challenge

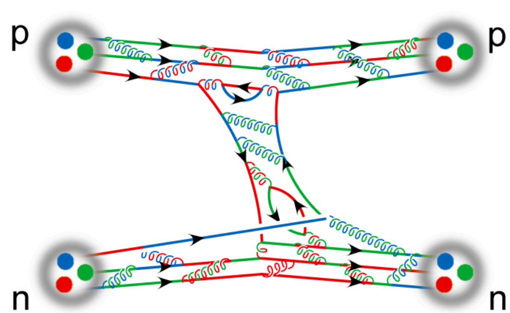
Many-body Schrödinger Equation

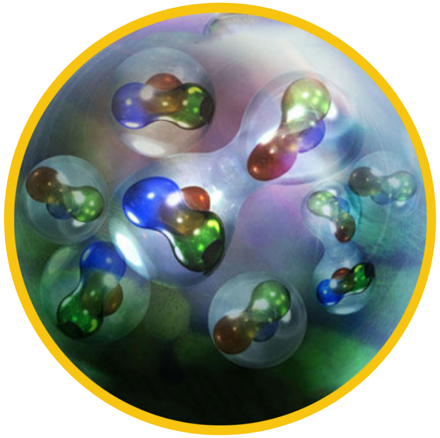
$$\sum_i \left\{-\frac{\hbar^2}{2m_i}\nabla_i^2\Psi(\vec{r}_1,\dots,\vec{r}_N,t)\right\} + U(\vec{r}_1,\dots,\vec{r}_N)\Psi(\vec{r}_1,\dots,\vec{r}_N,t) = i\hbar\frac{\partial}{\partial t}\Psi(\vec{r}_1,\dots,\vec{r}_N,t)$$

<u>Main Challenges:</u>

1. No ‘fundamental’ Interaction.
2. Complex phenomenological parametrizations (e.g. over 18 operators)

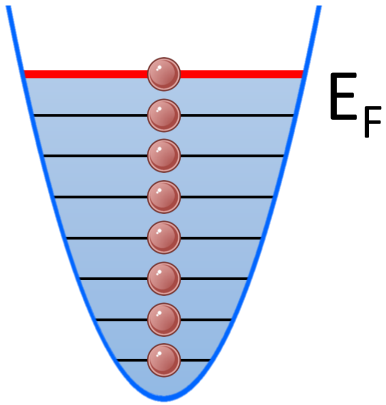






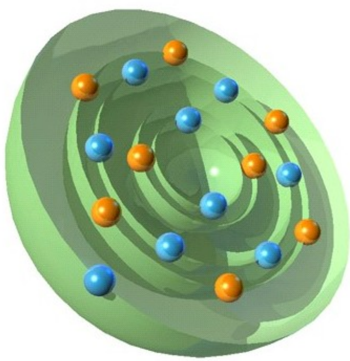
Solution: Effective Theories

Fermi Gas Model

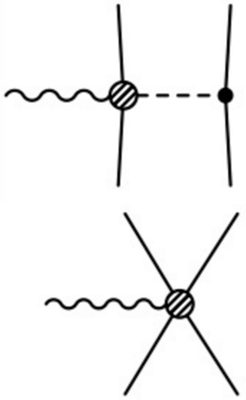


Liquid Drop Model

Shell Model



Chiral Perturbation Theory*

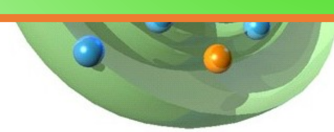


* Should converge to exact solution

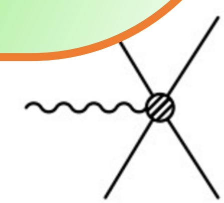
Solution: Effective Theories

Development of any theory is guided by experiment!

=> Theory alone has very little stand without experiment ☺



Theory*



* Should converge to exact solution

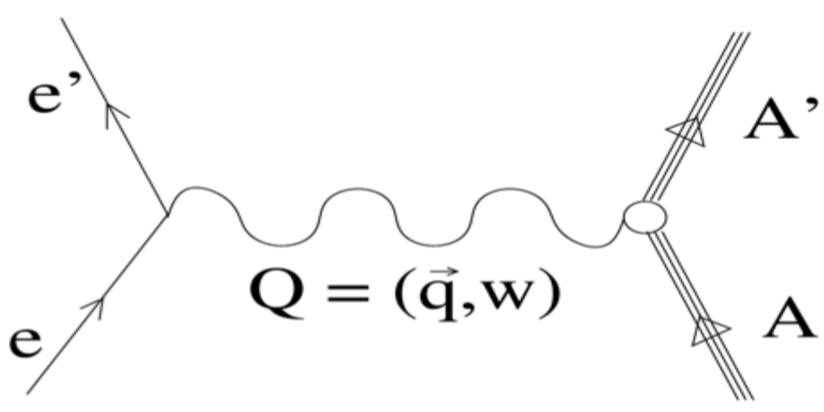
Electron Scattering: Nuclear Microscope

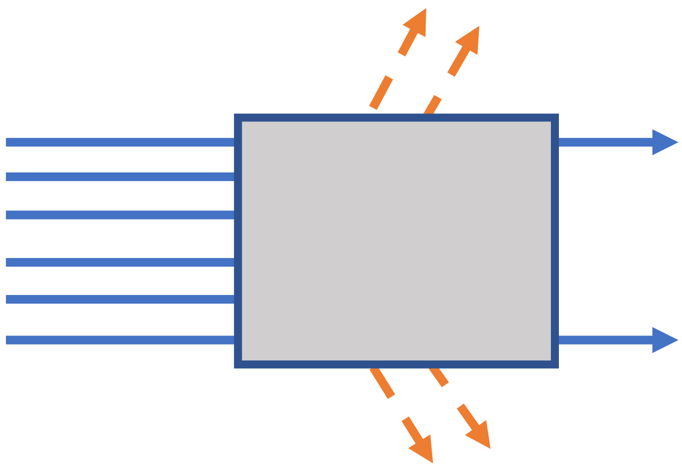
Goal: Study the internal structure (and dynamics) of complex objects

Means: using high energy lepton scattering

Reaction determined by two variables:

- $Q^2 = -q^2$ Interaction-Scale
- $x_B = Q^2/(2m_p\nu)$ Dynamics





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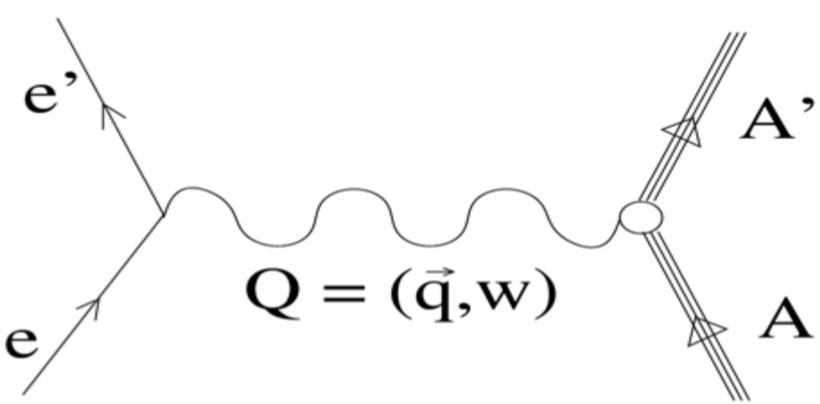

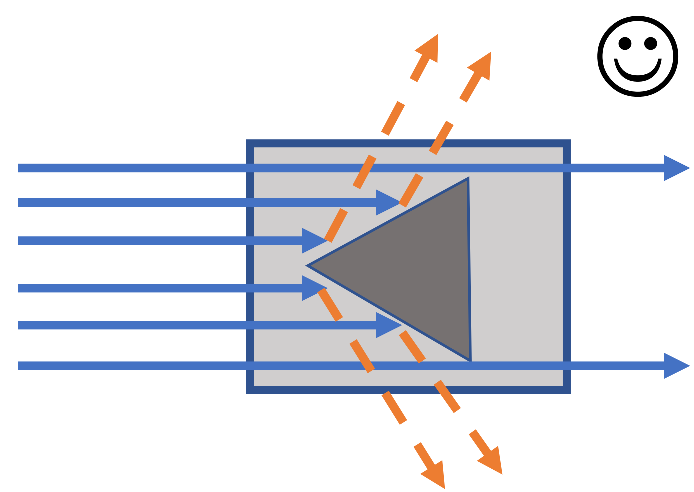

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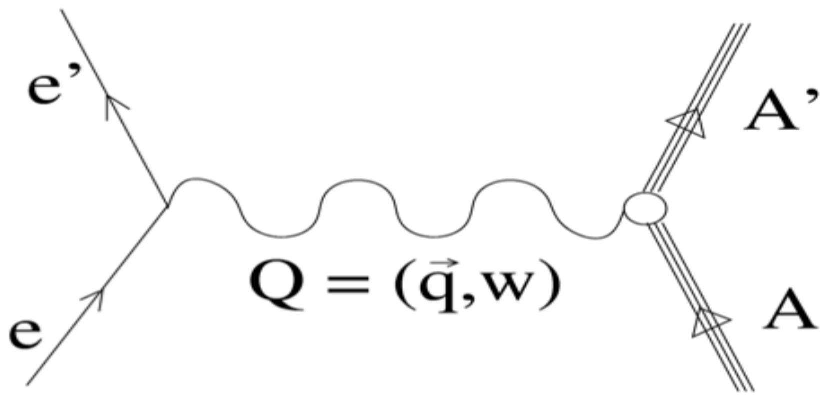

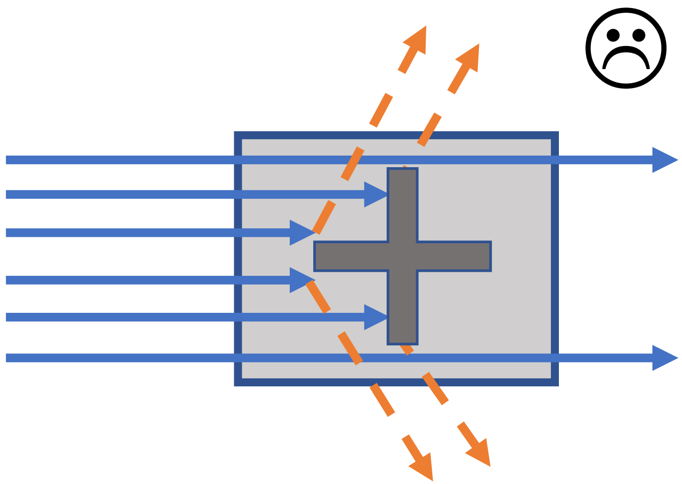

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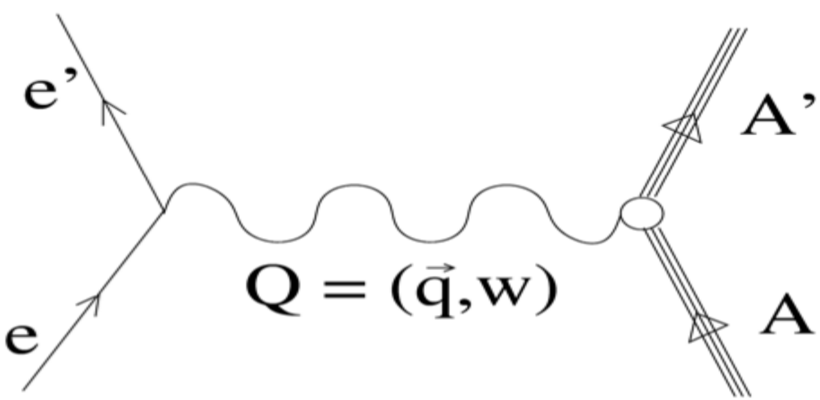

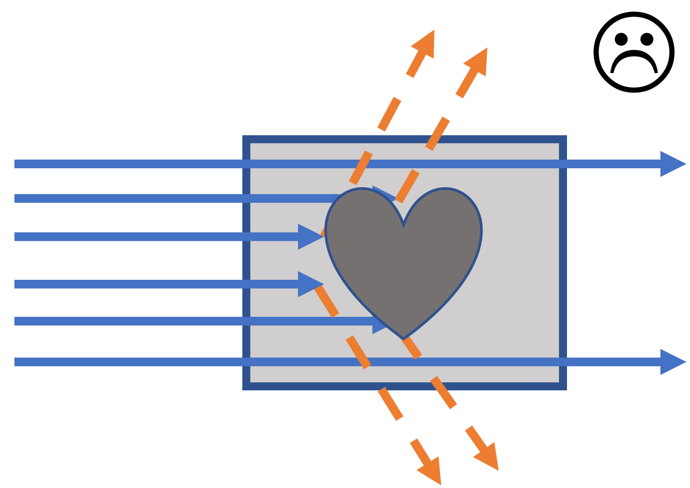

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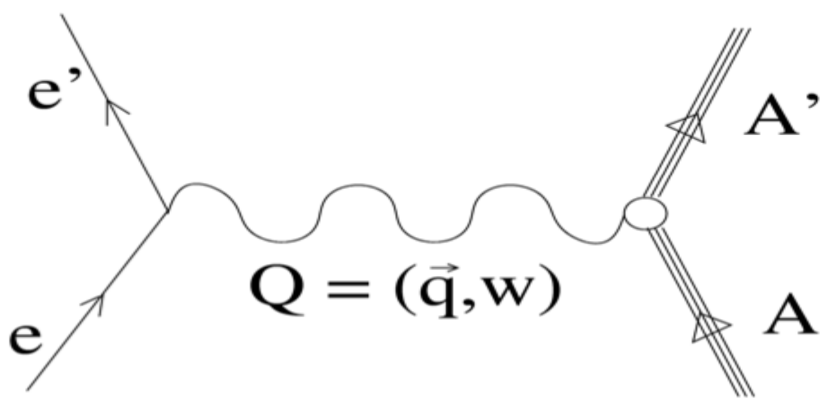
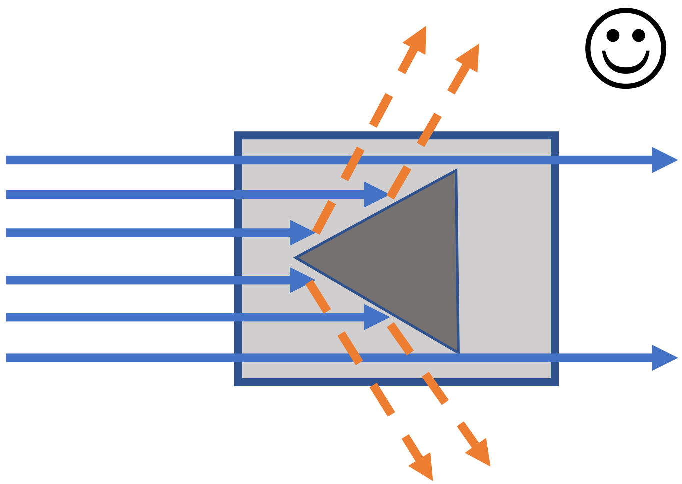


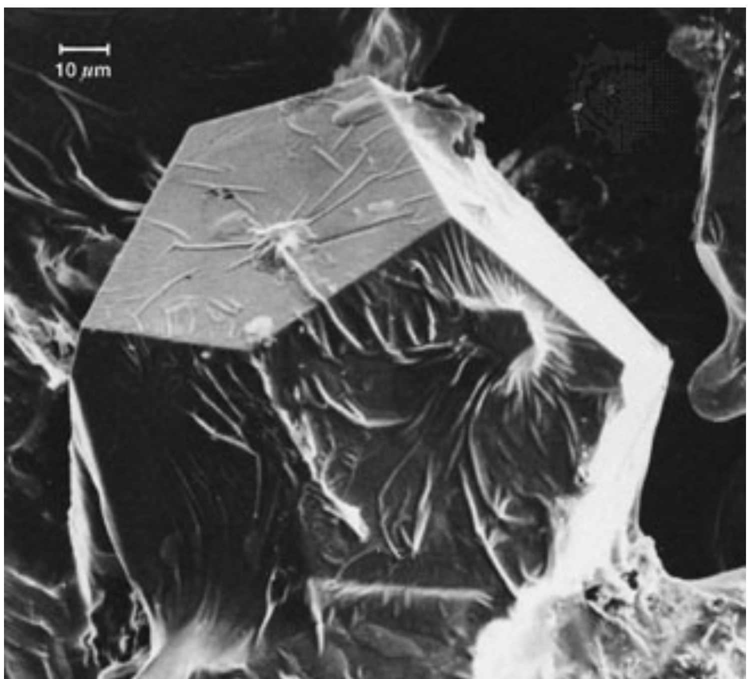


Electron Scattering: Nuclear Microscope

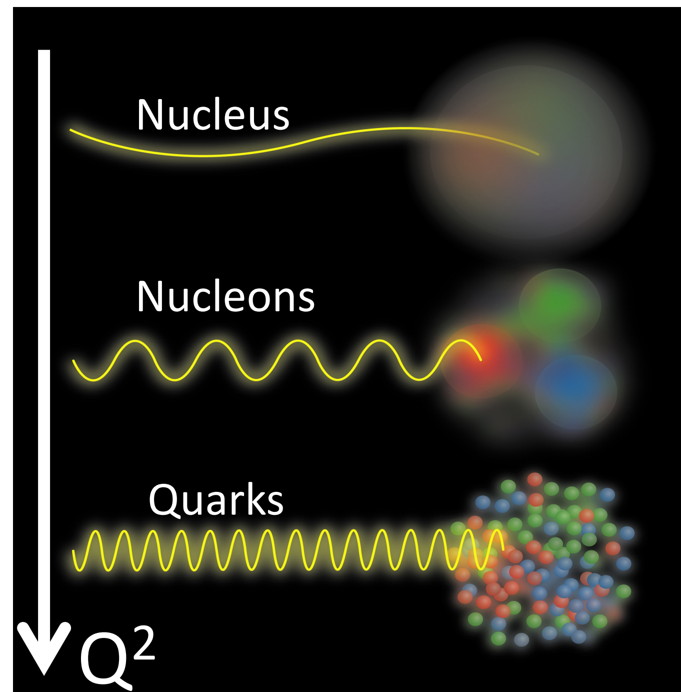
Goal: Study the internal structure (and dynamics) of complex objects

Means: using high energy lepton scattering

100s eV – 100s keV:
Material structure



100s MeV – 10s GeV:
Nuclear structure



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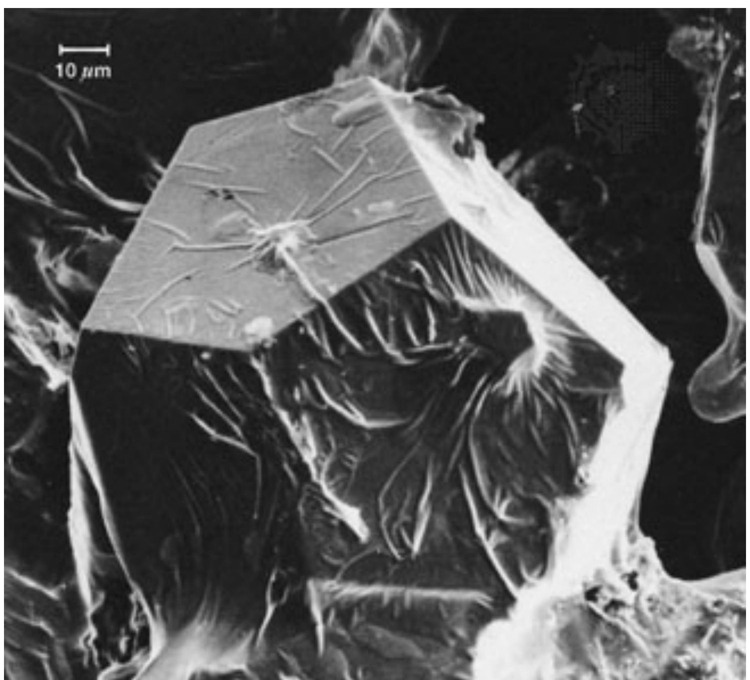
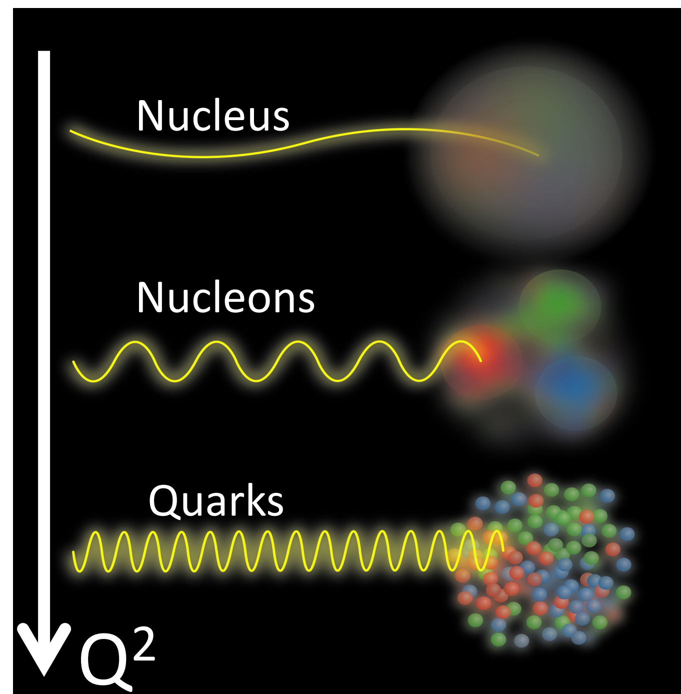


Energy
=
Resolution !

