QCD Dynamics in electron-nucleus collisions

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38th Annual Hampton University Graduate Summer Program (HUGS)

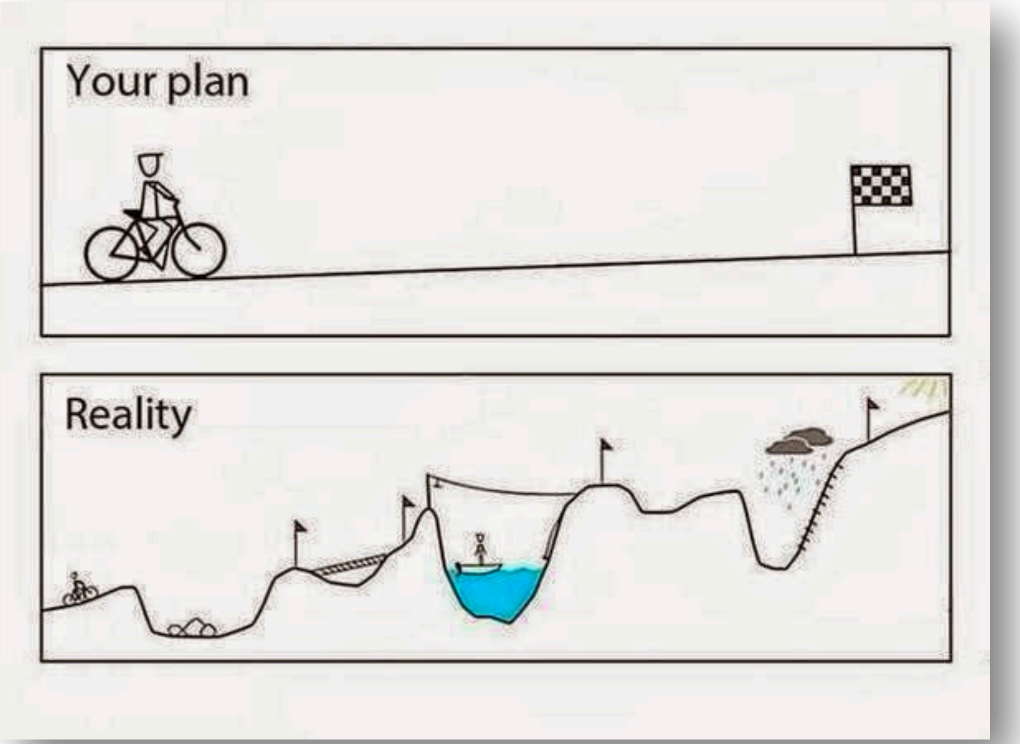
30 May – 16 June 2023

Jefferson Lab

Jefferson Lab

Course Overview

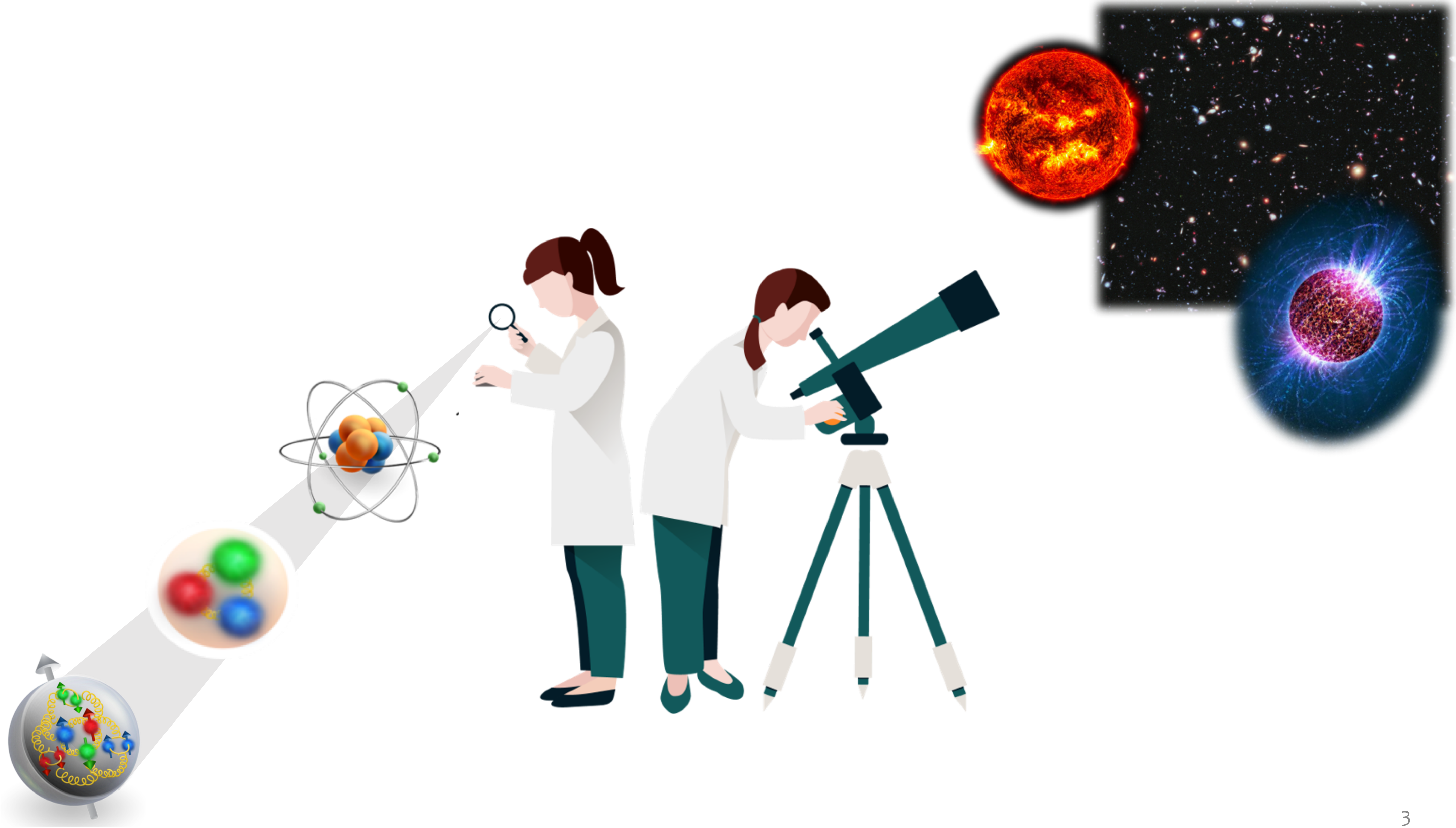
- Nuclear systems and the electron scattering probe
  - Elastic scattering
  - Quasielastic scattering
  - Deep inelastic scattering