100s MeV – 10s GeV:
Nuclear structure



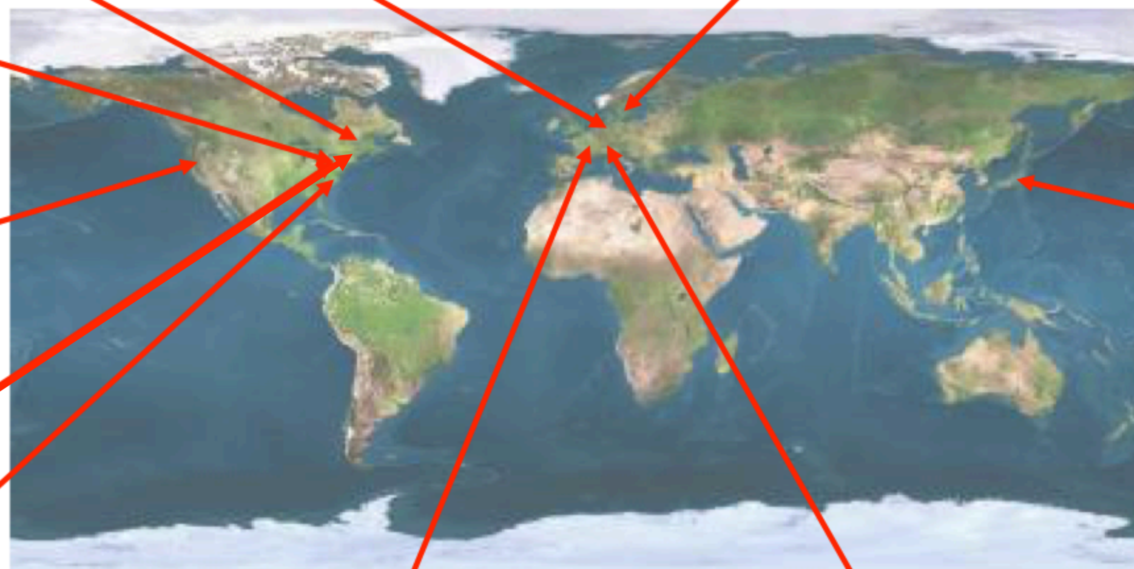
Worldwide Effort

LEGS
BNL
$E_{e-} = 2.8$ GeV

$E_{e-} = 27.5$ GeV
hermes

$E_{e-} = 0.15$GeV
MAX-lab

Jefferson Lab
$E_{e-} = 6$ GeV



SPring-8
$E_{e-} = 8$ GeV

Stanford Linear Accelerator Center
$E_{e-} = 25$ GeV

MIT (BATES)

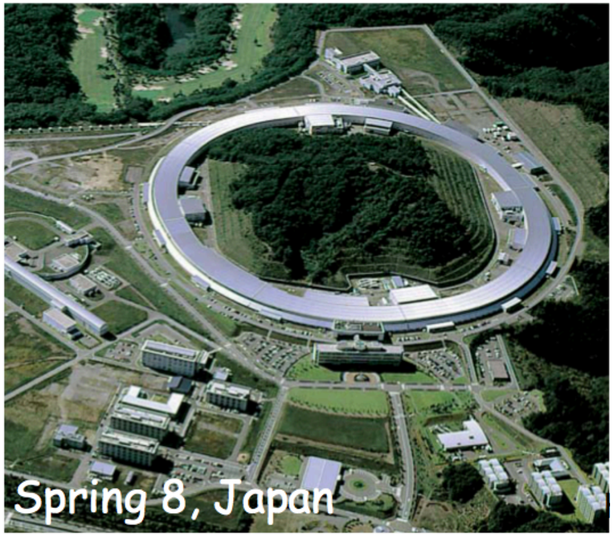
Duke University
Free Electron Laser Laboratory
H I γ S
$E_{e-} = 1.2$ GeV

ELSA
$E_{e-} = 3.5$ GeV

mami
MAINZER MIKROTRON
$E_{e-} = 1.5$ GeV

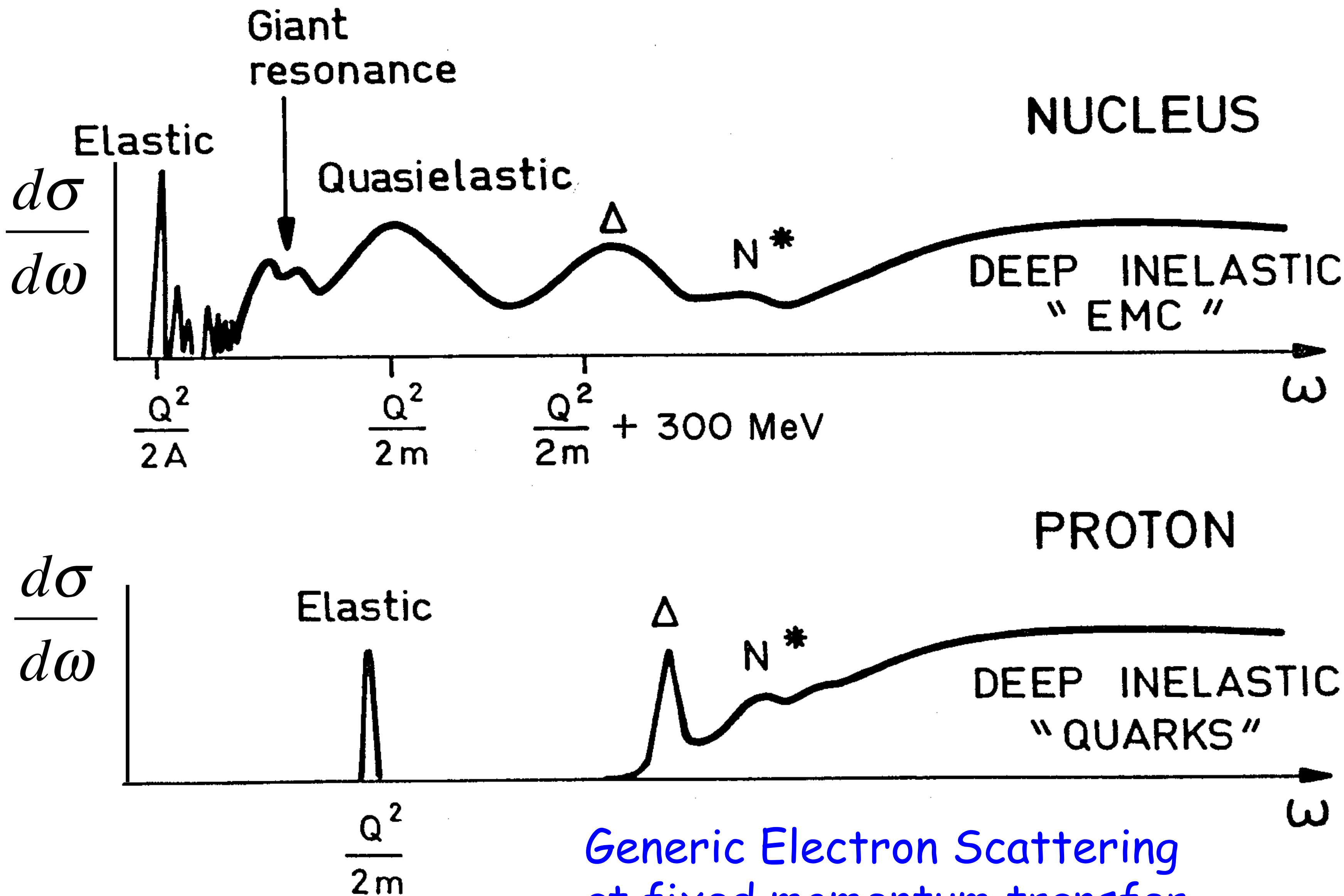
+ others... !

Postcard collection



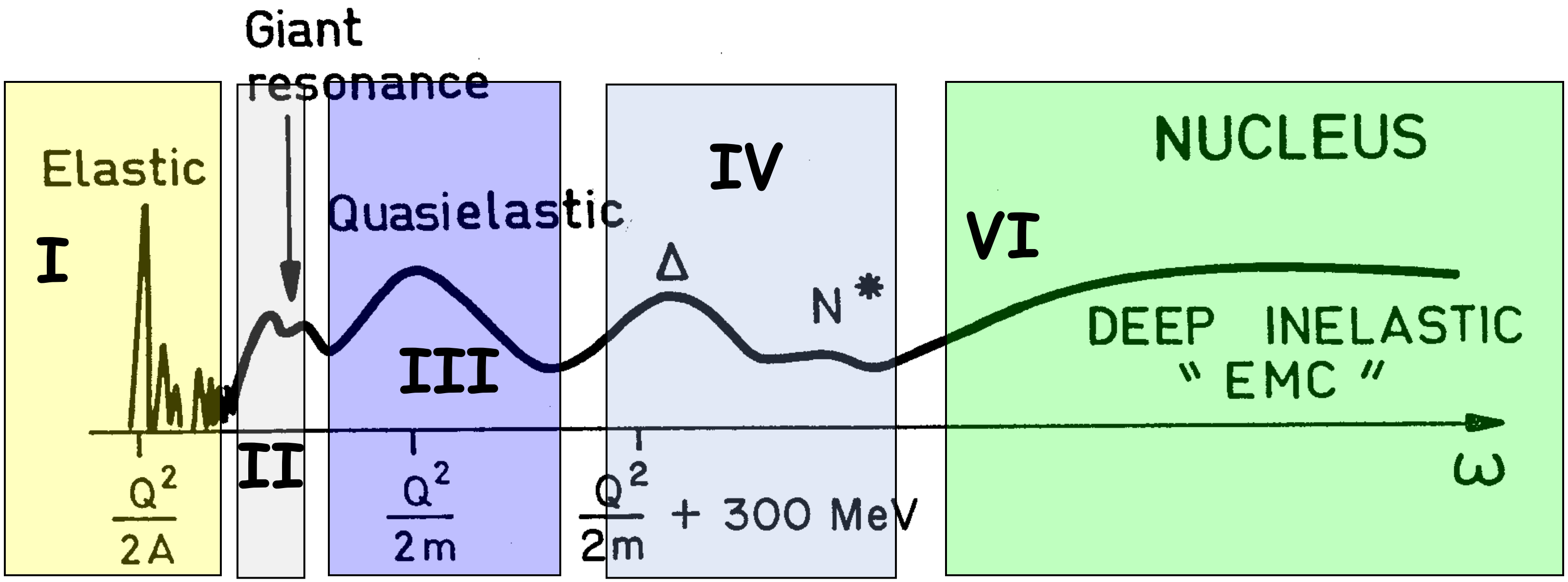
hysics Weinstein

(e,e'): Energy transfer defines physics

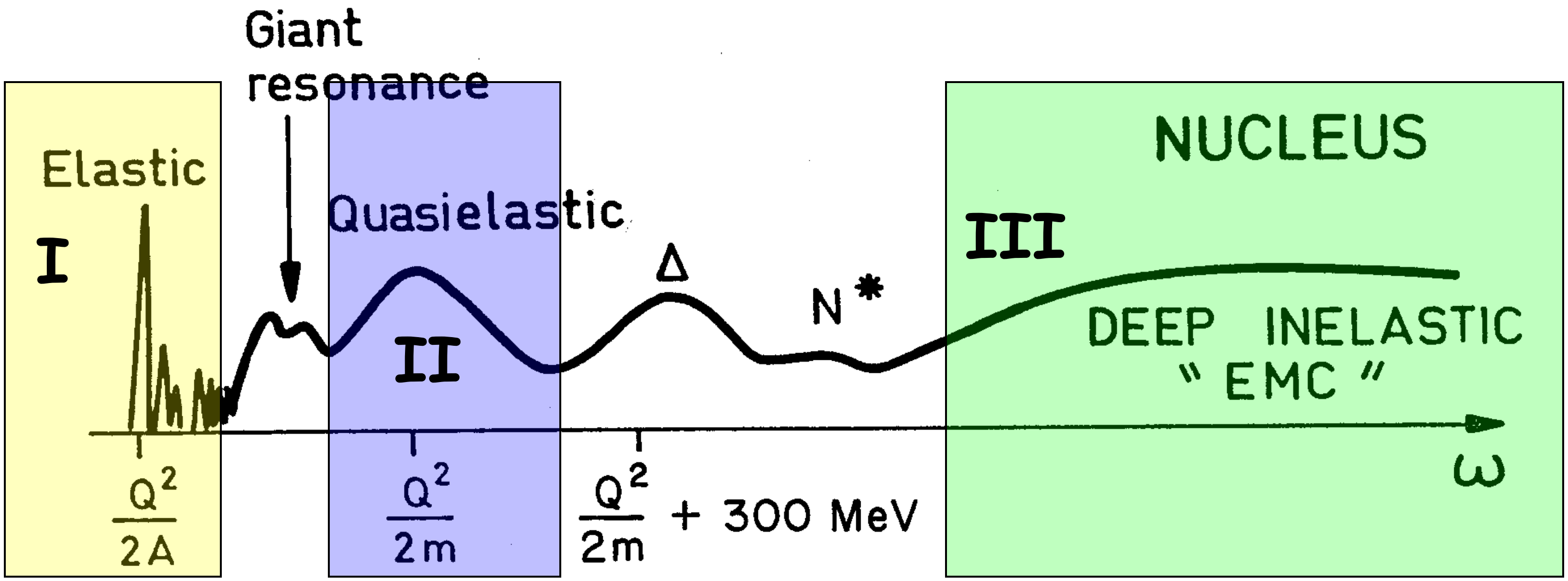


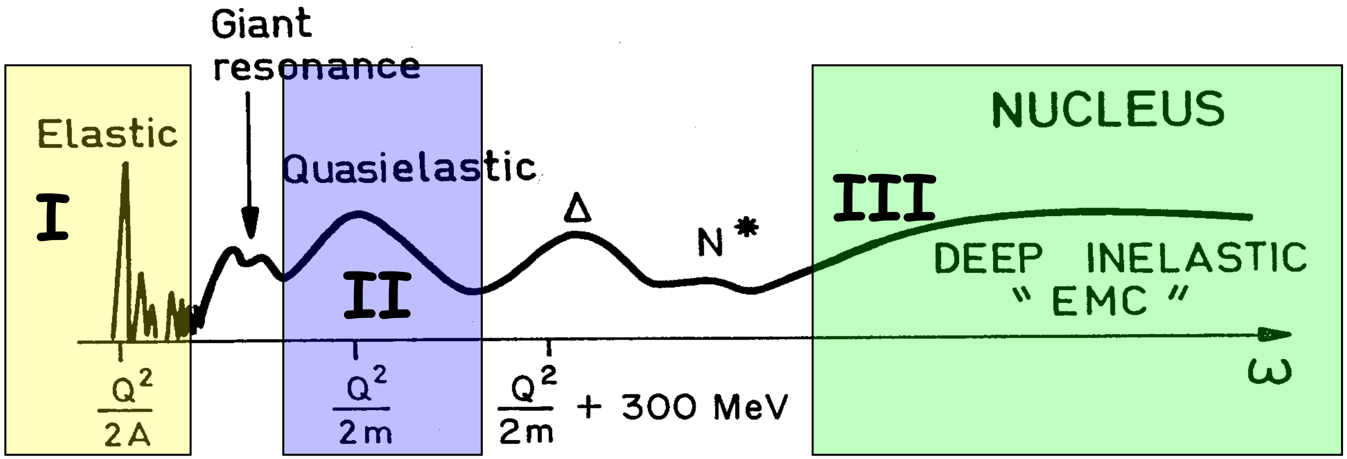
Generic Electron Scattering
at fixed momentum transfer

Everything is interesting...



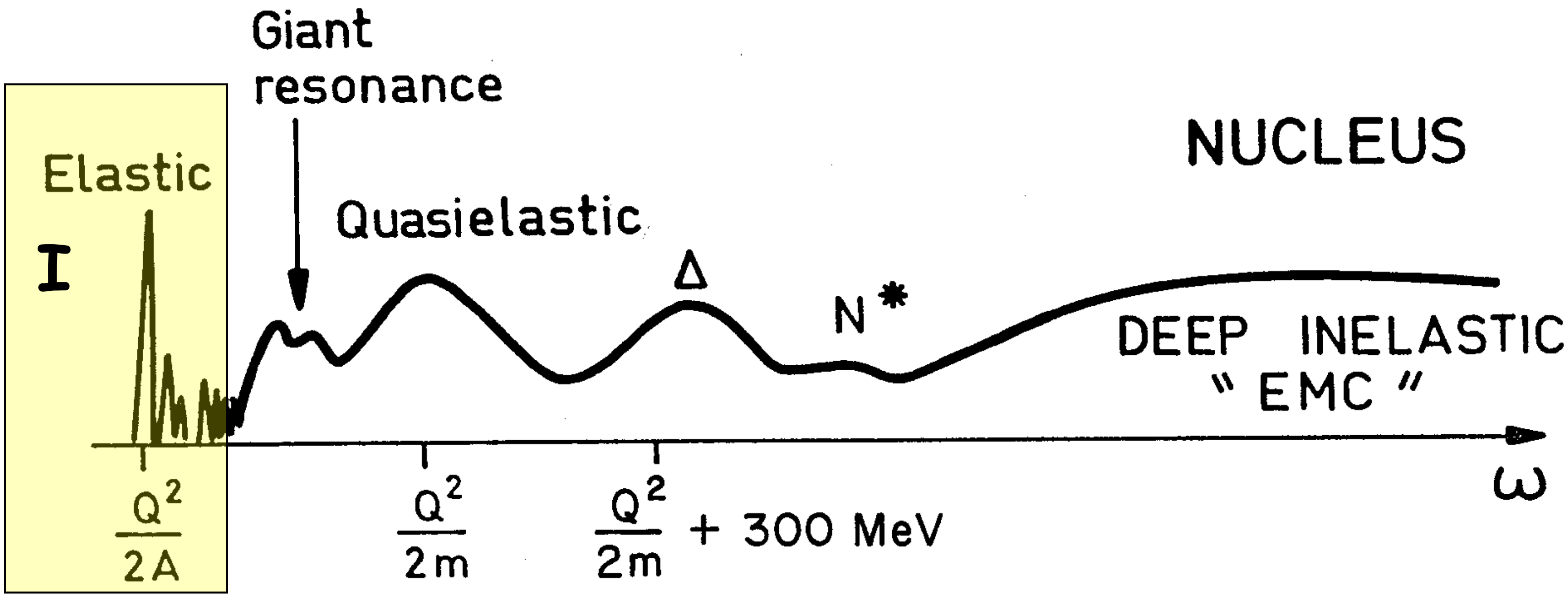
...But we will focus on 3 regions



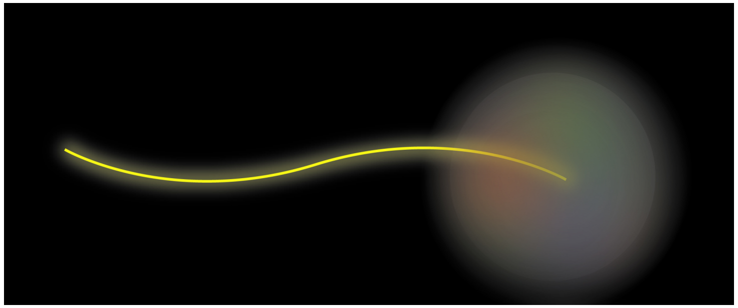


1. Elastic
   - structure of the nucleon / nucleus
     - Form factors, charge distributions, spin dependent FF
2. Quasielastic (QE)
   - Shell structure
     - Momentum distributions
     - Occupancies
   - Short Range Correlated nucleon pairs
   - Nuclear transparency and color transparency
3. Deep Inelastic Scattering (DIS)
   - The EMC Effect and Nucleon modification
   - Quark hadronization in nuclei