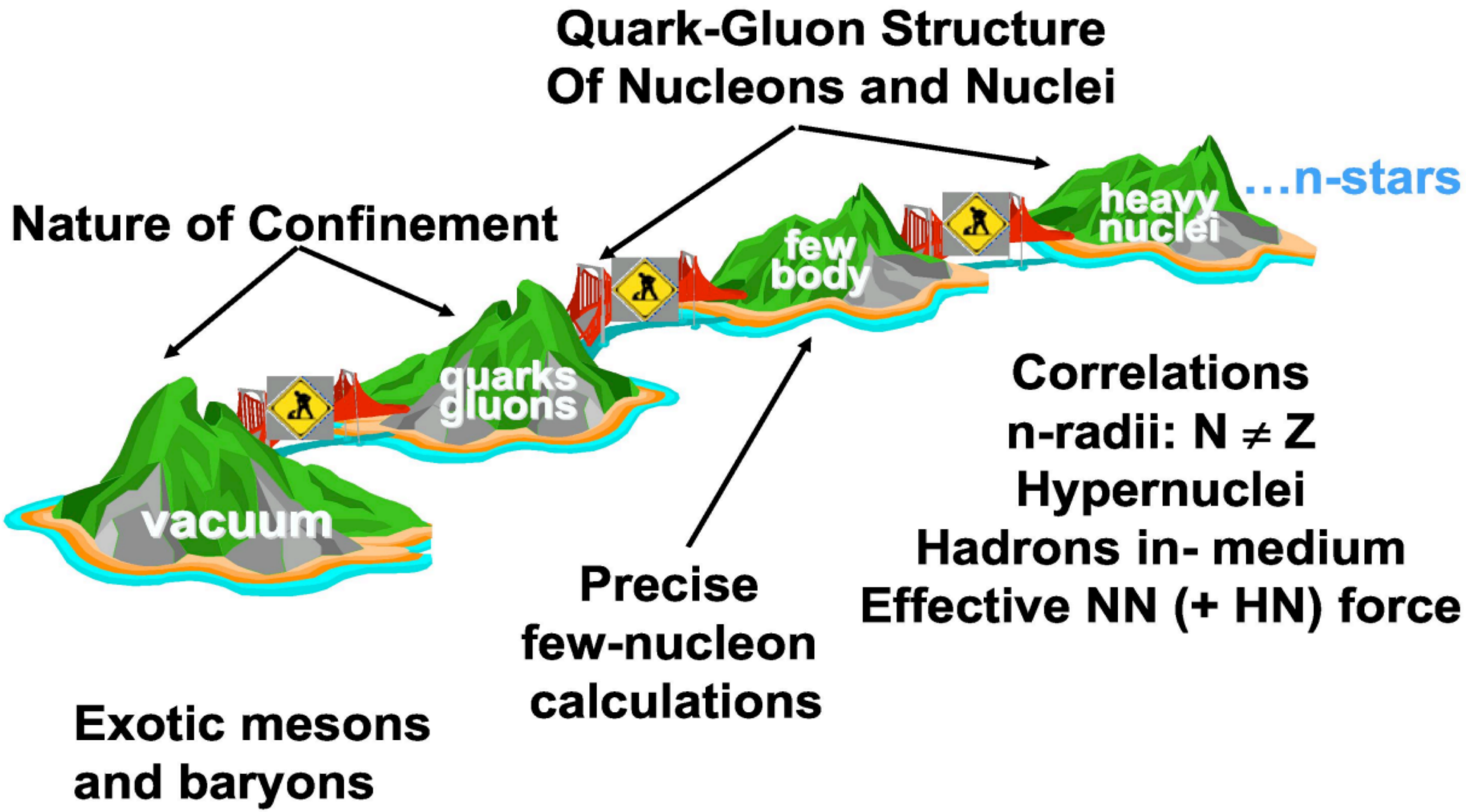
- Hadrons in the nucleus
  - Short and long range dynamics
  - EMC effect
  - Hadronization and color transparency

- Implications and open questions

What are we trying to learn about?



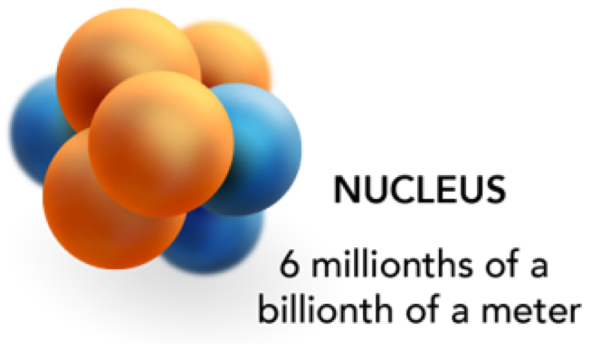
From nothing to everything!

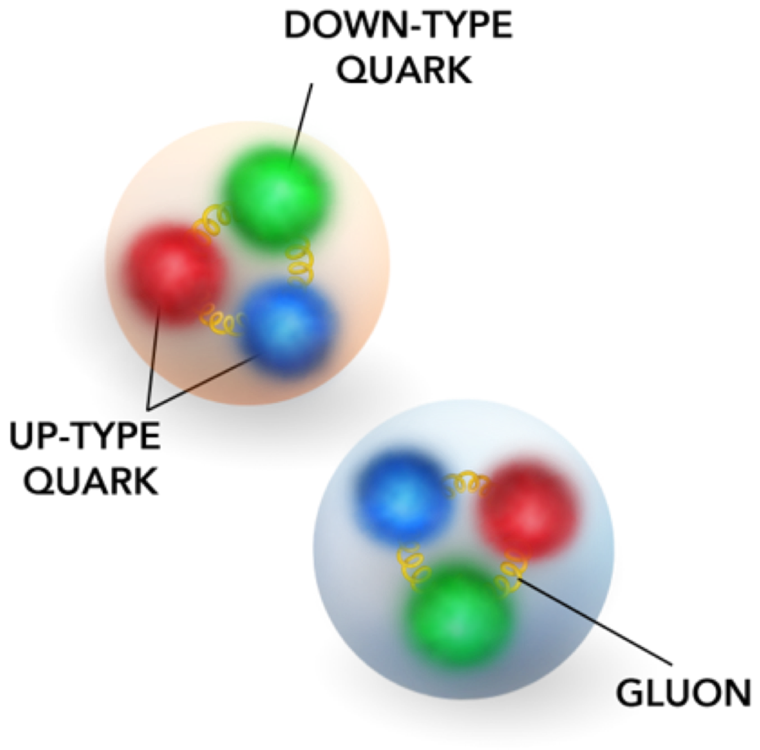


Systems

Nucleus as a system

- Collection of bound protons and neutrons





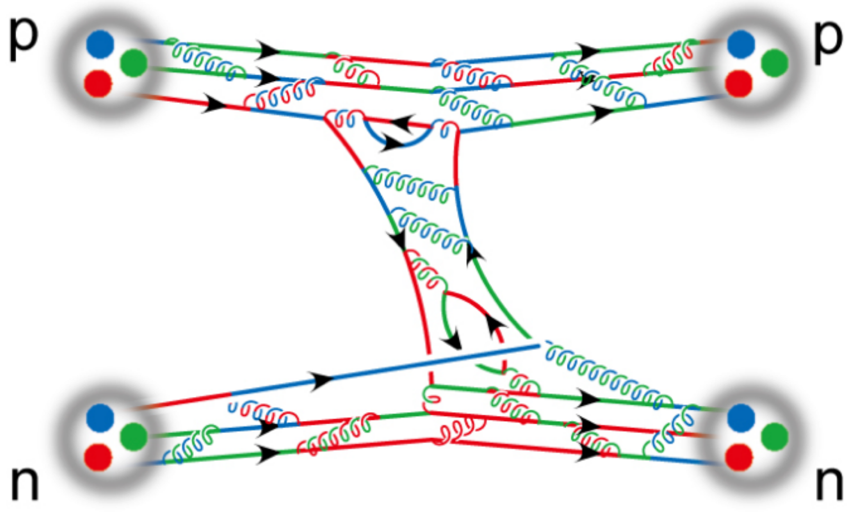
Nucleons as a system

- Collection of bound quarks

Interactions

Nuclear interaction

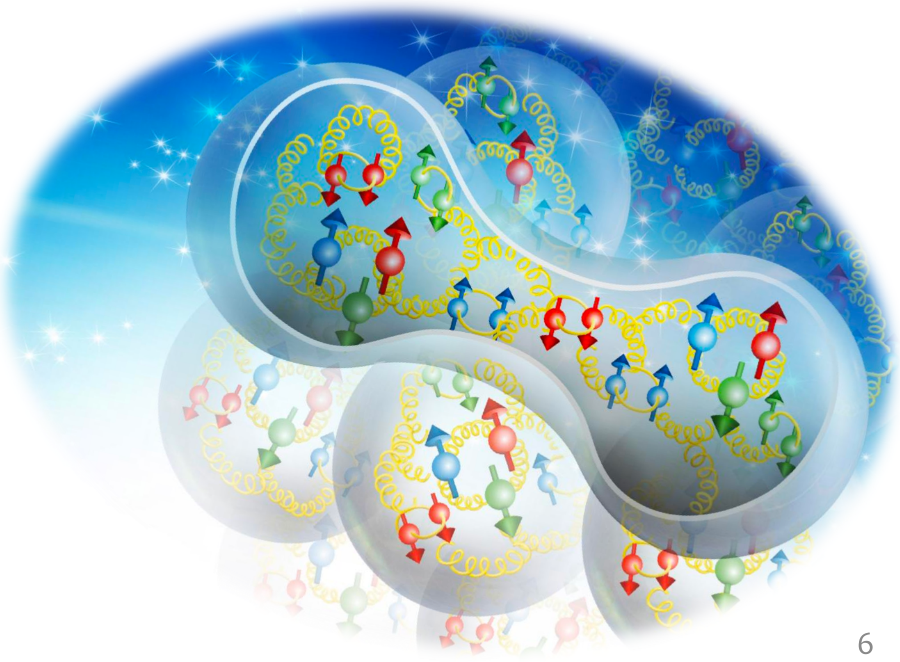
Arises from quark interactions



"It's an energy field created by all living things. It surrounds us and penetrates us. It binds the galaxy together."