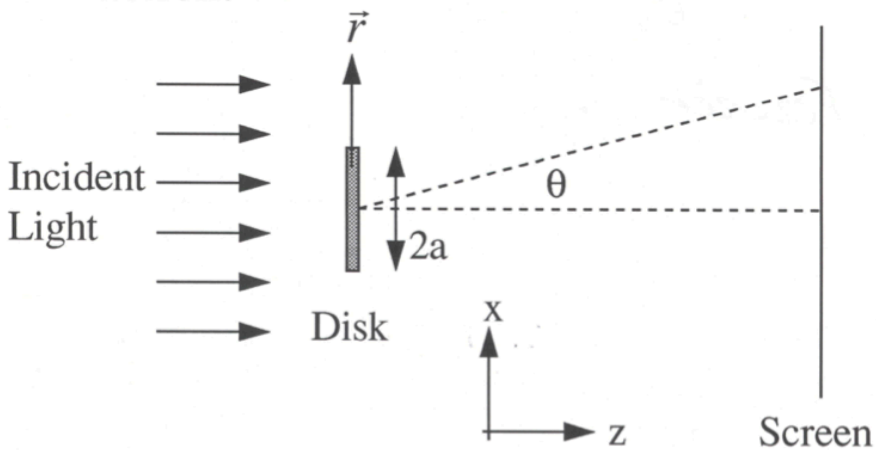
Quick Overview: Elastic

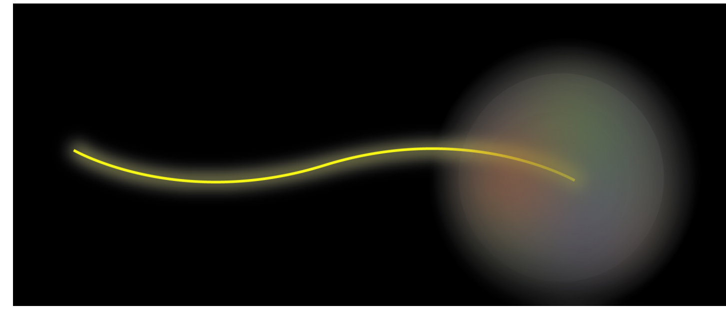


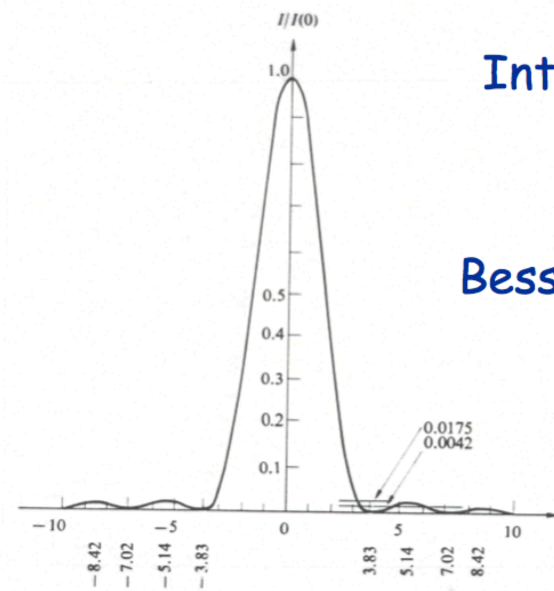
- Nuclear charge (proton) radius
- Nuclear Neutron radius
- Nucleon Form-Factors and charge densities



Diffraction Measurements of Small Radii







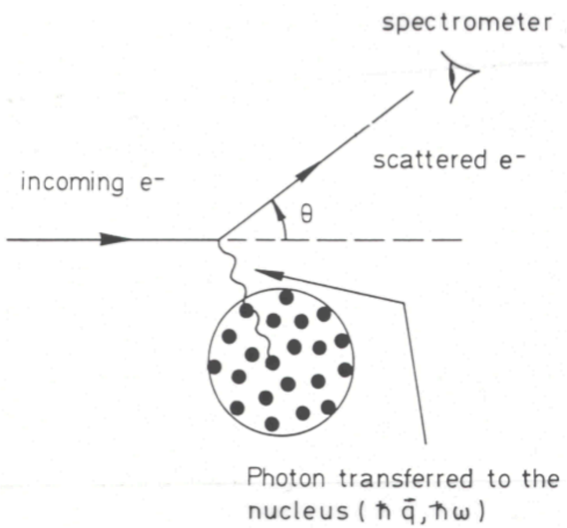
Intensity: $\Phi^2 \propto \left(\dfrac{J_1((2\pi a/\lambda)\sin\theta)}{\sin\theta} \right)^2$

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

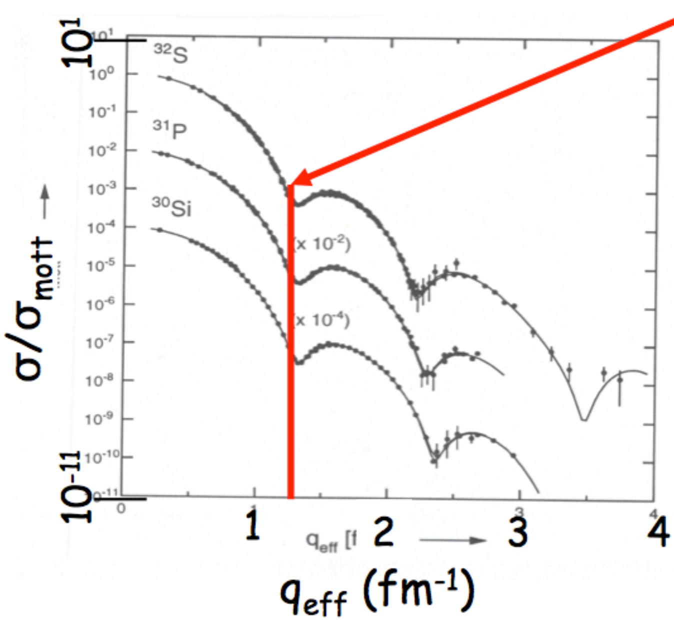
...some algebra...

Hence $2a \approx \dfrac{1.22\lambda}{\sin\theta}$

Diffraction Measurements of Small Radii



Cross Section ⇔ Charge Form Factor



1st minimum = 1.3 fm^{-1}

➔ $\theta = 32.8°$

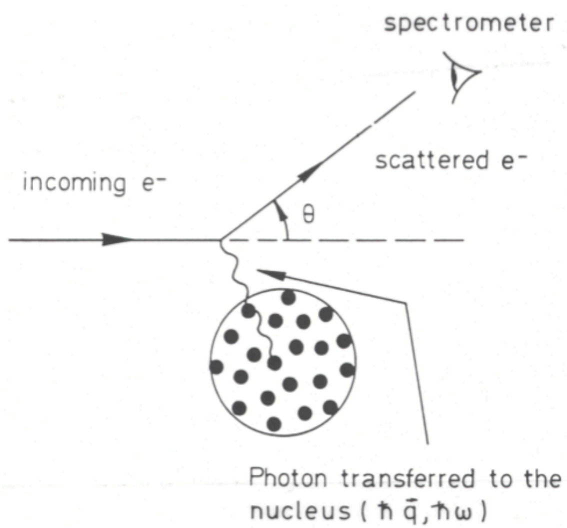
Electron energy = 454.3 MeV

➔ $\lambda = 2.73$ fm

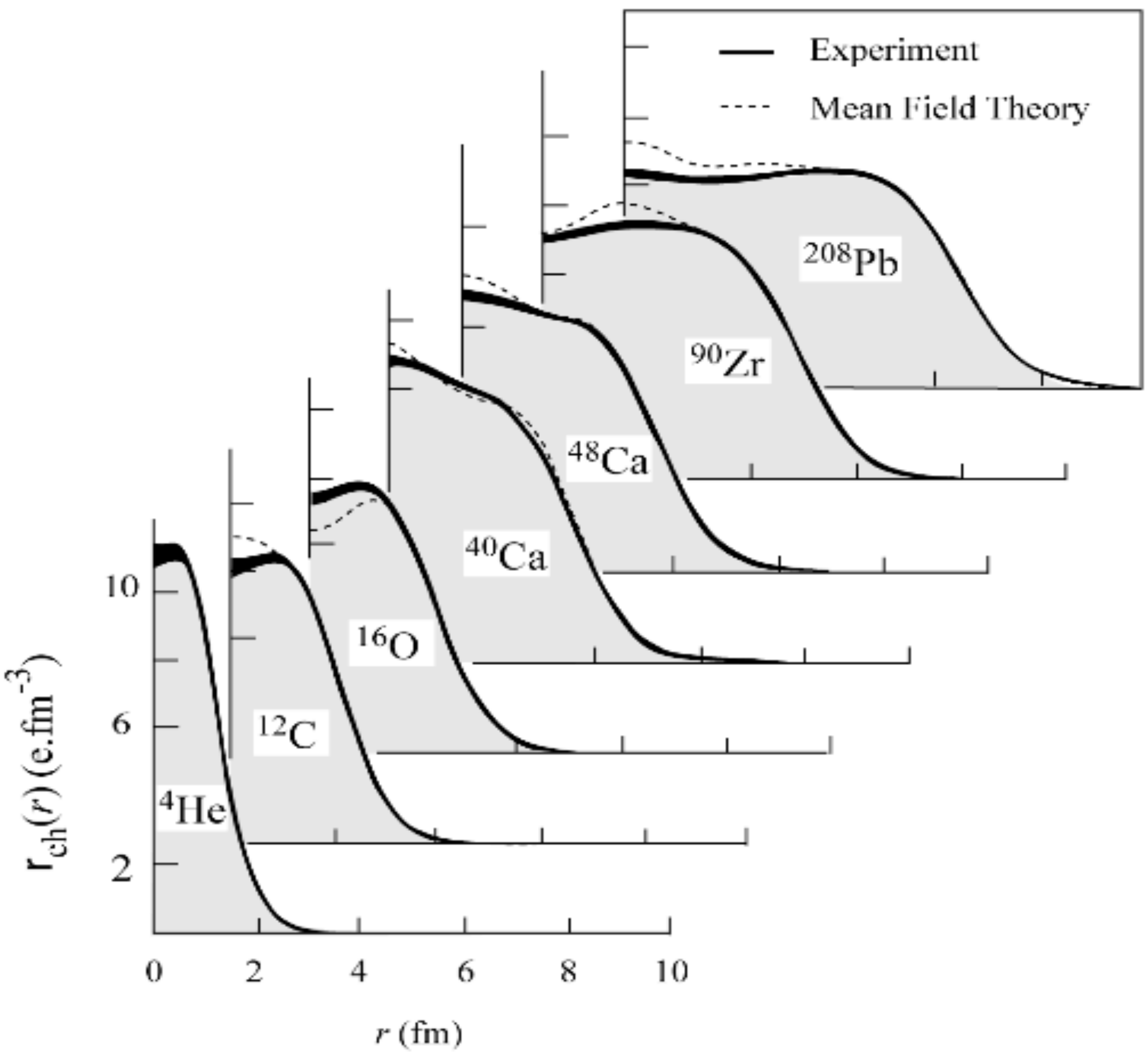
Calculated radius = 3.07 fm

Measured rms radius = 3.19 fm

Diffraction Measurements of Small Radii



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



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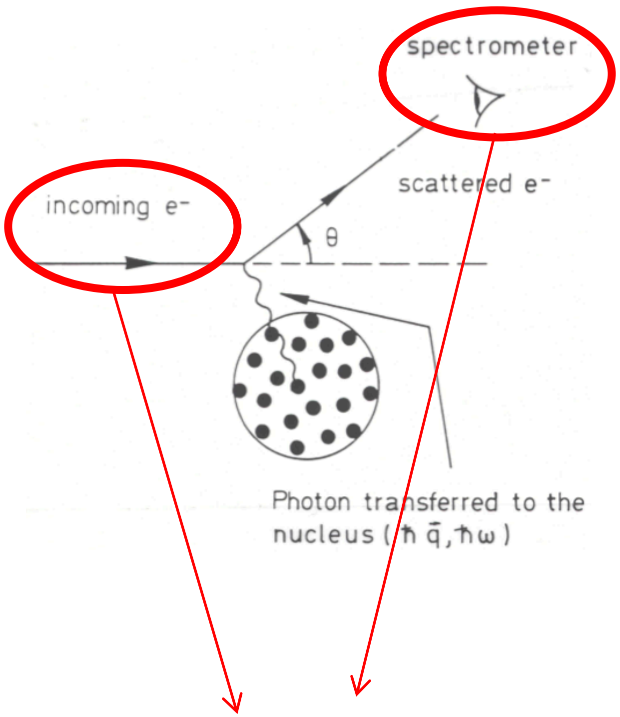
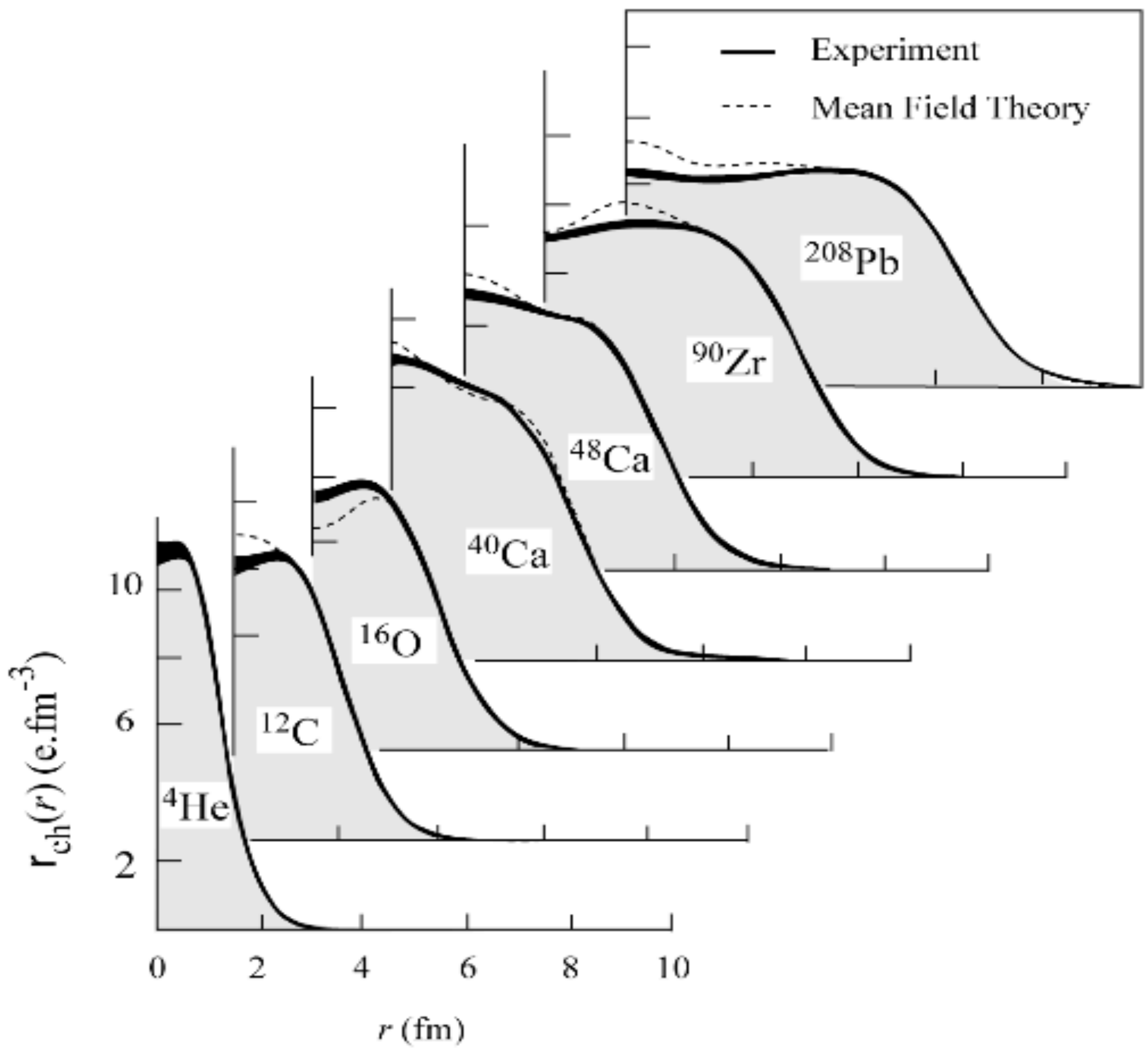


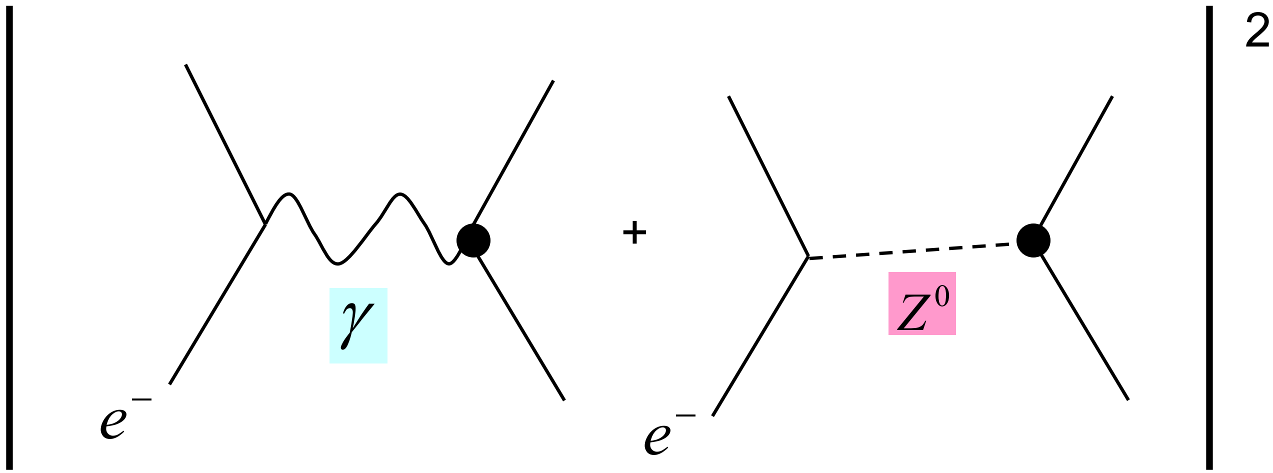
10s – 100s Million Dollar Machines



Weak Interaction: Neutron Distribution

Parity Violating Asymmetry

$\sigma \approx$



Applications of PV at Jefferson Lab

- Nucleon Structure (strangeness) -- HAPPEX / G0
- Standard Model Tests ($\sin^2\theta_W$) -- e.g. Qweak
- *Nuclear Structure (neutron density)* : *PREX*

Weak Interaction: Neutron Distribution

Z^0 of Weak Interaction:

Clean Probe Couples Mainly to Neutrons

$F_W(Q^2)$: ^{208}Pb
Weak Form Factor

$$A = \frac{\left(\frac{d\sigma}{d\Omega}\right)_R - \left(\frac{d\sigma}{d\Omega}\right)_L}{\left(\frac{d\sigma}{d\Omega}\right)_R + \left(\frac{d\sigma}{d\Omega}\right)_L} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_W(Q^2)}{F_P(Q^2)} \right]$$

$F_p(Q^2)$: ^{208}Pb
Charge Form Factor

Clean Probe Couples Mainly to Neutrons

	proton	neutron
Electric charge	1	0
Weak charge	0.08	1

Weak Interaction: Neutron Distribution

Z^0 of Weak Interaction:
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$F_p(Q^2)$: ^{208}Pb
Charge Form Factor

Clean Probe Couples Mainly to Neutrons

	proton	neutron
Electric charge	1	0
Weak charge	0.08	1

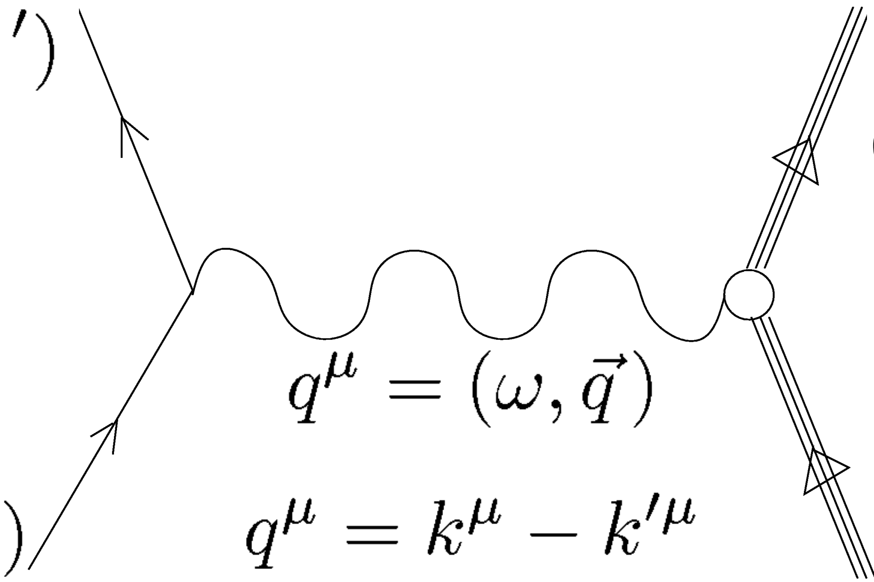
High Accuracy:

$$\frac{dA}{A} = 3\% \quad \rightarrow \quad \frac{dR_n}{R_n} = 1\%$$

R_n = neutron matter radius

From Intuition to Formalism

Lab frame kinematics



Invariants:

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

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

From Intuition to Formalism (Elastic)

Recoil factor

Form factors

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

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

$$= \sigma_M \frac{E'}{E}\left[\frac{Q^4}{\vec{q}^{\,4}} R_L(Q^2) + \left(\frac{Q^2}{2\vec{q}^{\,2}} + \tan^2\frac{\theta}{2}\right) R_T(Q^2)\right]$$

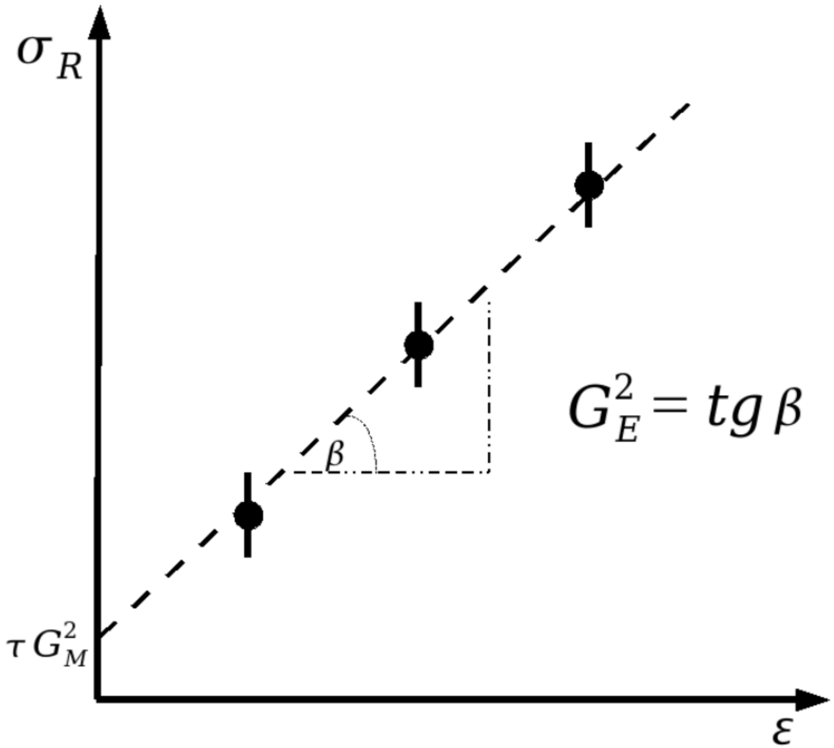
Mott cross section: $\sigma_M = \dfrac{\alpha^2 \cos^2\left(\frac{\theta_e}{2}\right)}{4E^2 \sin^4\left(\frac{\theta_e}{2}\right)}$

nucleons:

- F_1, F_2: Dirac and Pauli form factors
- G_E, G_M: Sachs form factors (electric and magnetic)
  - $G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2)$ $\tau = Q^2/4M^2$
  - $G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$ (more standard definition of F_1 and F_2)
- R_L, R_T: Longitudinal and transverse response fn

Form Factors: Cross-Sections

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



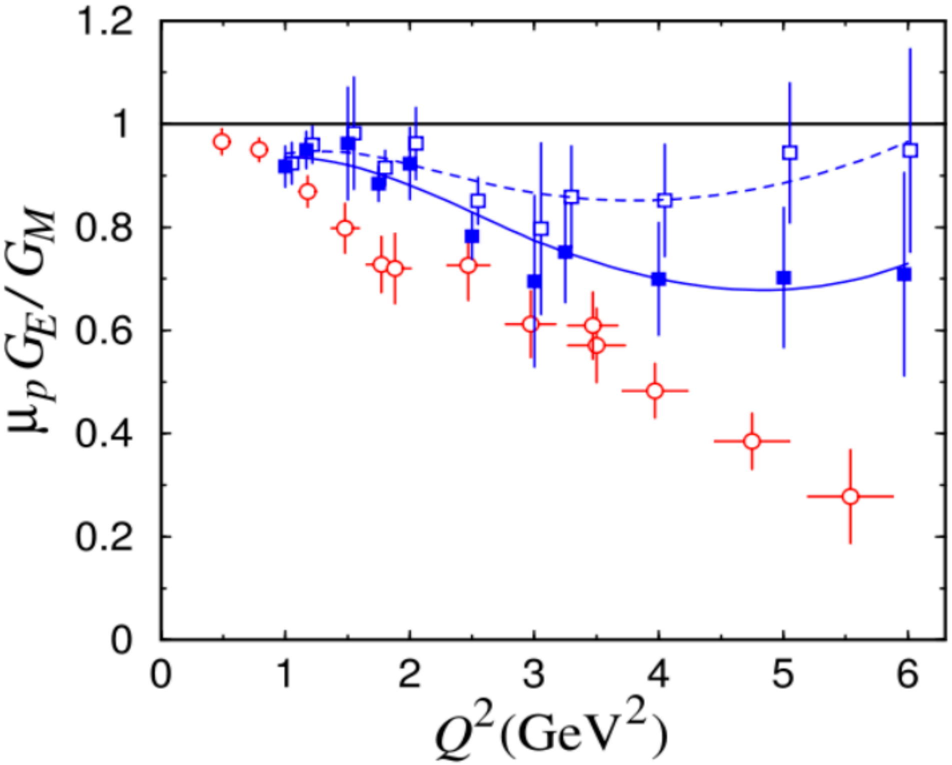
See D. Higinbotham talk

Form Factors: Polarization Transfer

$$I_0 P_x = -2\sqrt{\tau(1+\tau)}\, G_E G_M \tan(\theta/2)$$

$$I_0 P_z = \frac{1}{M}(E-E')\sqrt{\tau(1+\tau)}\, G_M^2 \tan^2(\theta/2)$$

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



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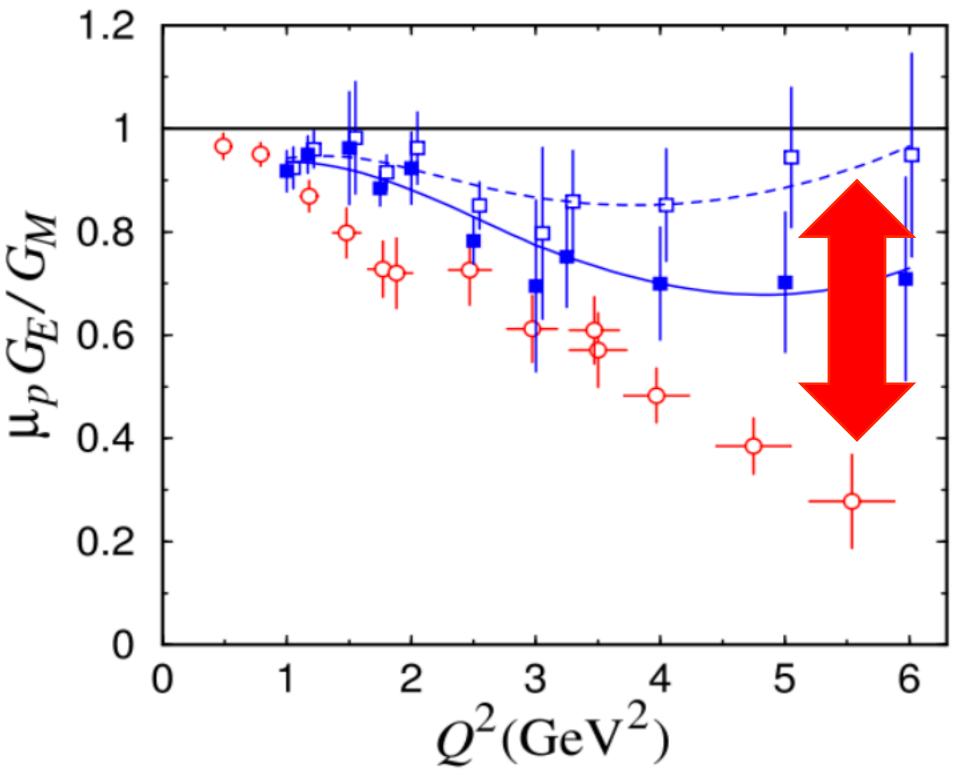
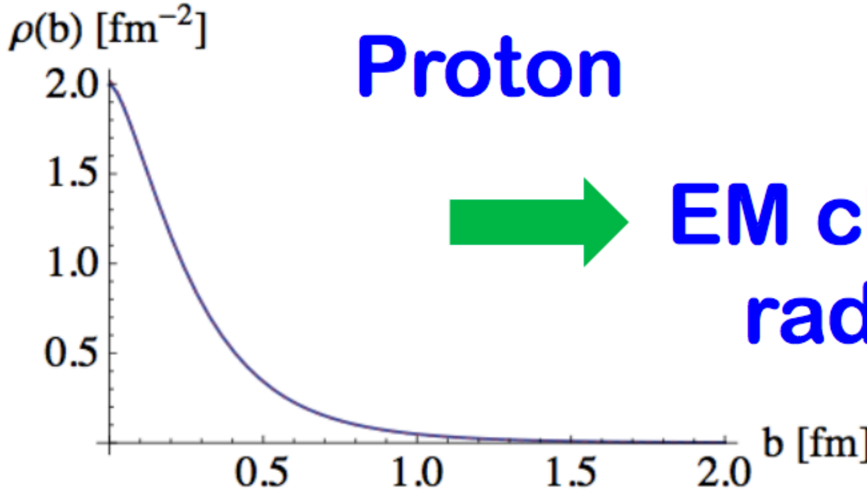


LARGE Discrepancy!

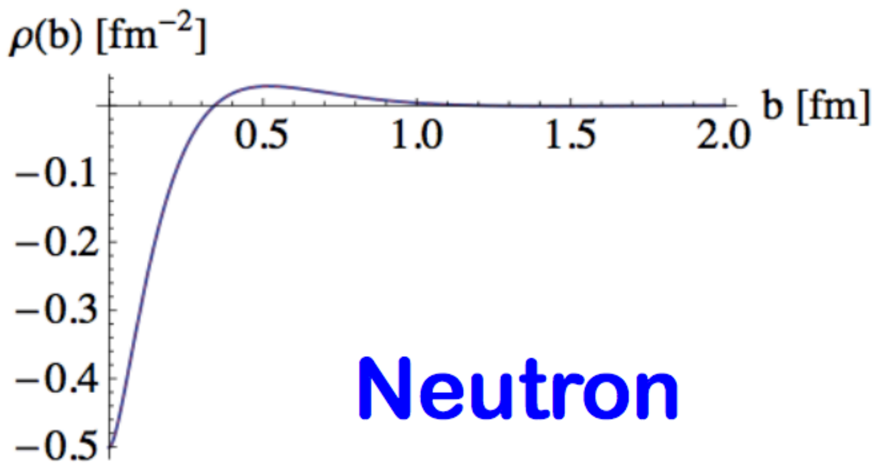
(2 photon exchange? More on this if we have time at the end)

Electric charge distribution

Proton

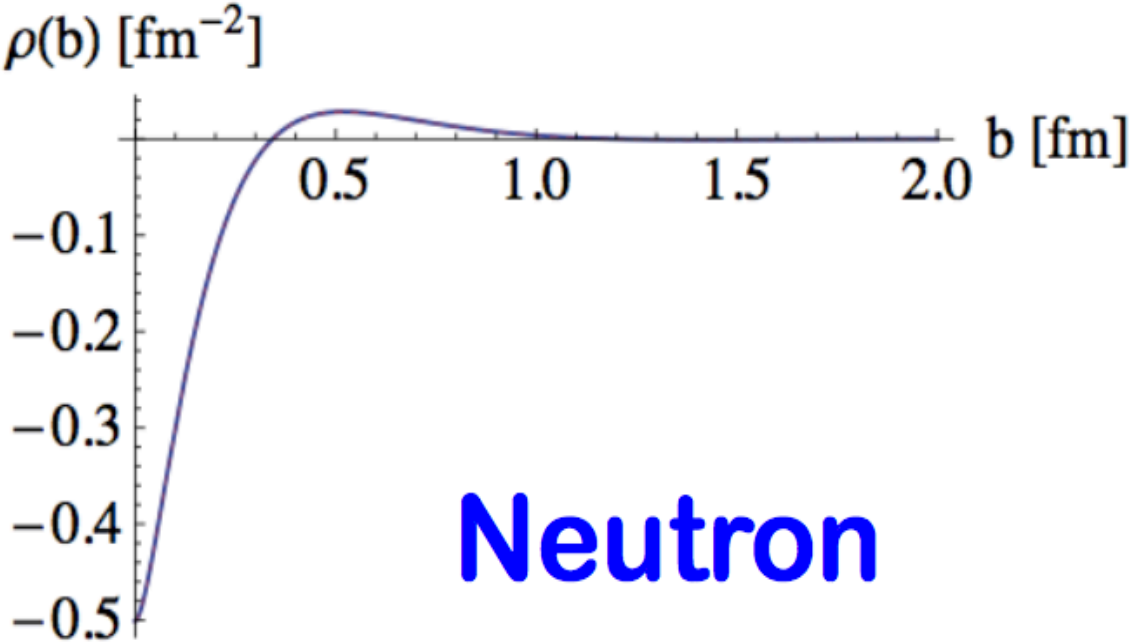


EM charge radius!

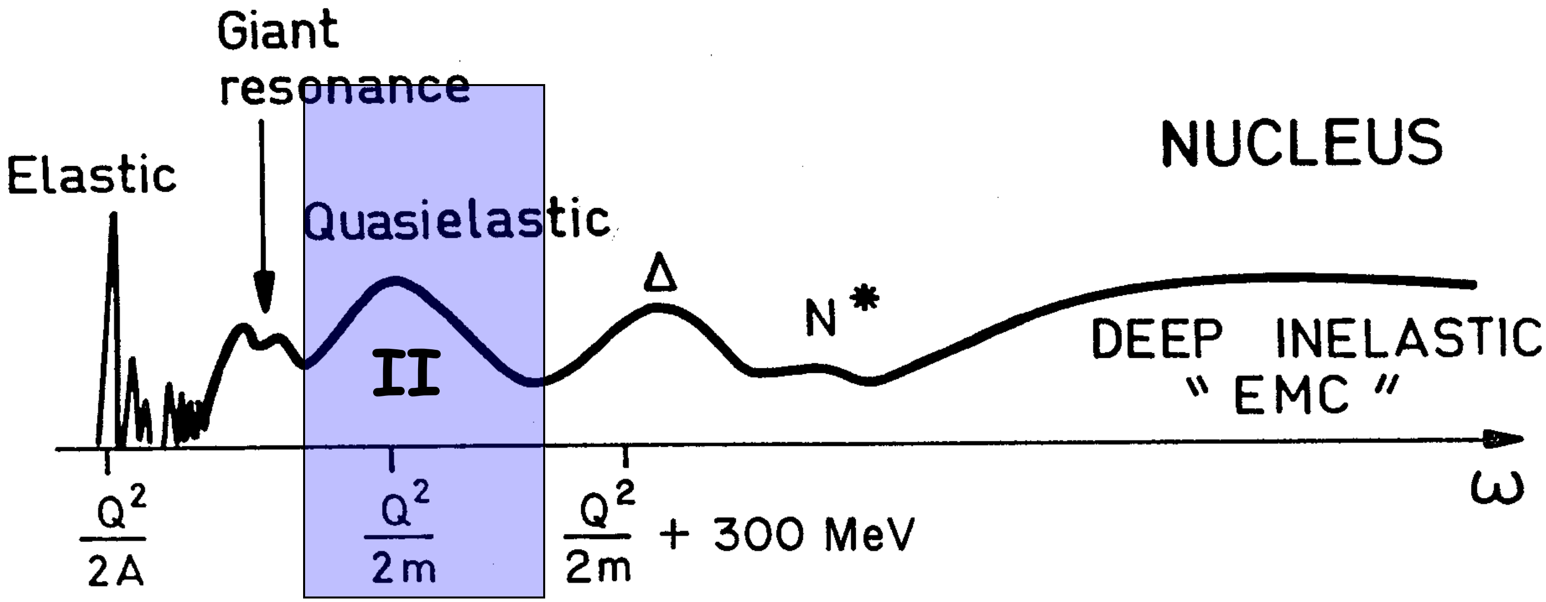


Neutron

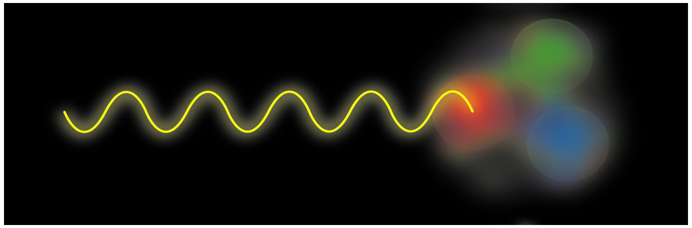
Neutron is negative in its center and positive in the edge!!!



Quick Overview: Quasi-Elastic

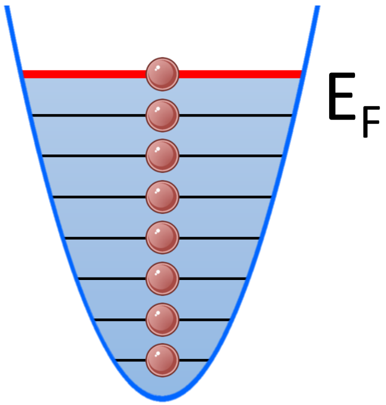


- Momentum Densities: Fermi Gas
- Y-Scaling
- Shell Structure and spectroscopic factors



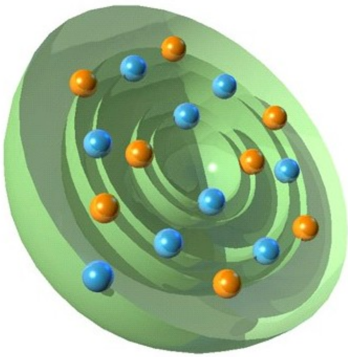
What is a Nucleus ?

Fermi Gas Model

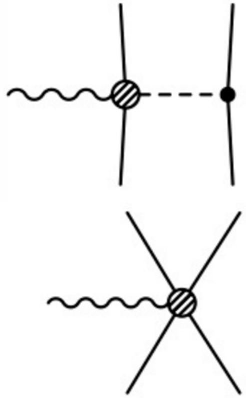


Liquid Drop Model

Shell Model



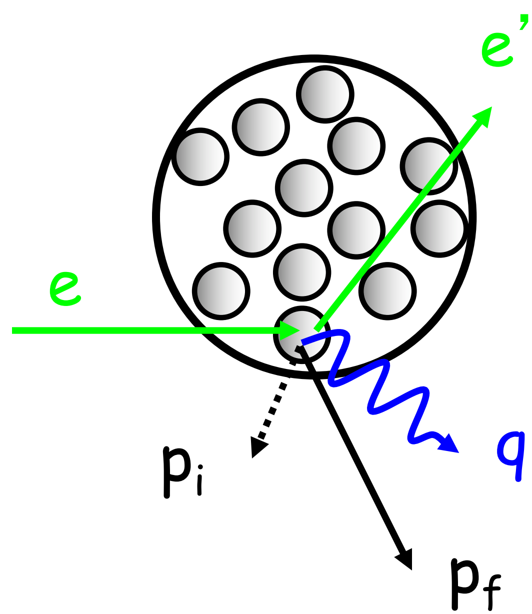
Chiral Perturbation Theory*



* Should converge to exact solution

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 = $Z\sigma_{ep} + N\sigma_{en}$