Nuclear in-medium effects

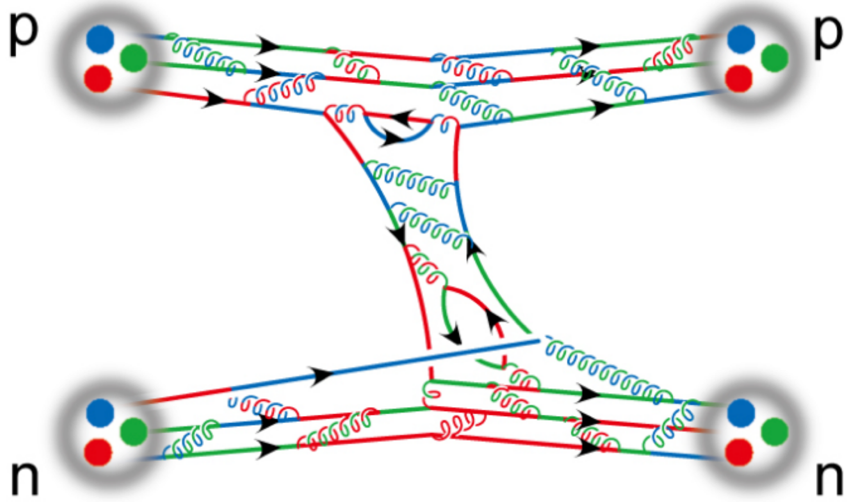
Affecting quark distributions



Interactions

Nuclear interaction

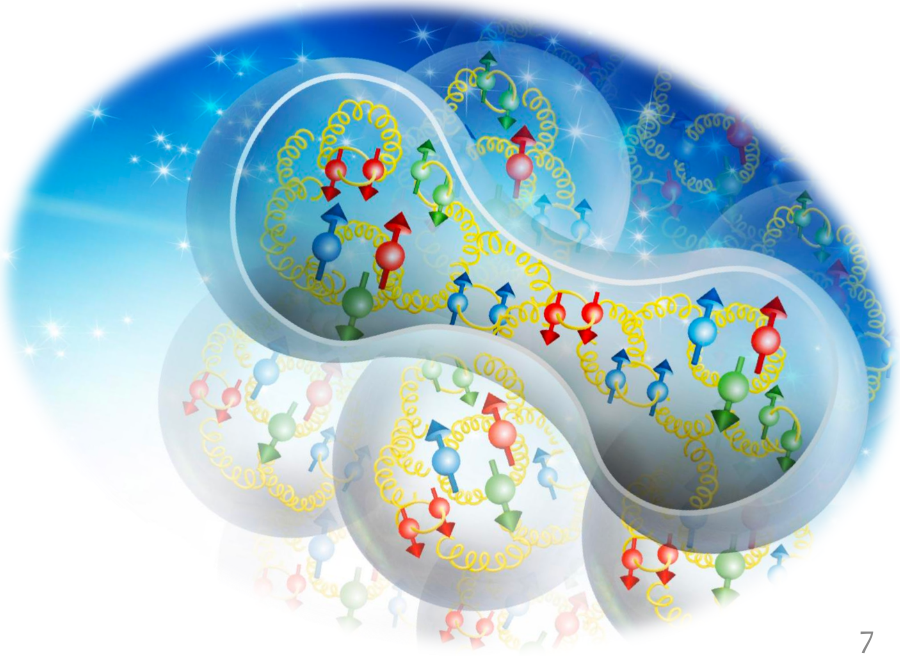
Arises from quark interactions



“It’s an ~~energy field~~ interaction created by all ~~living things.~~ quarks & gluons It surrounds us and penetrates us. It binds the ~~galaxy~~ nucleus together.”

Nuclear in-medium effects

Affecting quark distributions



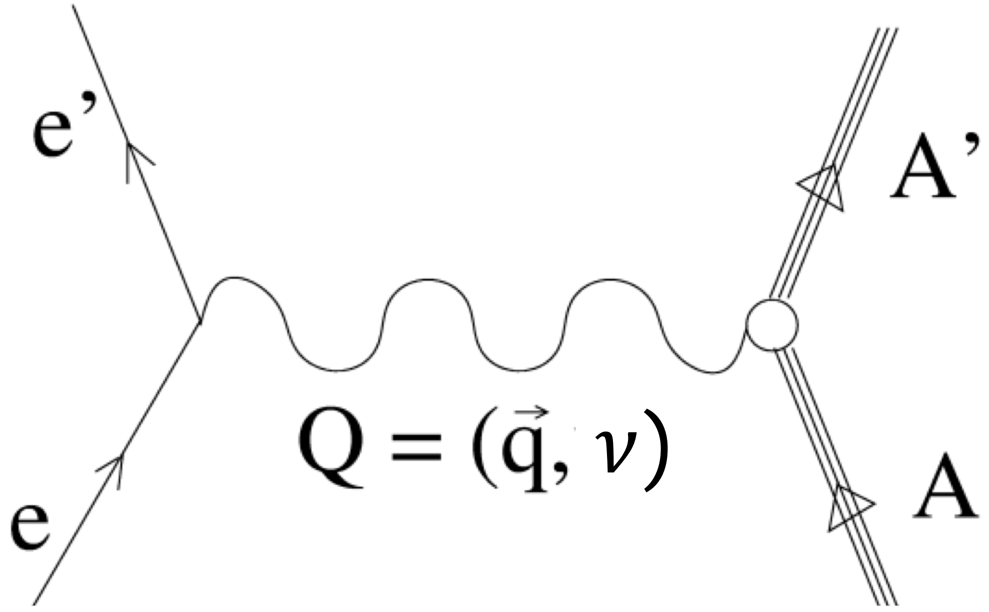
Relevant quantities

- Shape (radius, deformation…)
- EM charge distribution (form factors)
- Nucleon momentum distributions (wave function)
- Clustering and correlations
- Nuclear forces from quark interactions
- Quark structure of bound and free nucleons
- Gravitational density of gluons (gluonic gravitational form factors)
- Transparency and hadronization (QCD confinement)

Electron scattering as a nuclear microscope

Good stuff:

- Probe structure is understood (point-like)
- Electromagnetic interaction is well-described (QED)
- Interaction is weak (α = 1/137…)
  - Theory works! First Born Approximation/ single photon exchange
  - Probe interacts once
  - Probe the entire nuclear volume



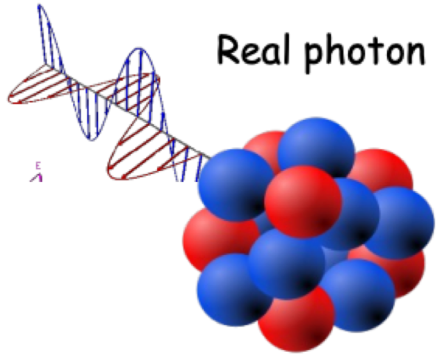
Drawbacks:

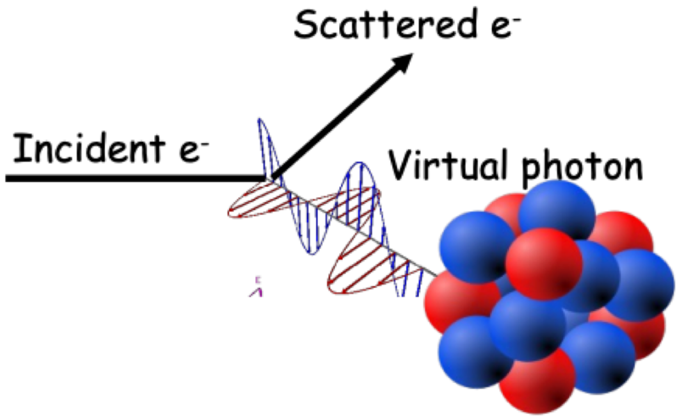
- Cross sections are small
- Electrons radiate

A

It’s all photons!