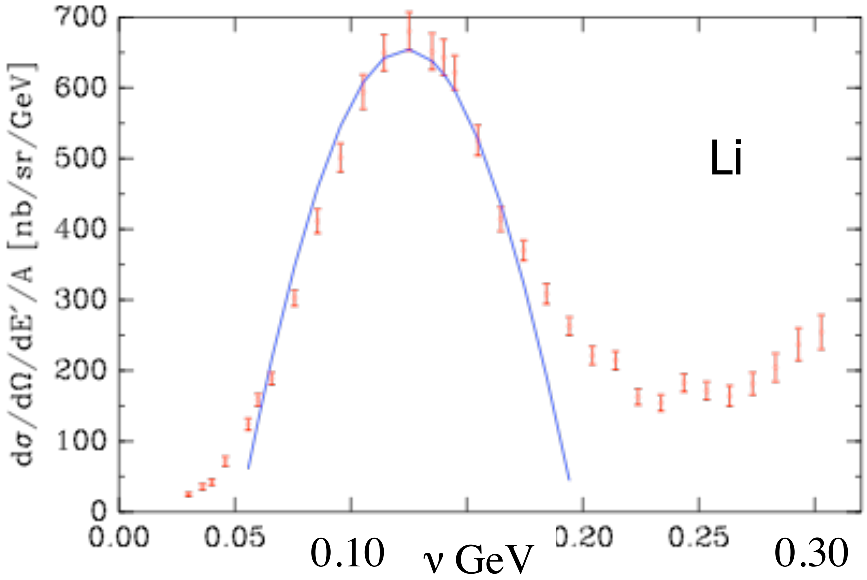
Early 1970's Quasielastic Data

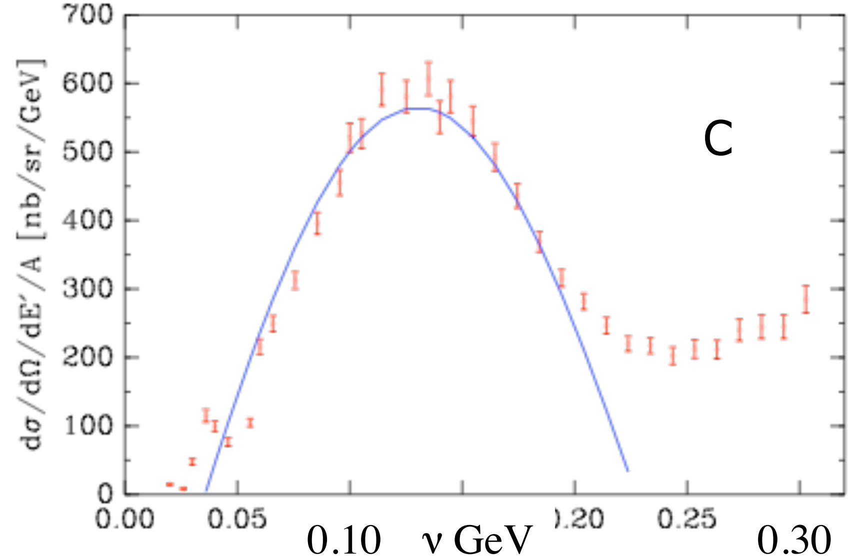
-> getting the bulk features

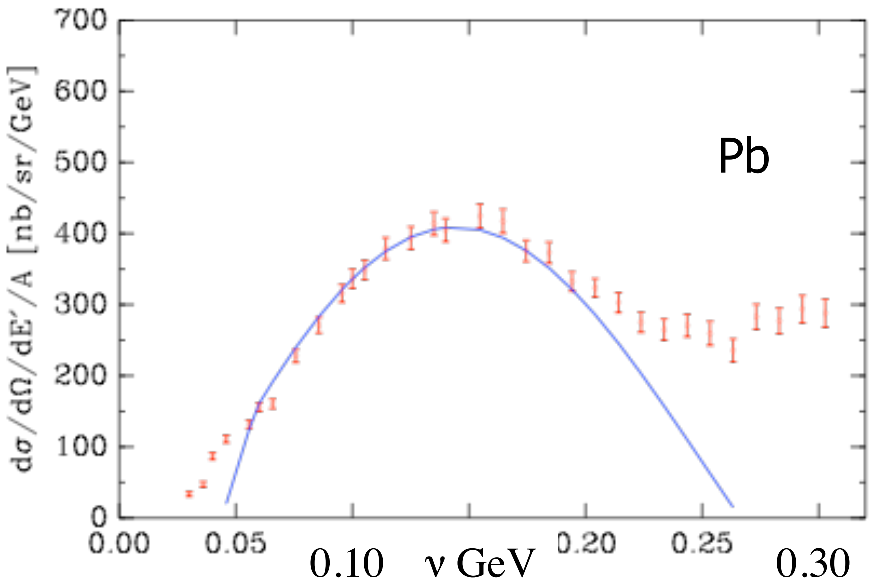
500 MeV, 60 degrees

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

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







Nucleus	k_F MeV/c	$\overline{\epsilon}$ 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

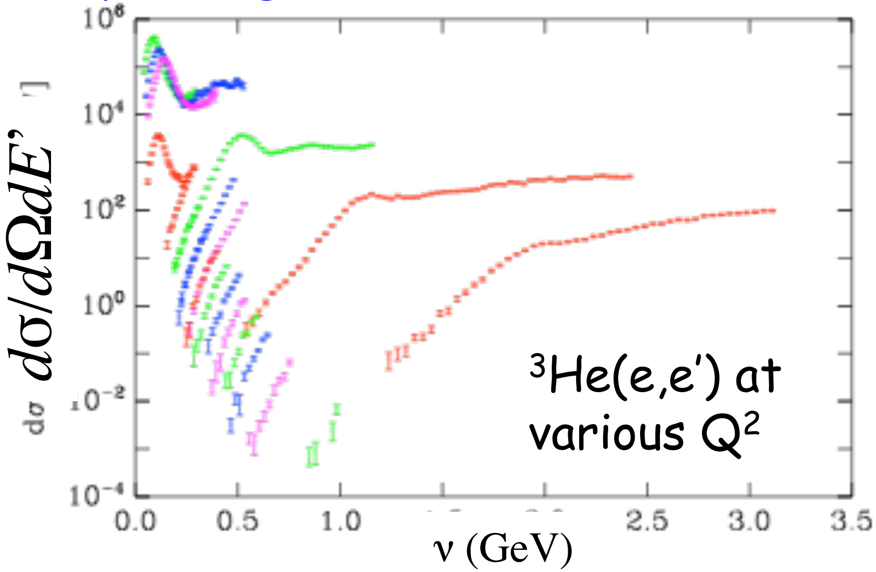
Scaling

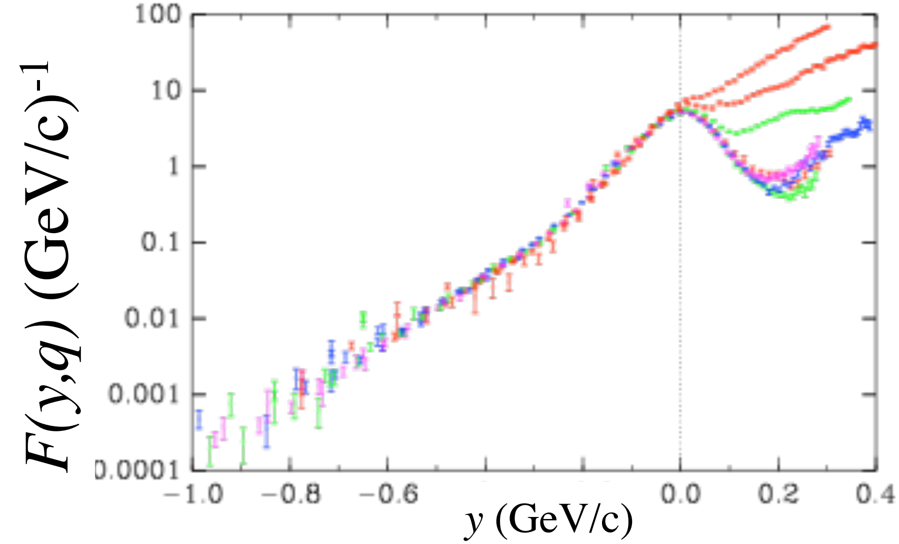
- The dependence of a cross section, in certain kinematic regions, on a single variable.
  - scaling validates the scaling assumption.
  - Scale-breaking indicates new physics.

- 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 ^3He





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

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

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)

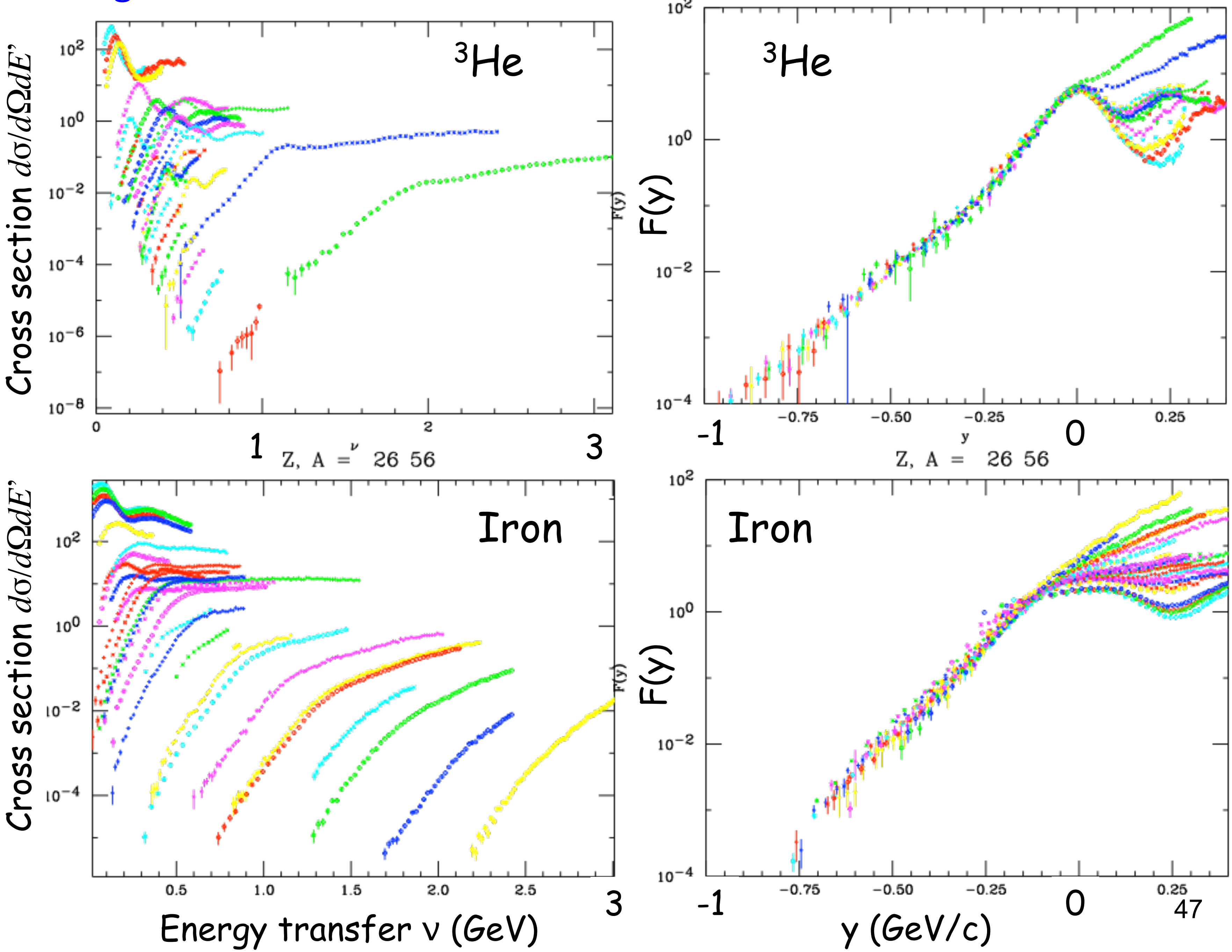
IF the scattering is quasifree, then $F(y)$ is the integral over all perpendicular nucleon momenta (nonrelativistically).

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

Assumptions & Potential Scale Breaking Mechanisms

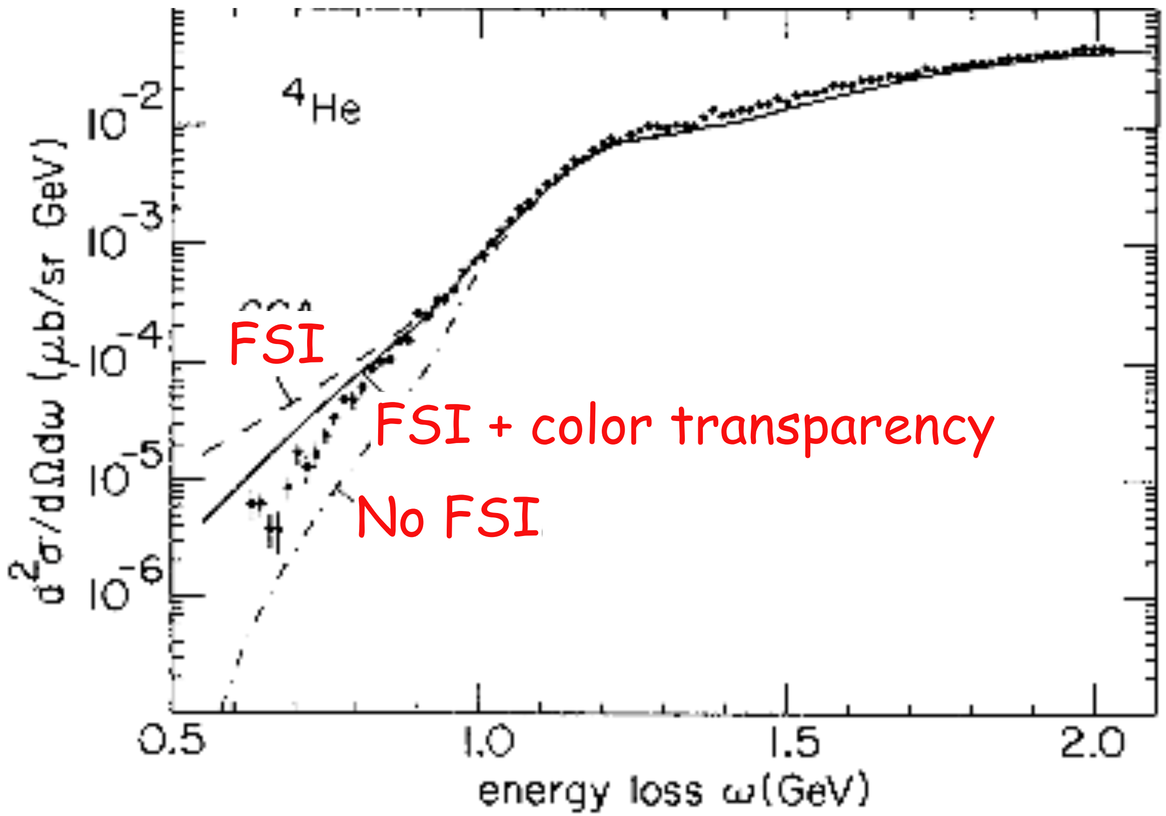
- No Final State Interactions (FSI)
- No internal excitation of (A-1)
- Full strength of Spectral function can be integrated over at finite *q*
- No inelastic processes (choose $y<0$)
- No medium modifications (discussed later)

Y-scaling works!



Final State Interactions (FSI) complicate this simple picture

$^4He(e,e')$ at 3.595 GeV, 30°

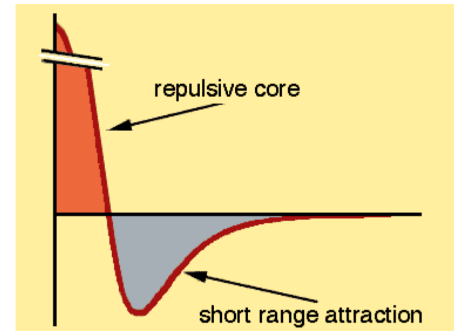


Benhar et al. PRC 44, 2328
Benhar, Pandharipande, PRC 47, 2218
Benhar et al. PLB 3443, 47

But what about the Shell Model?

- Many-Body Hamiltonian:

$$H = \sum_{i=1}^{A} \frac{p^2}{2m_N} + \sum_{i<j=1}^{A} v_{2body}(i,j) + \sum_{i<j<k=1}^{A} v_{3body}(i,j,k) + \ldots$$

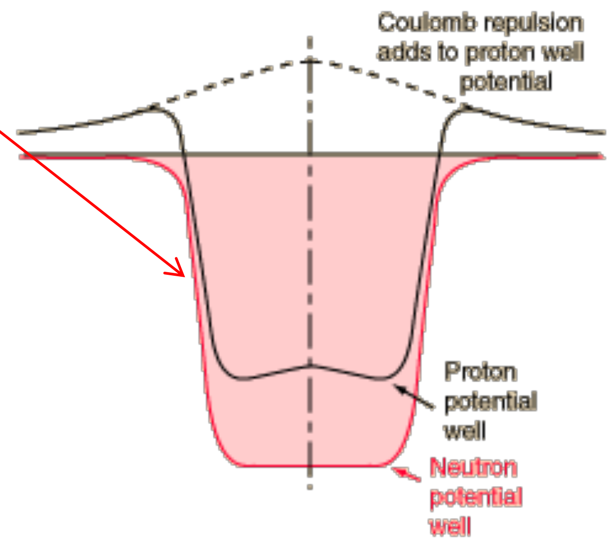


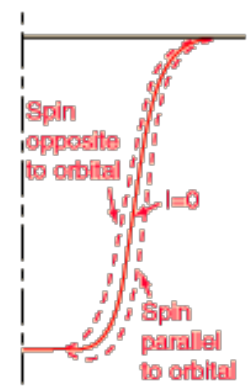
- Mean-Field Approximation:

$$H = \sum_{i=1}^{A} \frac{p^2}{2m_N} + \sum_{i=1}^{A} V(i)$$

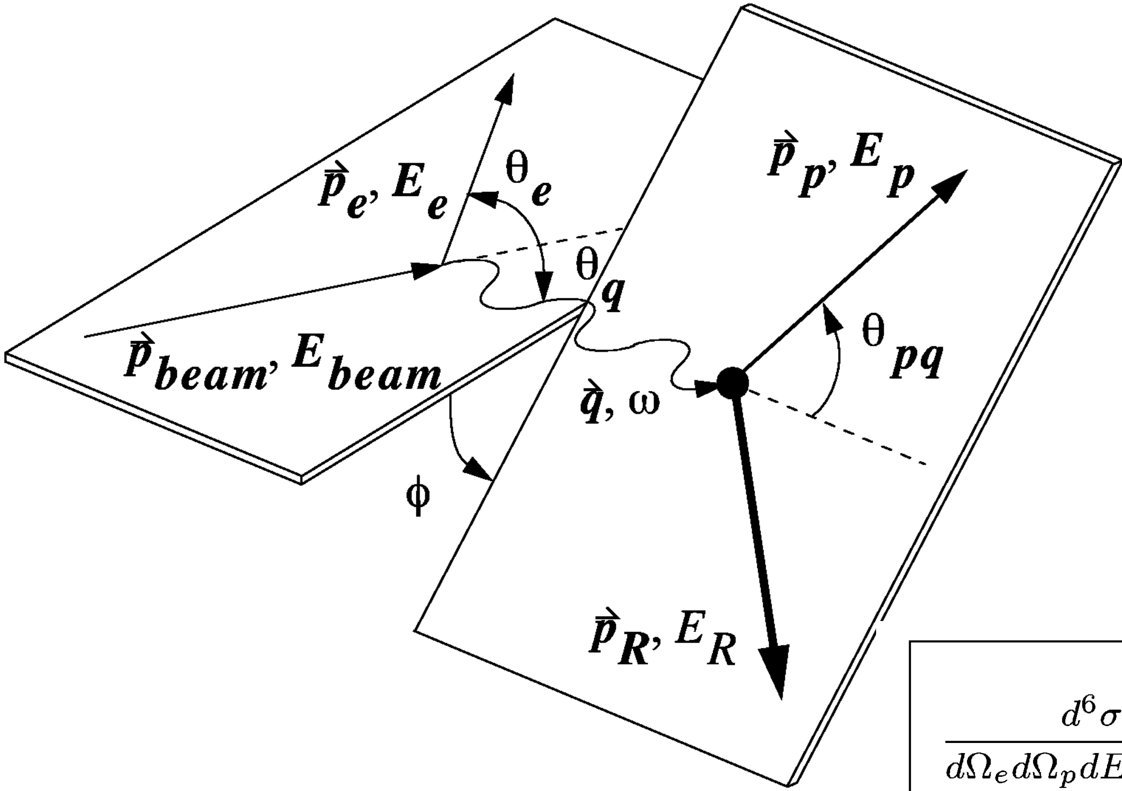
Results in an “atom-like” shell model:

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





E. Wigner, M. Mayer, and J. Jenson, 1963 Nobel Prize



(e,e'p) Spectroscopy

$$\frac{d^6\sigma}{d\Omega_e d\Omega_p dE_{\text{miss}} d\omega} = K\sigma_{\text{Mott}} \left[\, v_L \mathbf{R_L} + v_T \mathbf{R_T} + v_{LT} \mathbf{R_{LT}} \cos(\phi) + v_{TT} \mathbf{R_{TT}} \cos(2\phi) \,\right]$$

where

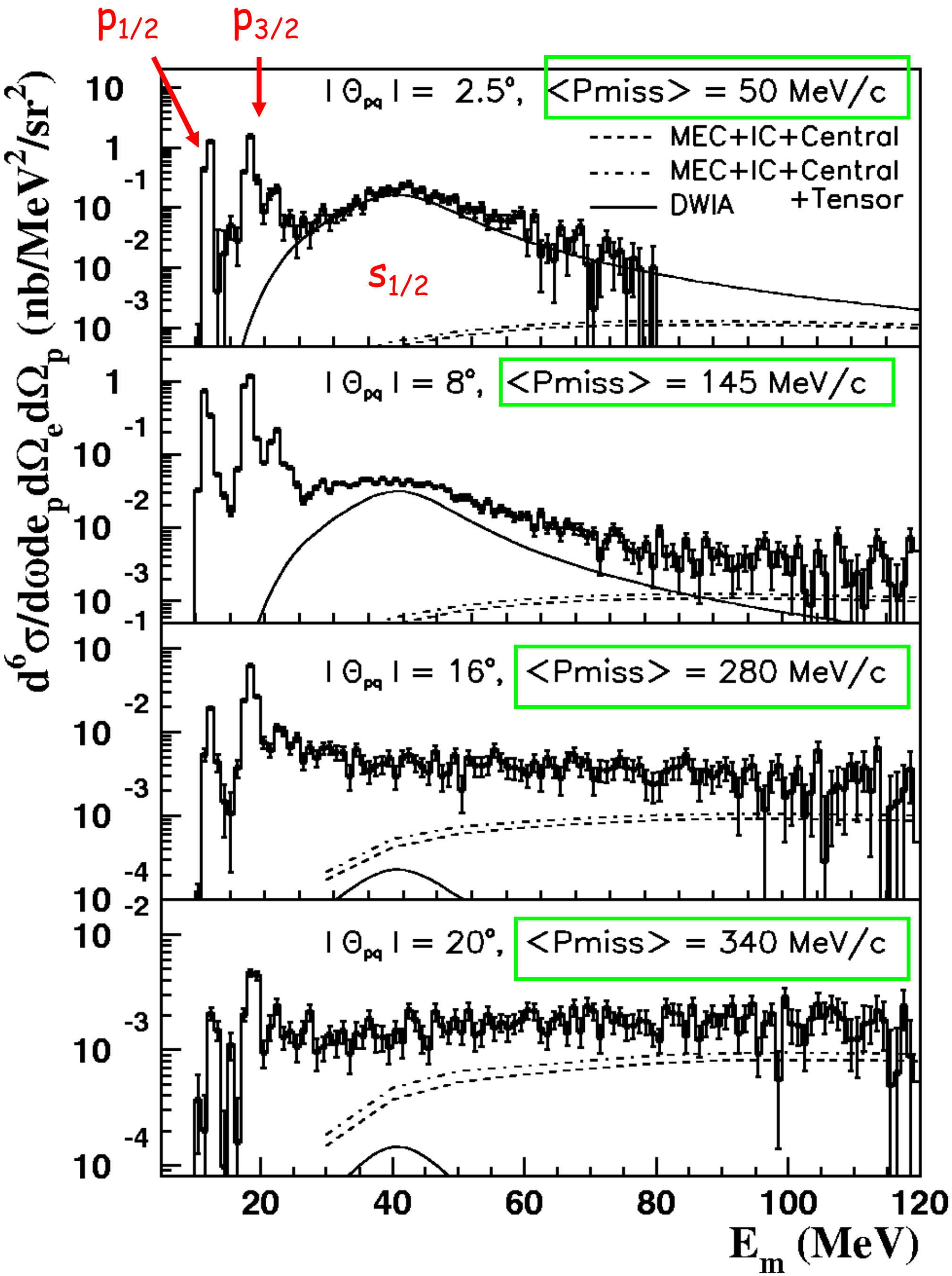
$$K = \text{(phase space)}$$
$$\sigma_{\text{Mott}} = \text{(relativistic Rutherford scattering)}$$
$$v = v\ (q,\omega)\ \text{(electron kinematics)}$$

And then there were four (response functions, that is)

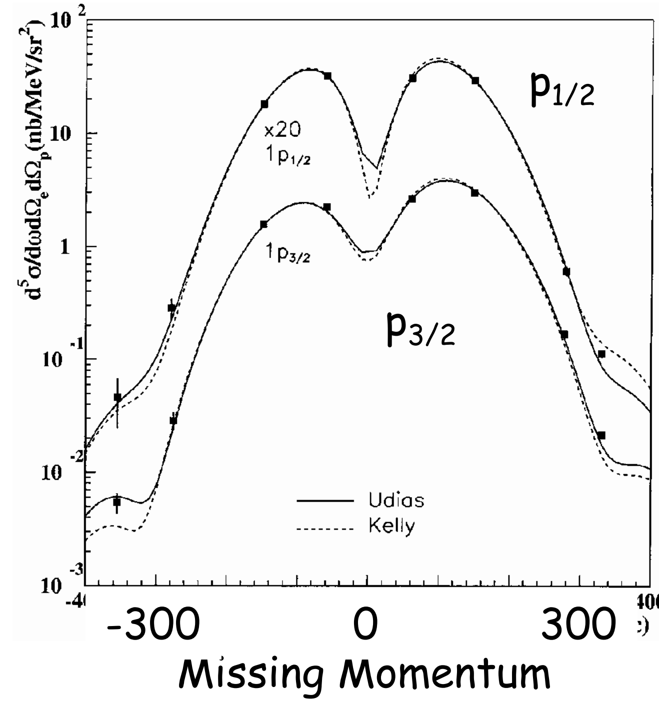
Each R now depends on more variables $R = R(q, \omega, p_{miss}, E_{miss})$

(When you include electron and proton spin, there are 18!)

(And if you scatter from a polarized spin-1 target, there are 41. Double Yikes!!)



^{16}O(e,e'p) and shell structure

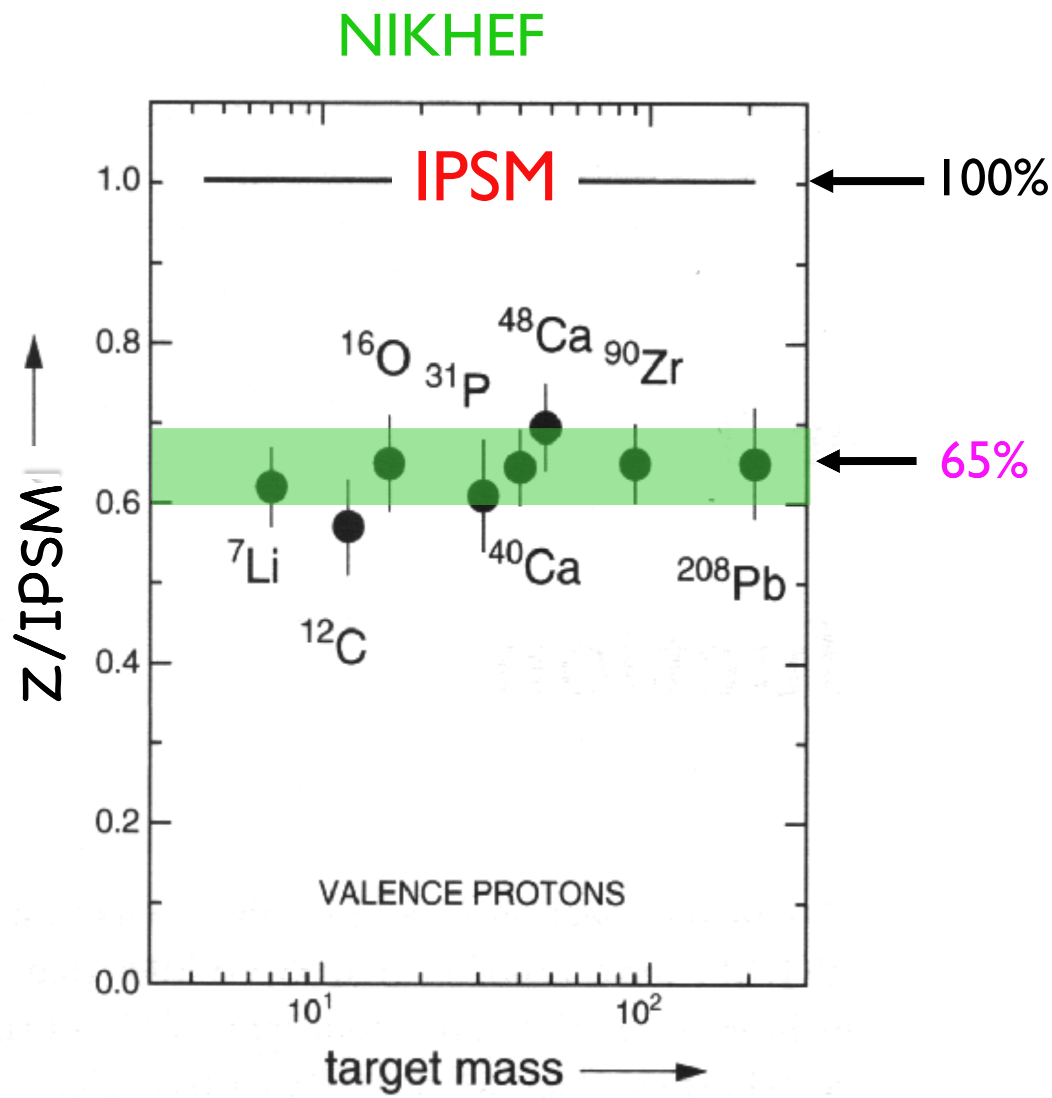


$1p_{1/2}$, $1p_{3/2}$ and $1s_{1/2}$ shells visible

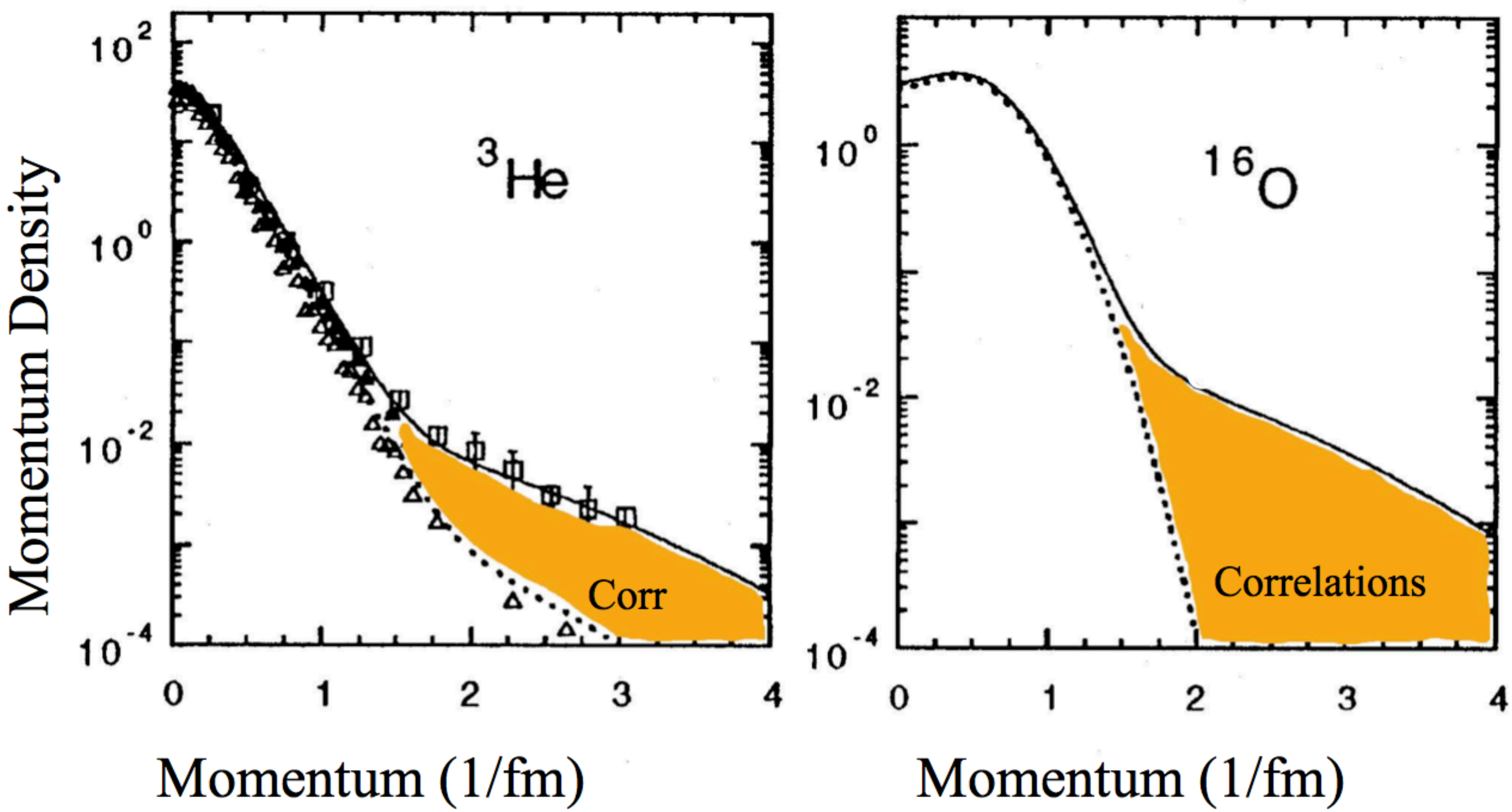
Momentum distribution as expected for $l = 0, 1$

Fissum et al, PRC 70, 034606 (2003)

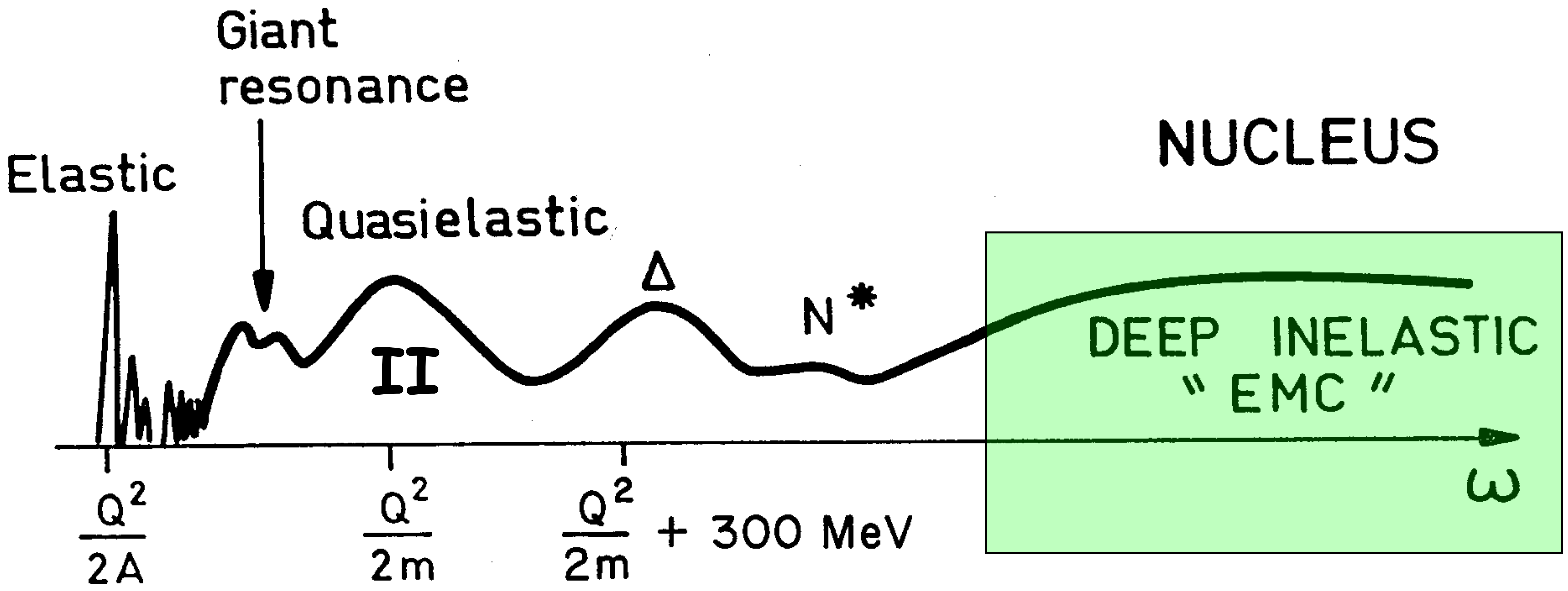
But we do not see enough protons!



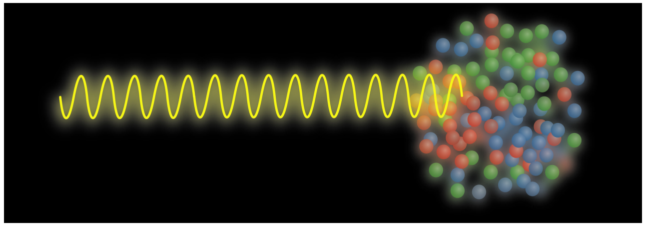
But we do not see enough protons! (More to come…)