The electron interacts with the nucleus by exchanging and single virtual photon





Real photon:
Momentum, q = Energy, ν
Mass, Q^2=$|q|^2 - \nu^2 = 0$

Virtual photon (massive):
Momentum, q > Energy, ν
Mass, Q^2=$-q_\mu q^\mu = |q|^2 - \nu^2 > 0$

Probing the structure of the proton

Interaction of the virtual photon with the proton depends strongly on wavelength

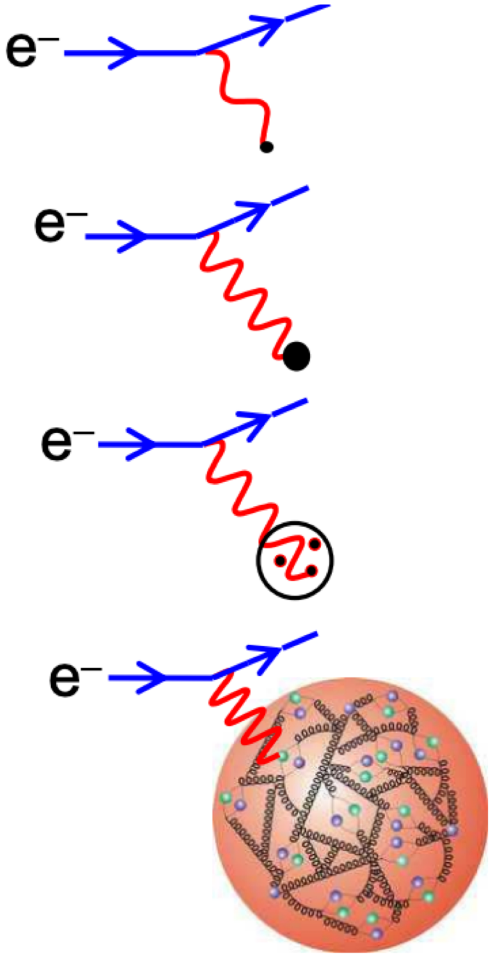
i.e. $\lambda \approx \frac{\hbar}{q}$ describes the spatial resolution

$\lambda \gg r_p$ Very low electron energies, scattering is equivalent to that from a "point-like" spin-less object

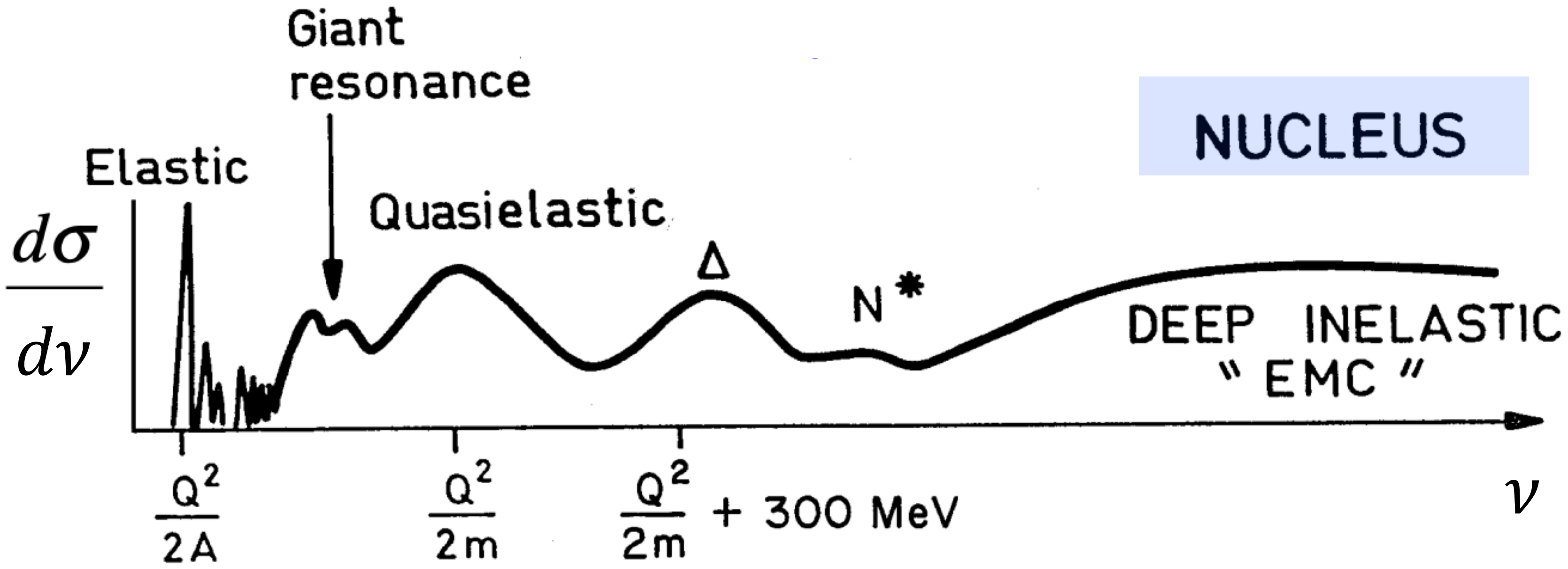
$\lambda \sim r_p$ Low electron energies (0.2-1 GeV/c), scattering is equivalent to that from extended charged object

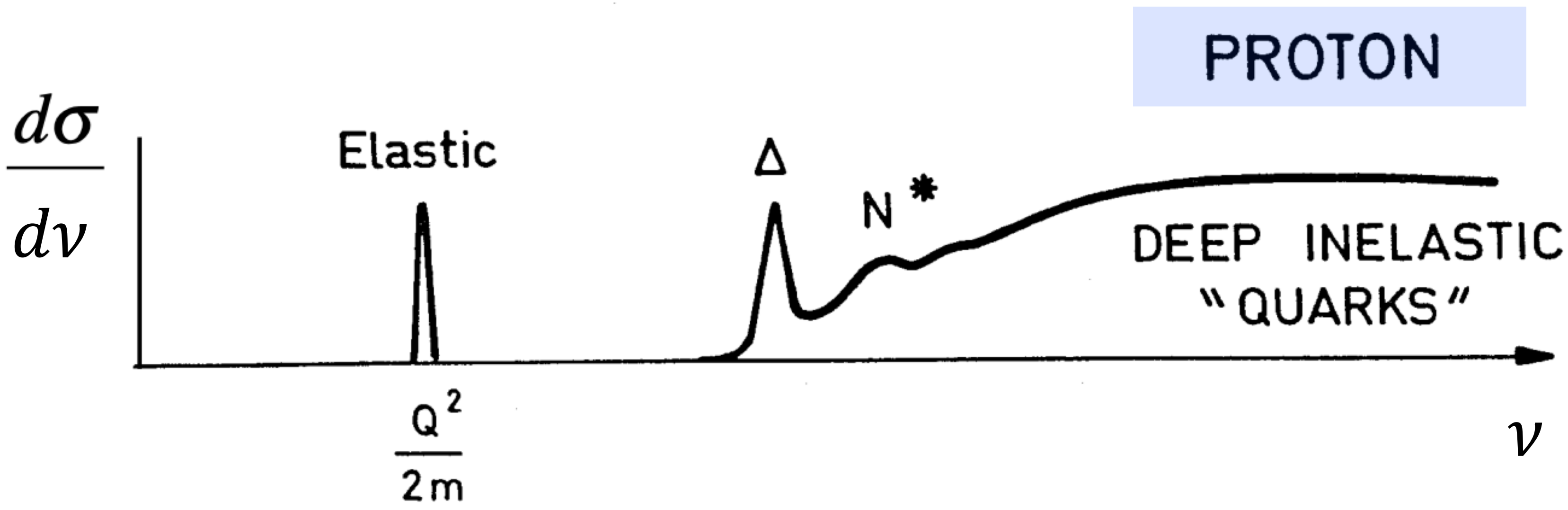
$\lambda < r_p$ High electron energies (1 GeV/c +), scattering from constituent quarks and resolve sub-structure

$\lambda \ll r_p$ Very high electron energies, proton appears to be a sea of quarks and gluons

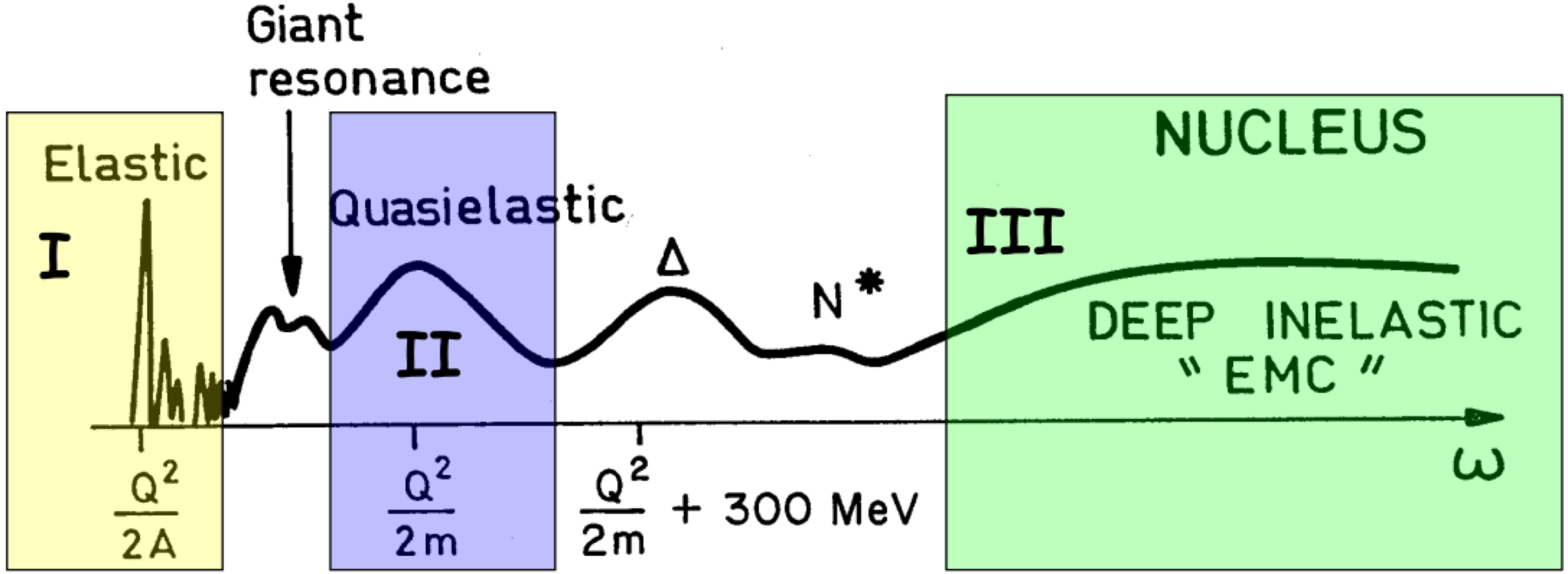


Generic (e,e') at fixed momentum transfer

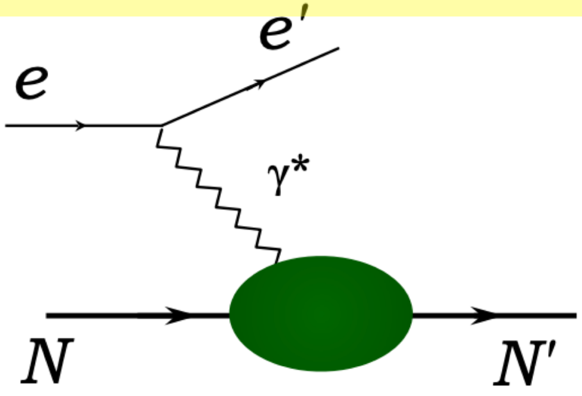




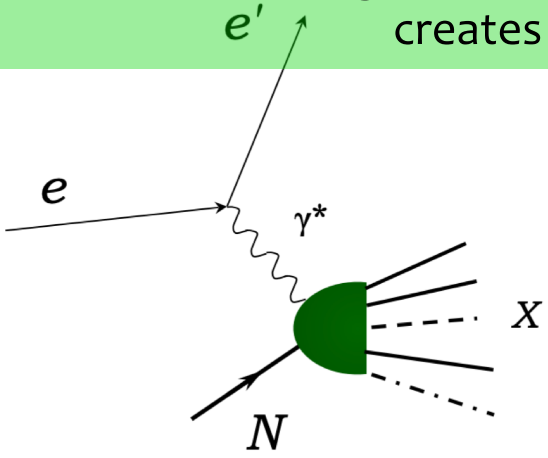
Different kinematics teach us different things



Elastic scattering: nucleon initial and final state the same



Deep inelastic scattering: nucleon state has changed, creates new particles



What can we learn?

Elastic

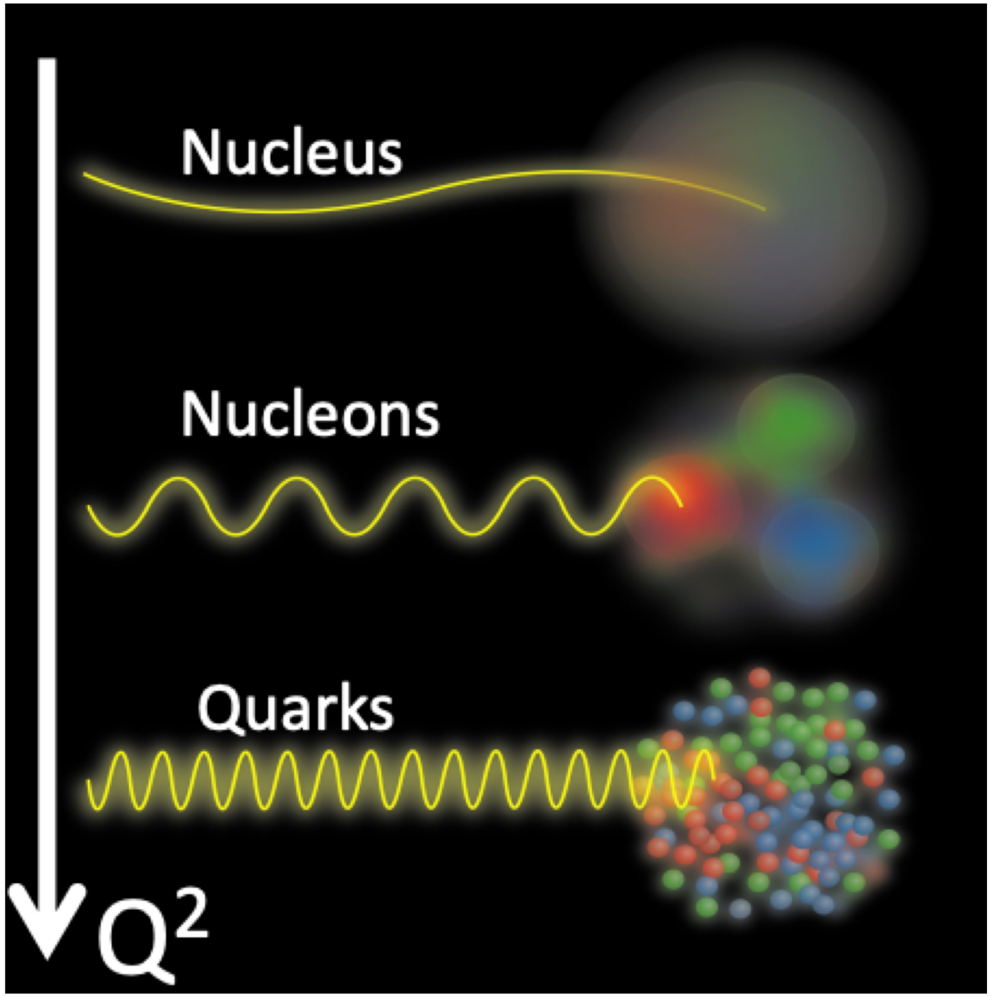
- Nuclear structure: Nuclear charge radius, nuclear neutron radius, electromagnetic form factors and charge distributions