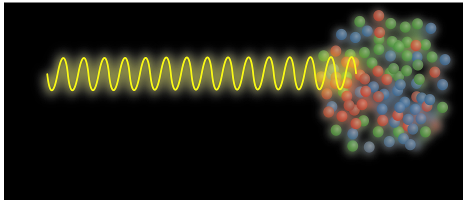
Quick Overview: Deep Inelastic

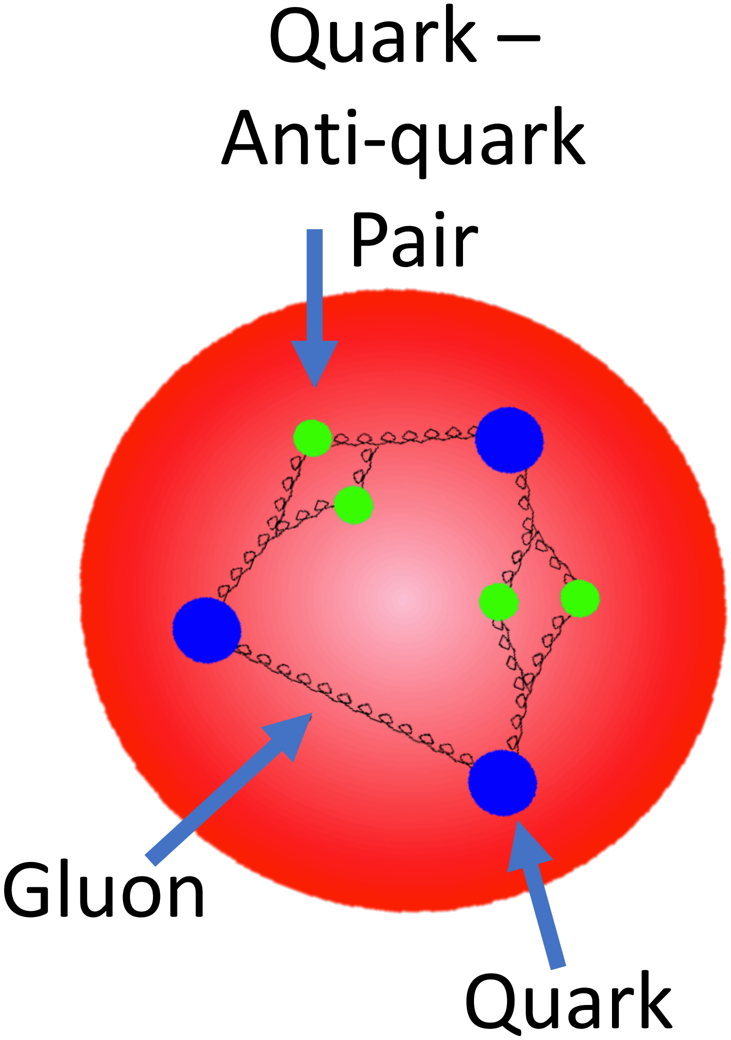


- Structure Functions
- EMC Effect

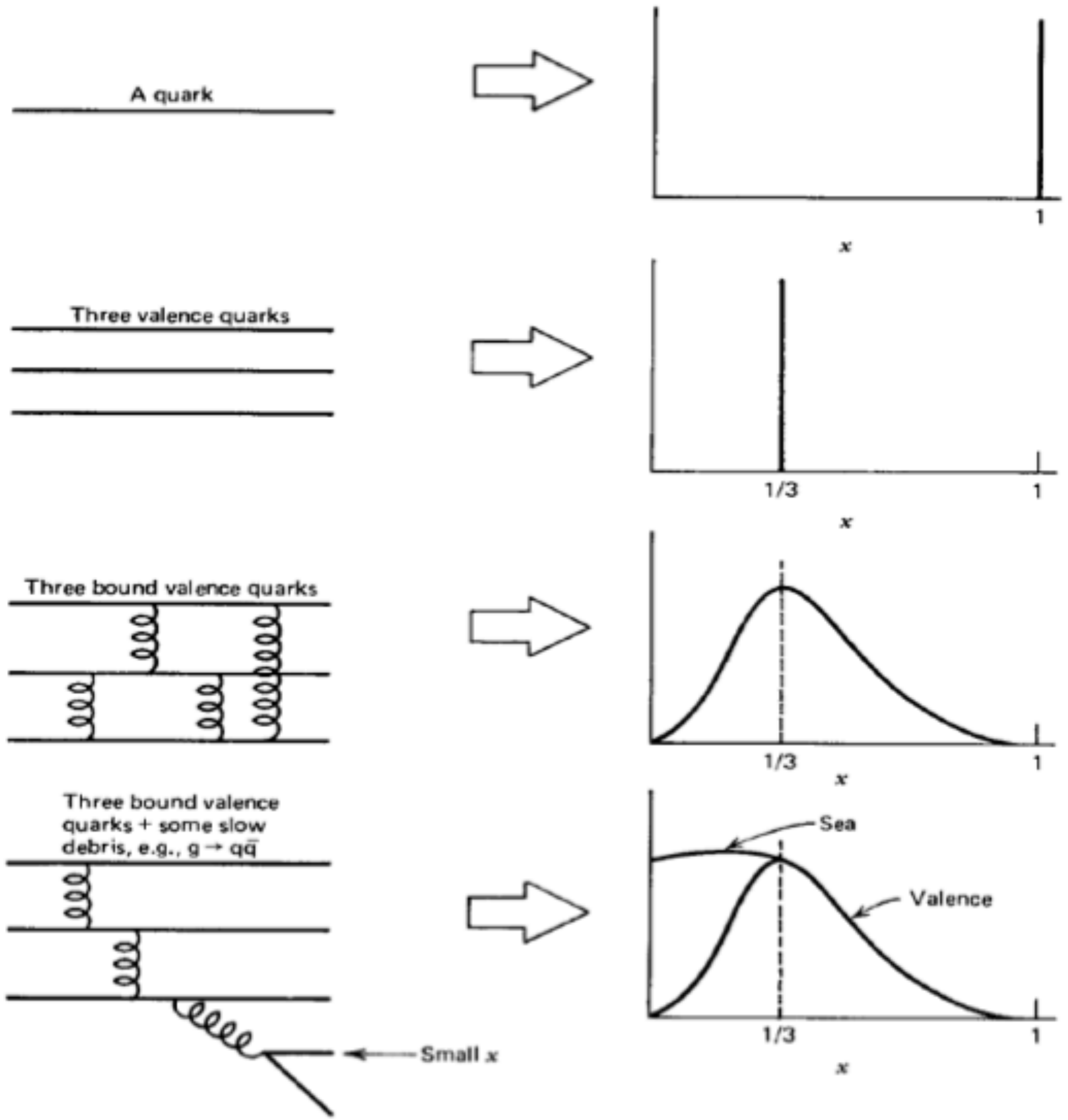


Partonic Structure





Partonic Structure: $F_2\left(x,Q^2\right)=\sum_i e_i^2\cdot x\cdot f_i(x)$



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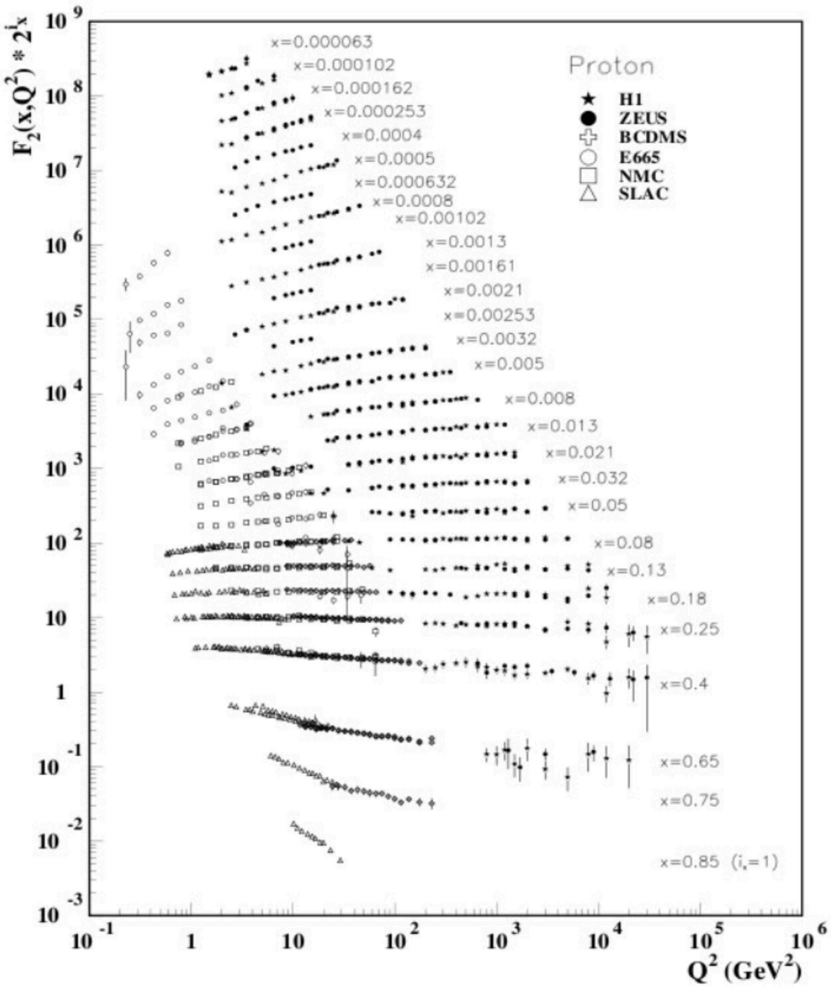

$$\frac{d^2\sigma}{d\Omega dE'}=\sigma_A=\frac{4\alpha^2E'^2}{Q^4}\left[2\frac{F_1}{M}\sin^2\left(\frac{\theta}{2}\right)+\frac{F_2}{\nu}\cos^2\left(\frac{\theta}{2}\right)\right]$$

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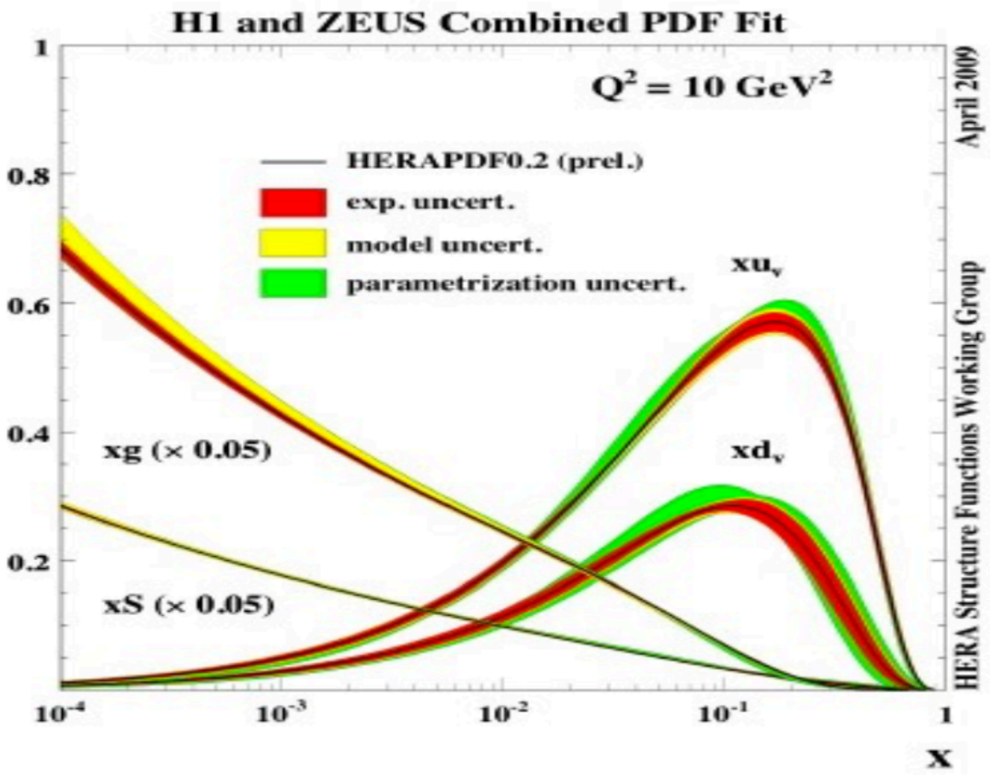

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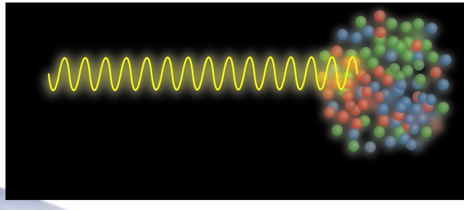
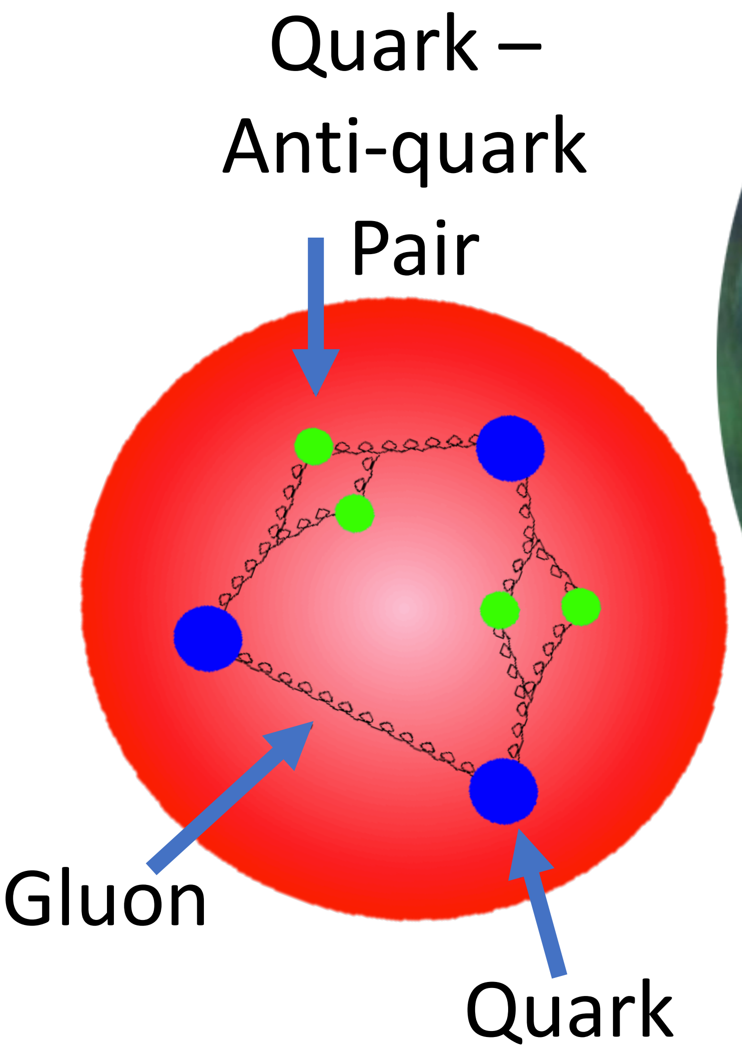
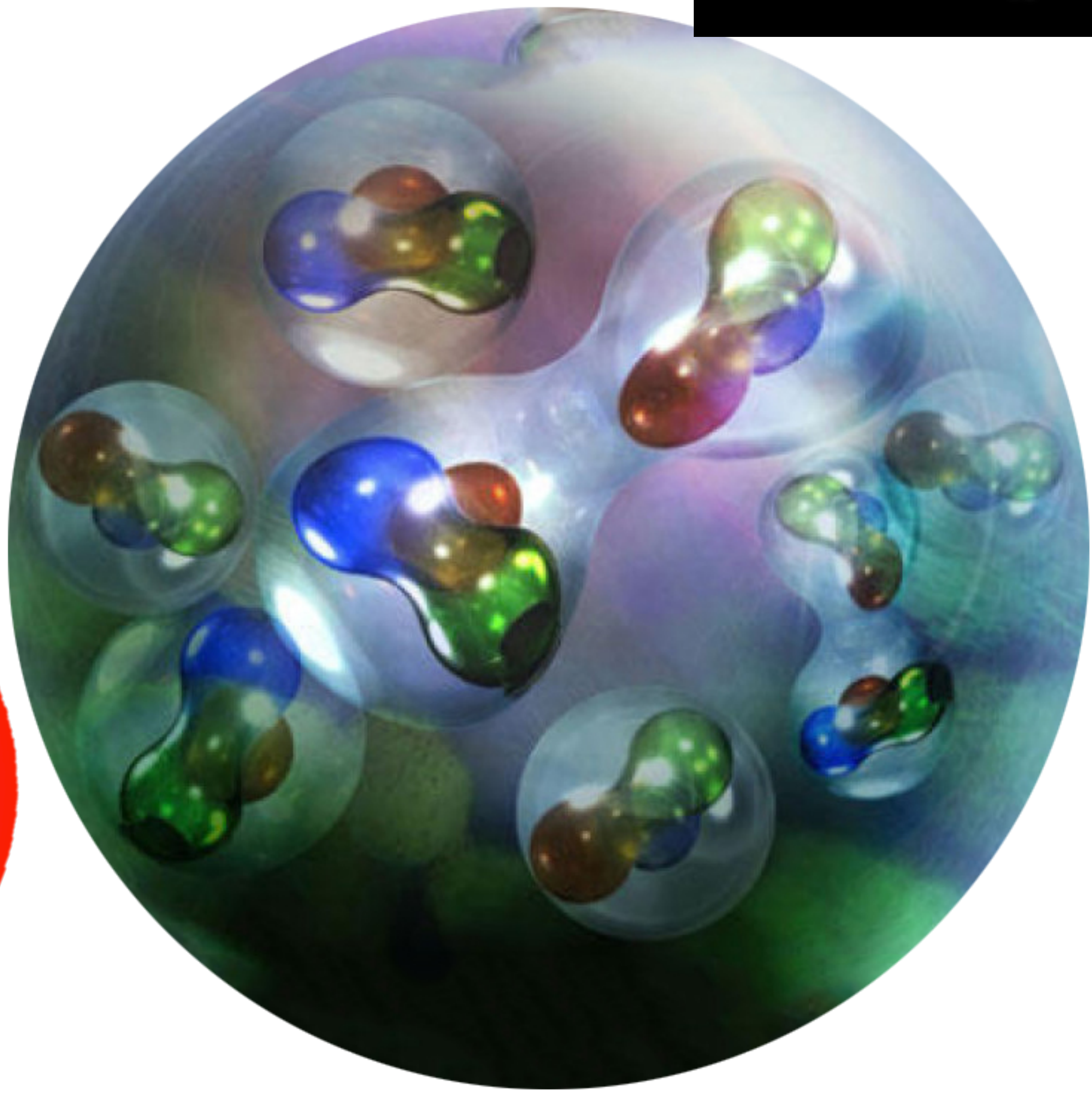
Partonic – Nucleonic Interplay







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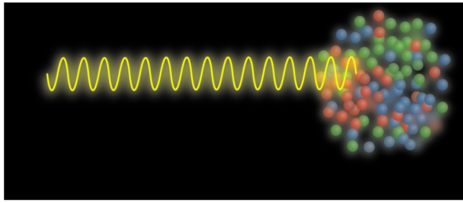
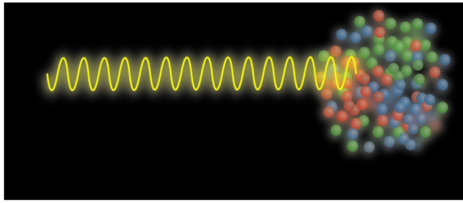


Quiz: What is the ***simplest*** example of nuclear interaction affecting partonic properties?

(winner gets a beer)

Partonic – Nucleonic Interplay

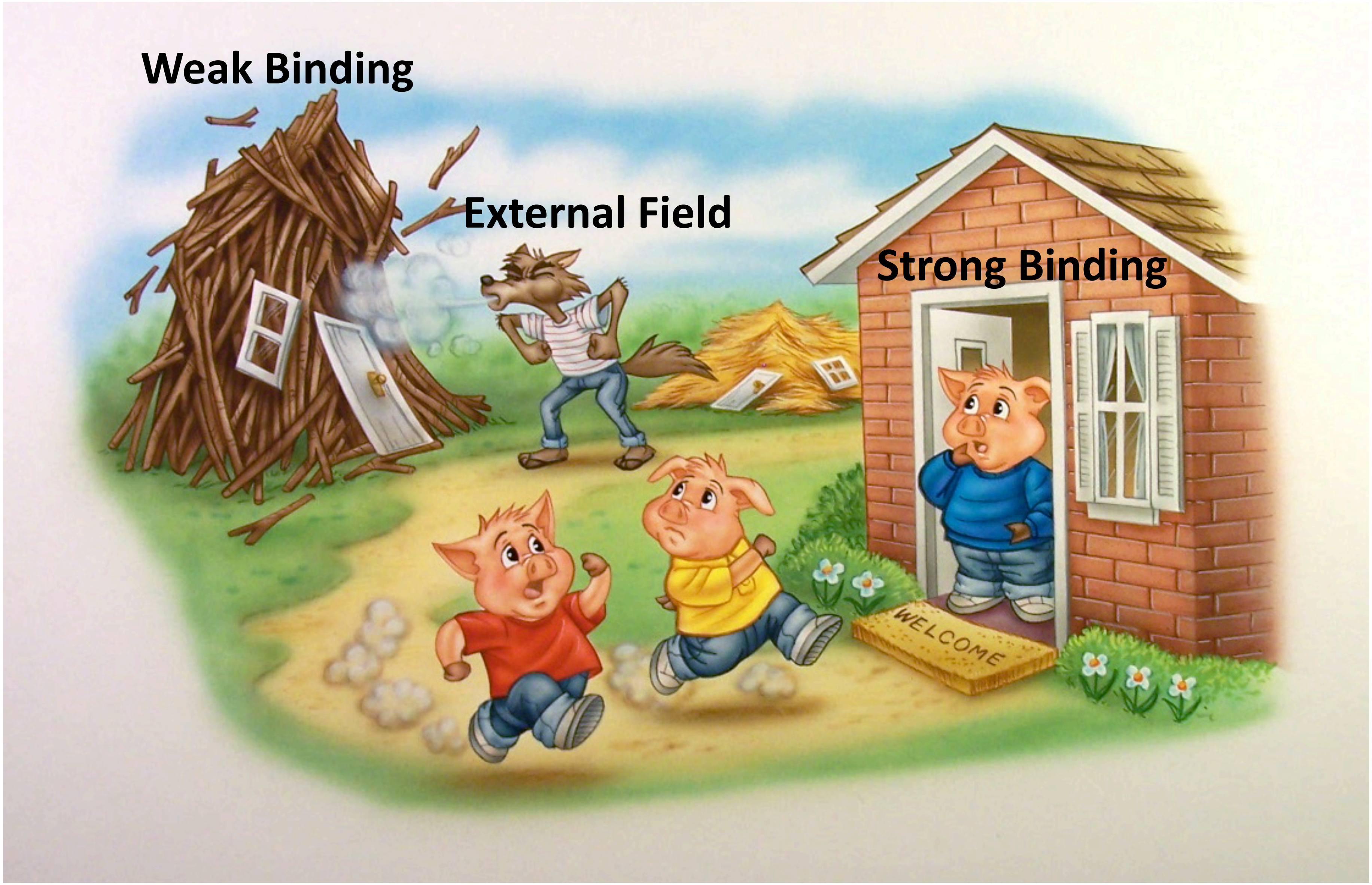


Quiz: What is the *simplest* example of nuclear interaction affecting partonic properties?

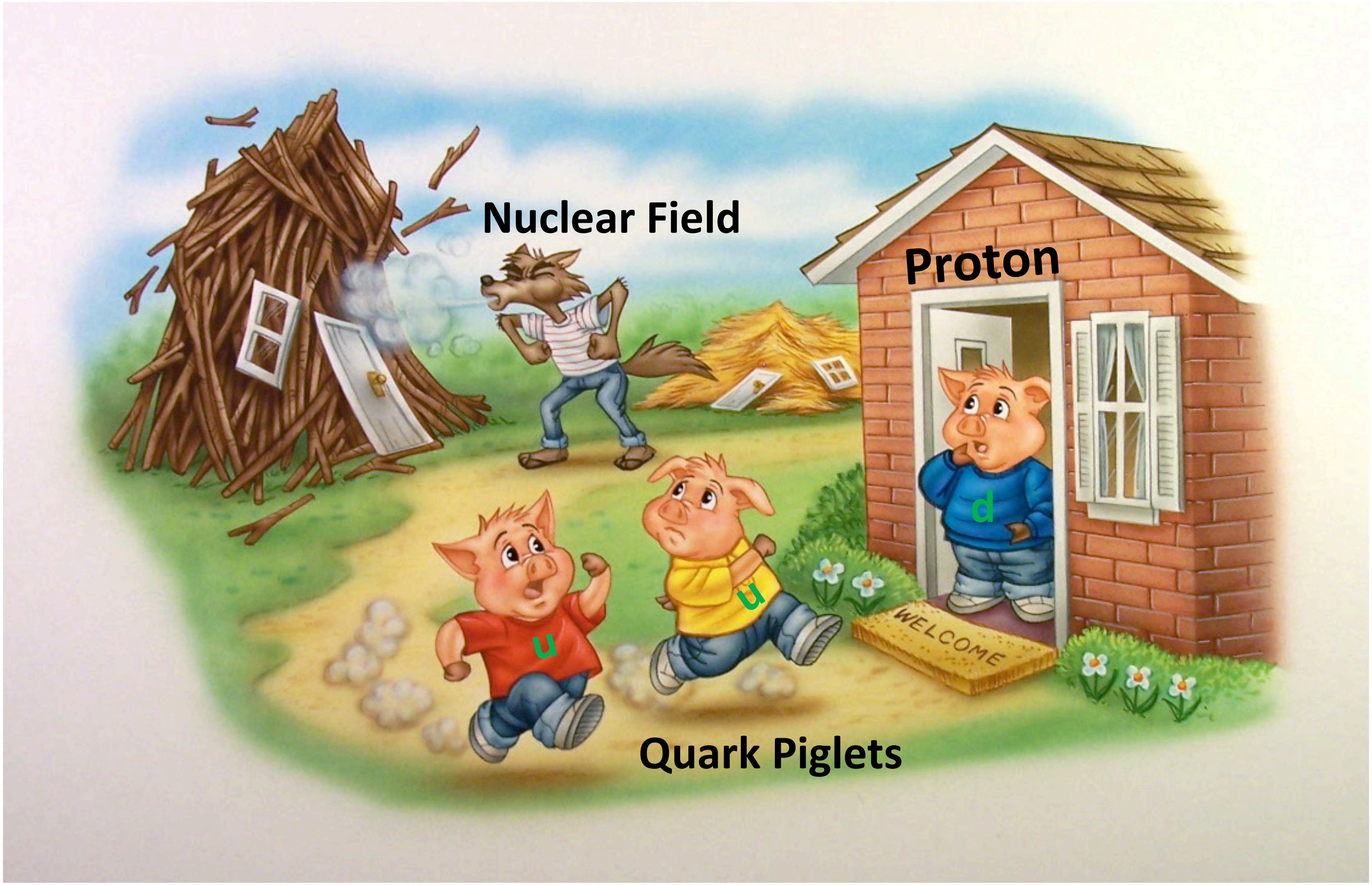
Answer:
The nuclear interaction that binds the deuteron also makes the neutron stable.