Quasielastic

- Momentum distributions, shell structure, shell occupancies, short-range correlated pairs, transparency, medium modification

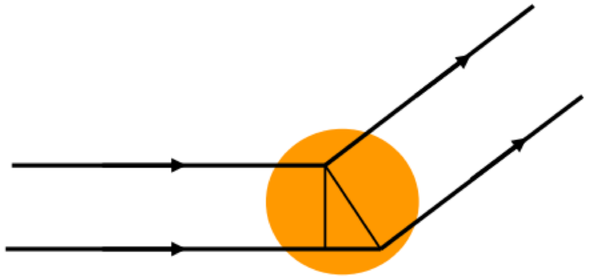
Deep inelastic

- EMC effect, nucleon modification, hadronization, nucleon structure, meson production

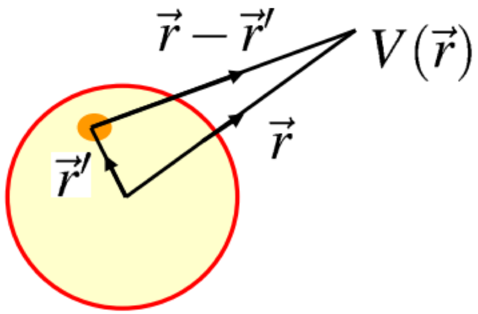


Elastic scattering: Form factors

Form factors are similar to the diffraction of plane waves in optics



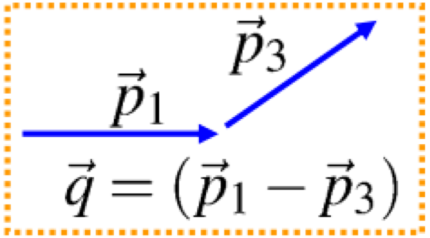
Scattering of the electron in the static potential due to an extended charge distribution:



The potential at $\vec{r}$ from the center is given by:

$$V(\vec{r}) = \int \frac{Q\rho(\vec{r}')}{4\pi|\vec{r}-\vec{r}'|} d^3\vec{r}' \qquad \text{where} \qquad \int \rho(\vec{r})\mathrm{d}^3\vec{r} = 1$$

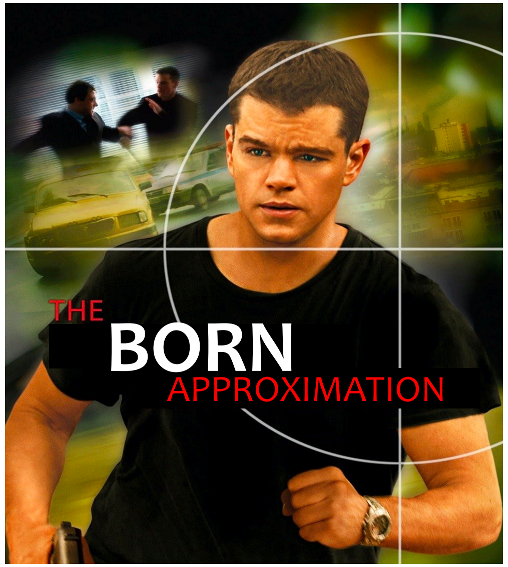
Elastic scattering: Form factors



Using first order perturbation theory to calculate the matrix element:

$$M_{fi} = \langle \psi_f | V(\vec{r}) | \psi_i \rangle = \int e^{-i\vec{p}_3.\vec{r}} V(\vec{r}) e^{i\vec{p}_1.\vec{r}} \mathrm{d}^3\vec{r}$$

$$= \int\int e^{i\vec{q}.\vec{r}} \frac{Q\rho(\vec{r}')}{4\pi|\vec{r}-\vec{r}'|} \mathrm{d}^3\vec{r}' \mathrm{d}^3\vec{r} = \int\int e^{i\vec{q}.(\vec{r}-\vec{r}')} e^{i\vec{q}.\vec{r}'} \frac{Q\rho(\vec{r}')}{4\pi|\vec{r}-\vec{r}'|} \mathrm{d}^3\vec{r}' \mathrm{d}^3\vec{r}$$



Fixing $\vec{r}'$ and integrating over the $\mathrm{d}^3\vec{r}$ distribution while substituting $\vec{R} = \vec{r} - \vec{r}'$:

$$M_{fi} = \int e^{i\vec{q}.\vec{R}} \frac{Q}{4\pi|\vec{R}|} \mathrm{d}^3\vec{R} \int \rho(\vec{r}') e^{i\vec{q}.\vec{r}'} \mathrm{d}^3\vec{r}' = (M_{fi})_{point} F(\vec{q}^2)$$

The resulting matrix element is equivalent to the matrix element for scattering from a *point source* multiplied by the ***form factor***!

The form factor is the Fourier transform of the charge distribution:

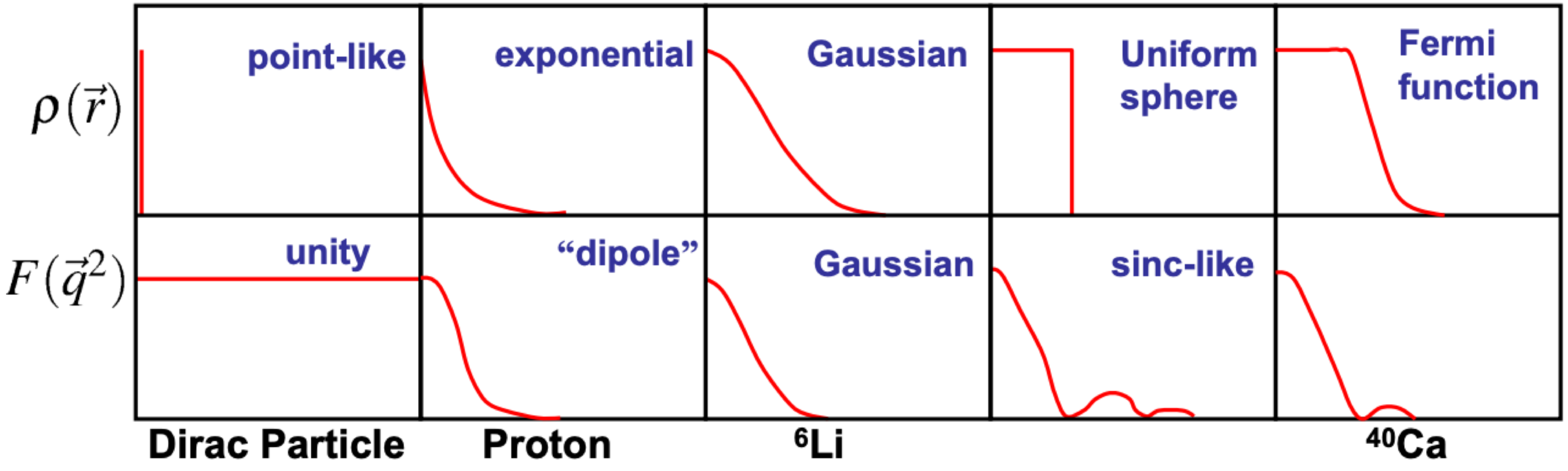
$$F(\vec{q}^2) = \int \rho(\vec{r}) e^{i\vec{q}.\vec{r}} \mathrm{d}^3\vec{r}$$

Elastic scattering: Form factors

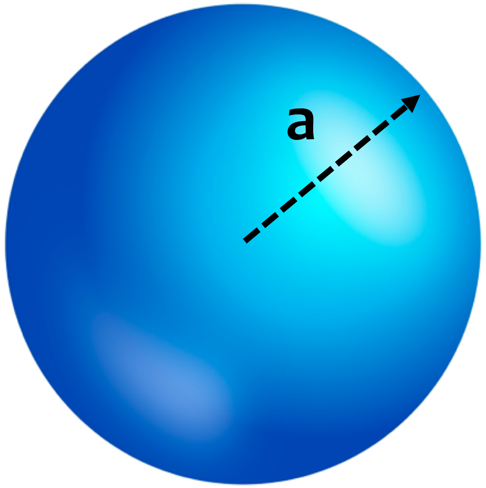
Recall the Mott cross section:

- Scattering from point-like object
- Target recoil neglected
- Scattered particle relativistic (E>>m_e)

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \rightarrow \underbrace{\overbrace{\frac{\alpha^2}{4E^2\sin^4\theta/2}}^{\text{Rutherford formula, rel.}}\overbrace{\cos^2\frac{\theta}{2}}^{\text{Overlap of initial/final state electron w.f.}}}_{\text{Mott XS}}\underbrace{|F(\vec{q}^{\,2})|^2}_{\text{FF}}$$



Imagine a sphere



Radius = a

Assume a uniform charge density, ρ_0

Thus, the charge is: $Z = \frac{4\pi}{3} a^3 \rho_0$

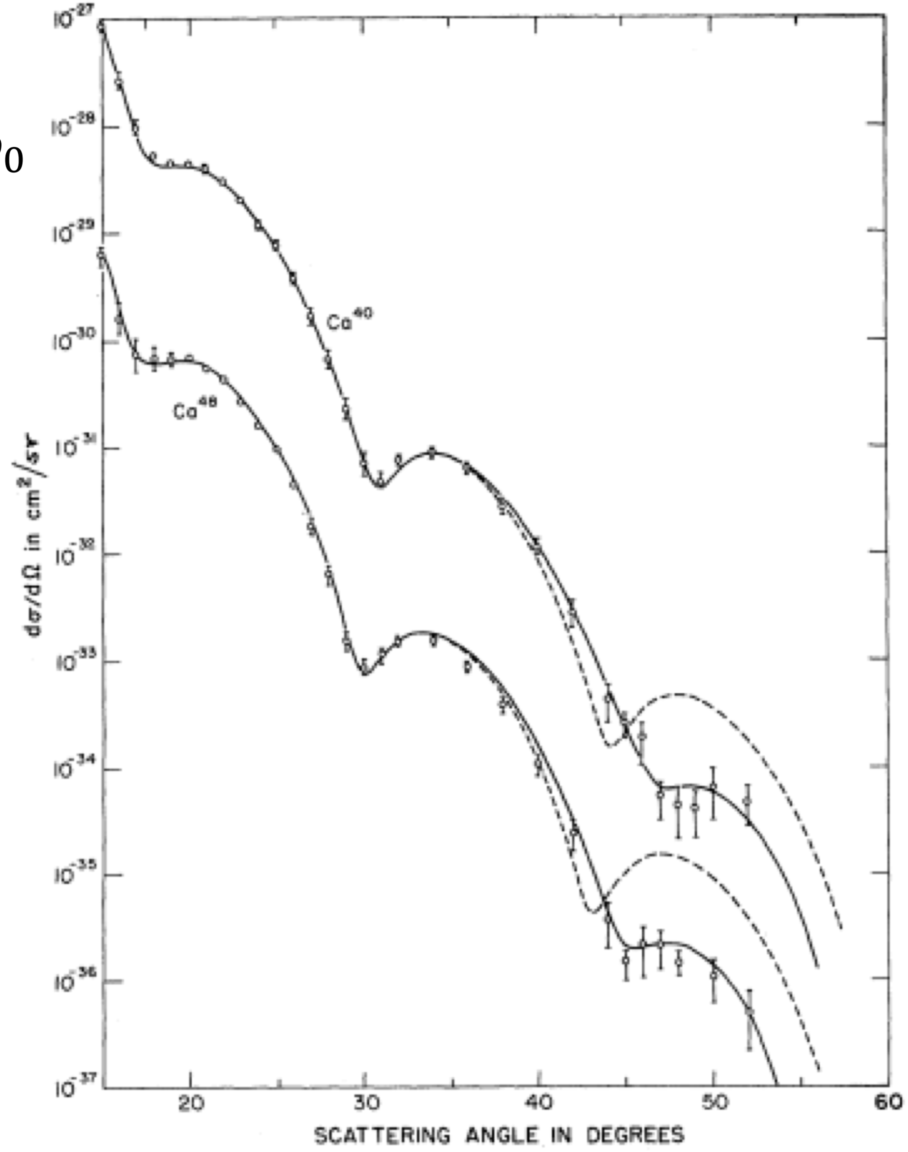


Figure 1: Elastic electron scattering off calcium. Taken from J. B. Bellicard et al, *Phys. Rev. Lett.*, **19**, 527 (1967)

The form factor (Fourier transform) is given:

$$\begin{aligned} F(q) &= \frac{1}{Z}\int d\vec{x}\rho_N(\vec{x})e^{i\vec{q}\cdot\vec{x}} \\ &= \frac{1}{Z}\int_0^{2\pi} d\phi \int_{-1}^{1} d\cos\theta \int_0^a r^2 dr \rho_0 e^{iqr\cos\theta} \\ &= \frac{1}{Z} 2\pi \int_0^a r^2 dr \rho_0 \frac{e^{iqr} - e^{-iqr}}{iqr} \\ &= 3\frac{\sin aq - aq\cos aq}{(aq)^3}. \end{aligned}$$