- Simplest nuclear system = Deuteron,
- Free neutron is unstable: decays in ~ 10 minuets,
- Bound in the Deuteron, a neutron can live forever!

Interplay Challenge: ‘Strength ’Scales

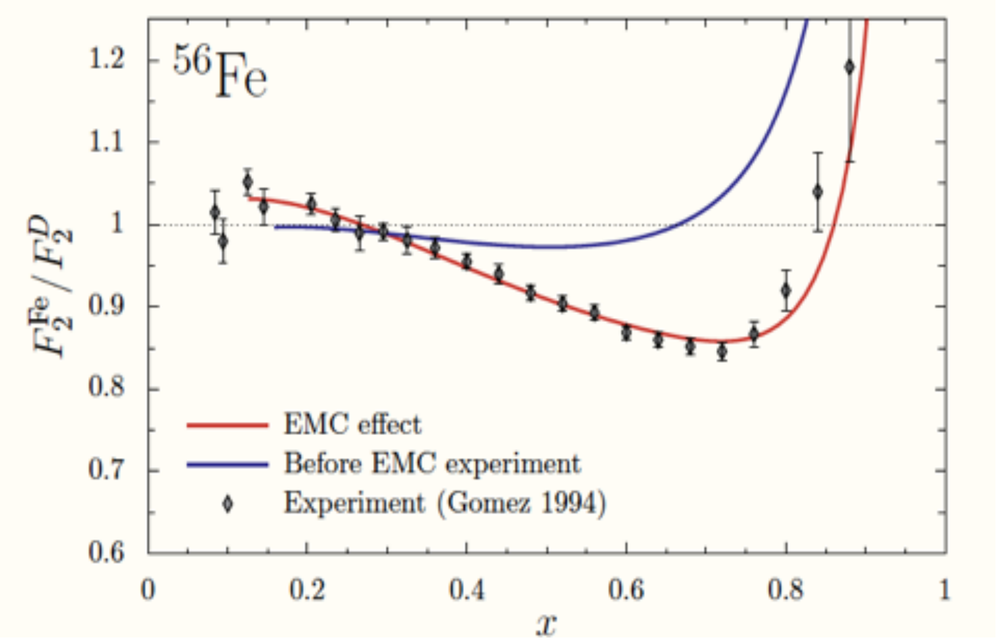


Interplay Challenge: 'Strength 'Scales



EMC Effect

- Deviation of the per-nucleon DIS cross section ratio of nuclei relative to deuterium from unity.
- Universal shape for 0.3<x<0.7 and 3<A<197.
- ~Independent of Q^2.
- Overall increasing as a function of A.
- No fully accepted theoretical explanation.



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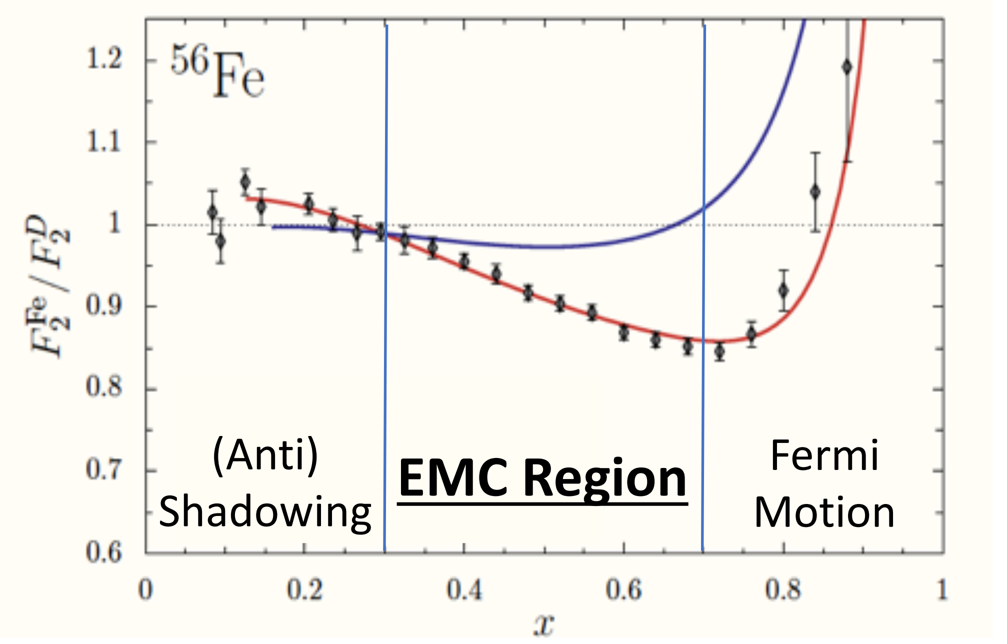

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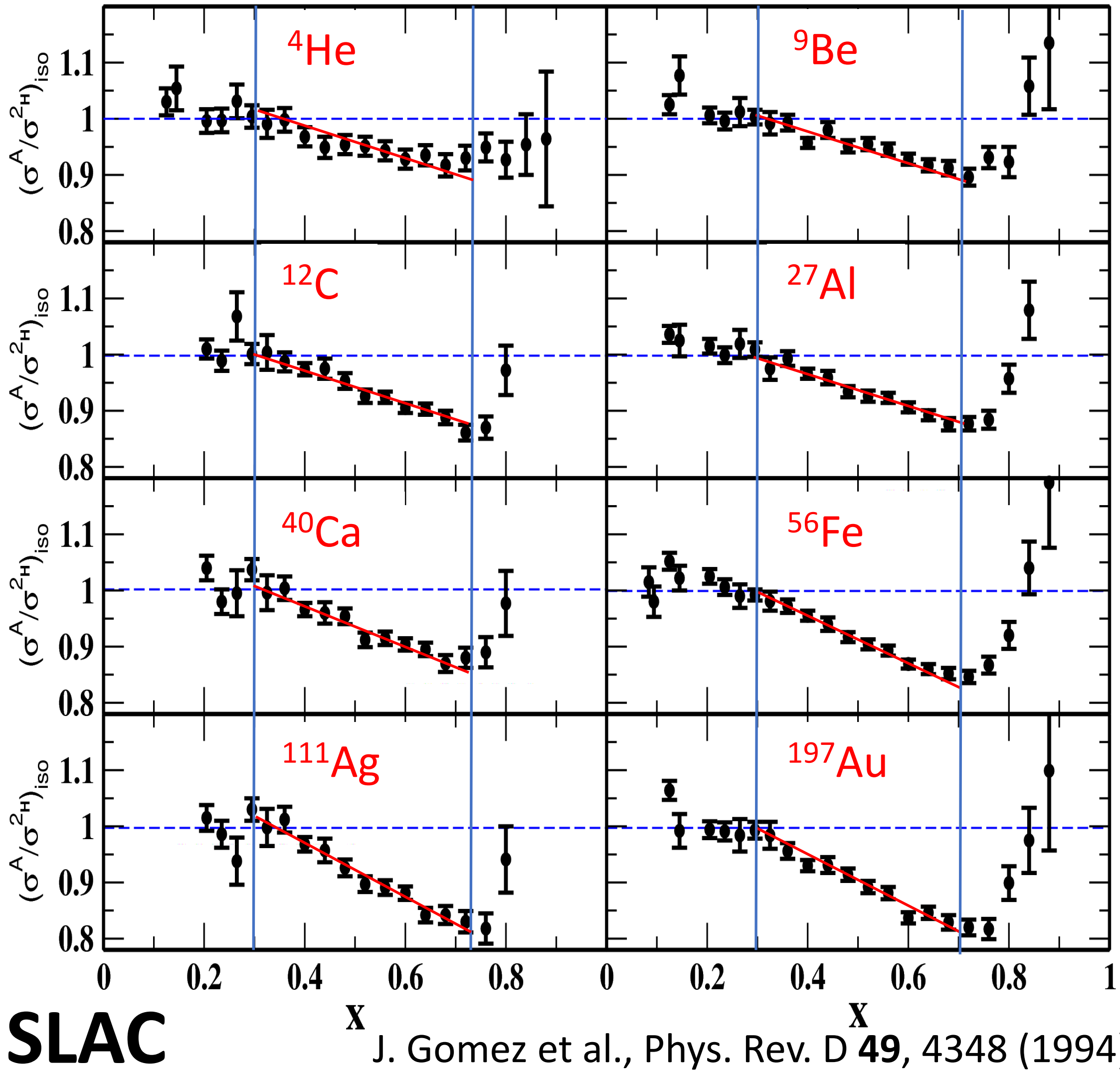
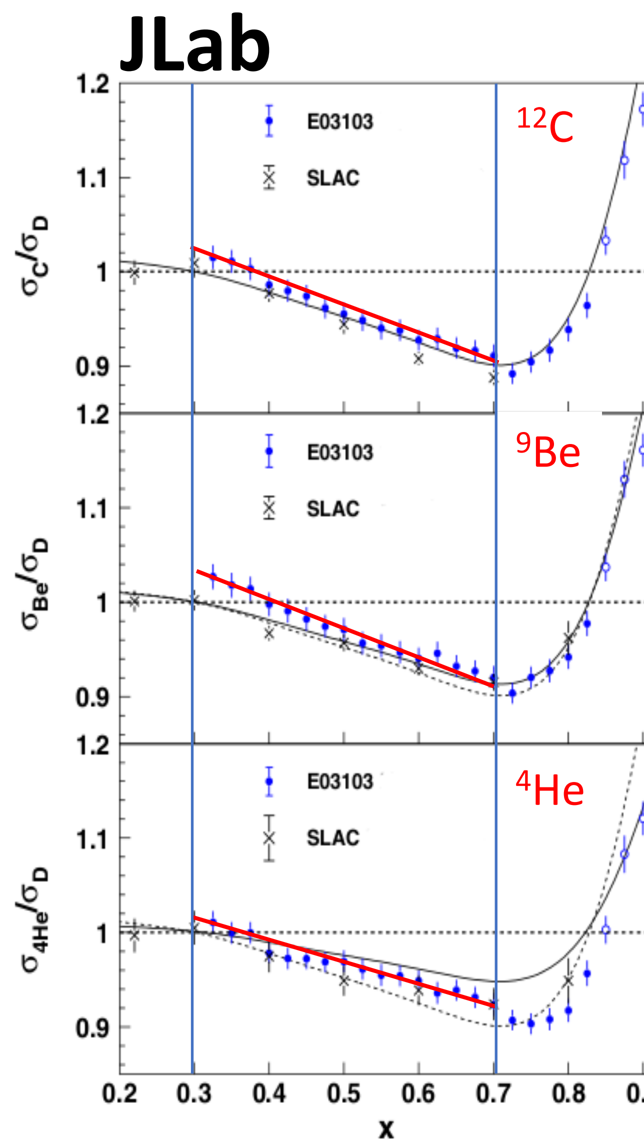
EMC: Nuclear Effect on Partons



J. Gomez et al., Phys. Rev. D **49**, 4348 (1994).



J. Seely et al., Phys. Rev. Lett. **103**, 202301 (2009).

More later in the week!

Theory: 1000 papers, 3 Ideas

1. Proper treatment of 'known' nuclear effects
   [explain some of the effect, up to x≈0.5. Sensitive to SRCs]
   - Nuclear Binding and Fermi motion, Pions, Coulomb Field.
   - **No modification of bound nucleon structure.**

2. Bound Nucleons are 'larger' than free nucleons.
   - Larger confinement volume => slower quarks.
   - Mean-Field effect.
   - Momentum Independent.
   - **Static.**

3. Short-Range Correlations
   - Beyond the mean-field.
   - Determined by SRC pairs counting.
   - **Dynamical!**

EMC – Everyone's Model is Cool (G. A. Miller)

Theory: 1000 papers, 3 Ideas

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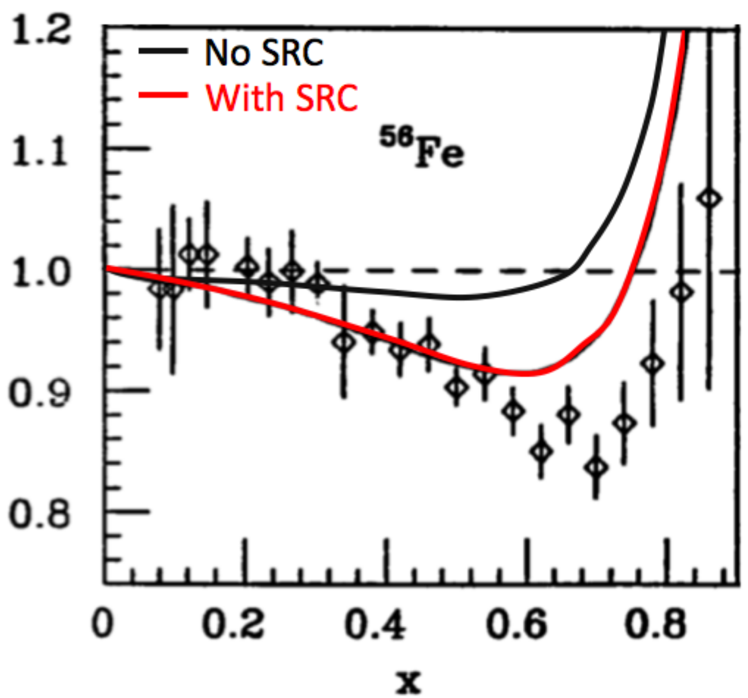

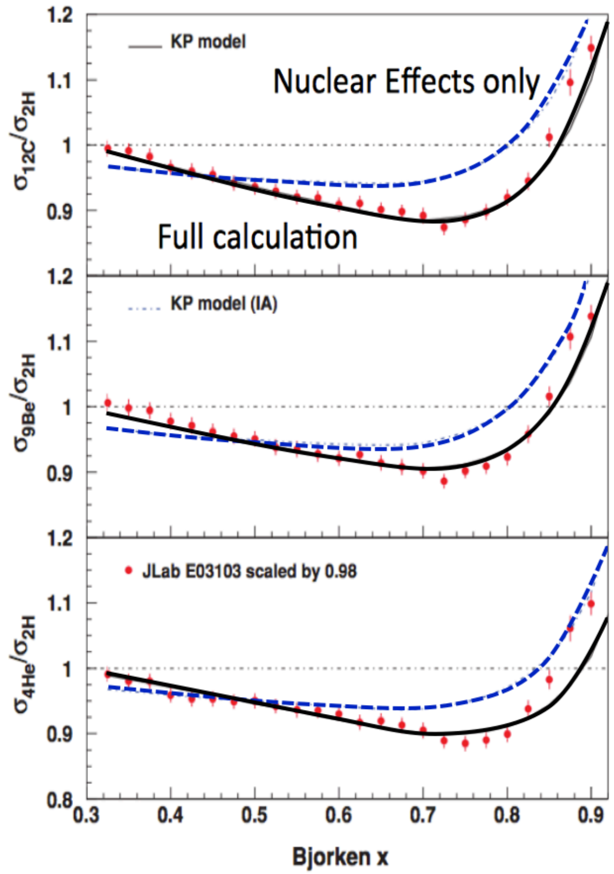

Theory: 1000 papers, 3 Ideas

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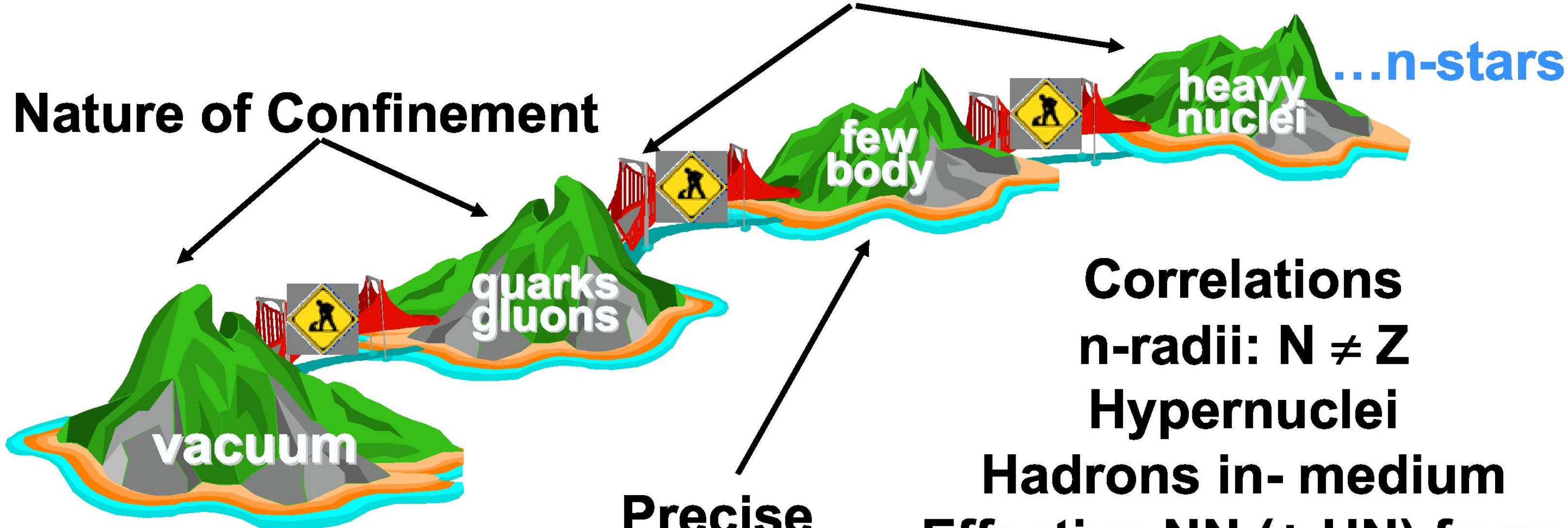
EMC – Everyone's Model is Cool (G. A. Miller)

Summary (1): Modern nuclear physics - From nothing to everything

Quark-Gluon Structure
Of Nucleons and Nuclei

Nature of Confinement



Correlations
n-radii: N ≠ Z
Hypernuclei
Hadrons in- medium
Effective NN (+ HN) force

Precise
few-nucleon
calculations

Exotic mesons
and baryons

Summary (2): Today's overview

Elastic scattering (Form Factors, FF):

- Nuclei + virtual photon => Nuclear charge FF
- Nuclei + Z boson => Nuclear neutron FF
- Nucleons + virtual photon => Nucleon charge FF
- Nucleons + Z boson => Nucleon strange FF + …

Quasielsatic scattering:

- Scaling and momentum distributions
- Shell structure and spectroscopic factors
- Correlations
- …

Deep Inelastic Scattering:

- Nucleons => Structure functions and PDFs
- Nuclei => In-medium structure functions and nuclear PDFs

Summary (3): Never mix between what we Know / Measure / Reconstruct / Extract

- Know:
  - Beam probe (particle type + energy)
  - Target
- Measure:
  - Scattered probe
  - Additional particles emitted
  - *Cross-sections*
- Reconstruct:
  - Short Lived particles
  - Missing momentum
  - Missing Energy
- Extract:
  - *Physics! (momentum distribution, shell occupancies …)*

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Increasing level of assumptions (i.e. model dependencies)

Tomorrow: Short-Range nuclear Structure

Theory:

1. Beyond the mean-field: NN Correlations,
2. Effective vs. ab-initio calculations
3. Phase-equivalent NN interactions
4. Reaction theory: confronting theory and experiment.

Experiment:

1. (e,e’), (e,e’N), (e,e’NN) => Details of NN correlations,
2. Correlations in asymmetric nuclei,
3. NN interactions at short distances.

Contact Formalism: Effective theory for short-distance.