Charge Distributions from scattering

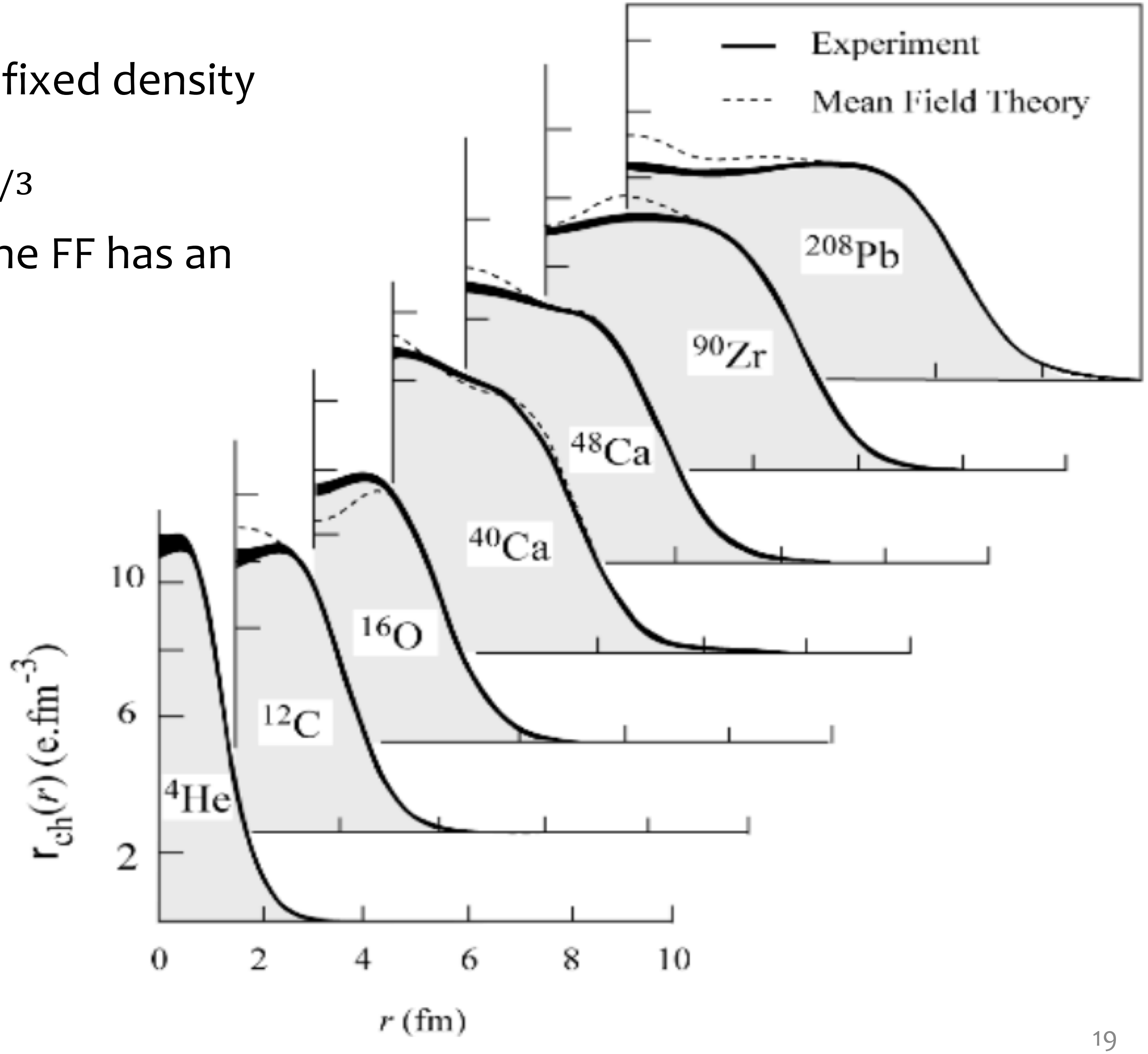
- Nuclei are approximately a spherical ball of fixed density
- General size of nucleus scales as $A^{1/3}$
- Nuclear radii are approximately 1.12 fm x $A^{1/3}$
- Precise scattering experiments show that the FF has an approximate dipole form:

$$F(q) \simeq \frac{1}{(1+q^2 a_N^2)^2}$$

where $\alpha_N \approx 0.26$ fm

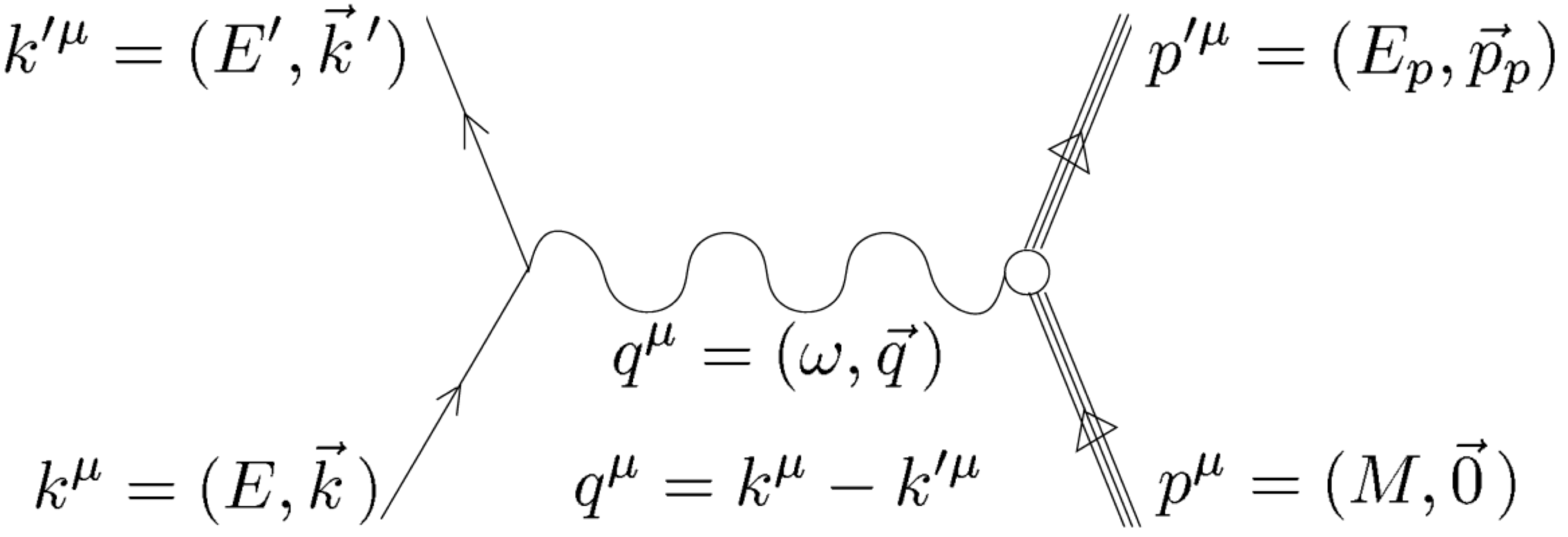
Hence, the charge density of the proton falls off as e^{-r/α_N}

A common description (different units) that we will revisit: $G_D = \left(1+\frac{Q^2}{0.71}\right)^{-2}$



Consider the recoiling proton

Lab frame kinematics



Invariants:

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

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

Proton of finite size

Elastic scattering (relativistic) from a point-like Dirac proton:

$$\frac{d\sigma}{d\Omega} = \underbrace{\frac{\alpha^2}{4E_1^2 \sin^4 \theta/2}}_{\text{Rutherford}} \underbrace{\frac{E_3}{E_1}}_{\text{Proton recoil}} \left(\underbrace{\cos^2 \frac{\theta}{2}}_{\text{Electric/Magnetic scattering}} - \underbrace{\frac{q^2}{2M^2} \sin^2 \frac{\theta}{2}}_{\text{Magnetic term due to spin}} \right)$$

But the proton is not point-like! The finite size of the proton accounted for by 2 structure functions

- Charge distribution described by $G_E(q^2)$
- Magnetic moment distribution described by $G_M(q^2)$

Rosenbluth Formula:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E_1^2 \sin^4 \theta/2} \frac{E_3}{E_1} \left(\frac{G_E^2 + \tau G_M^2}{(1+\tau)} \cos^2 \frac{\theta}{2} + 2\tau G_M^2 \sin^2 \frac{\theta}{2} \right)$$

Descriptions of the proton

Recall, the Mott XS: $\sigma_M = \dfrac{\alpha^2 \cos^2\left(\frac{\theta_e}{2}\right)}{4E^2 \sin^4\left(\frac{\theta_e}{2}\right)}$

Recoil factor — Form factors

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

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

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

Nucleon Form Factors:

- F_1, F_2: Dirac and Pauli form factors
- G_E, G_M: Sachs form factors (electric and magnetic)

$$G_E(Q^2) \equiv F_1(Q^2) - \tau\kappa F_2(Q^2)$$
$$G_M(Q^2) \equiv F_1(Q^2) + \kappa F_2(Q^2)$$

- R_L, R_T: Longitudinal and transverse response fn

where $\tau \equiv \frac{Q^2}{4M_N^2}$, κ is the anomalous magnetic moment

Measuring the form factors

We can rewrite the cross section as:

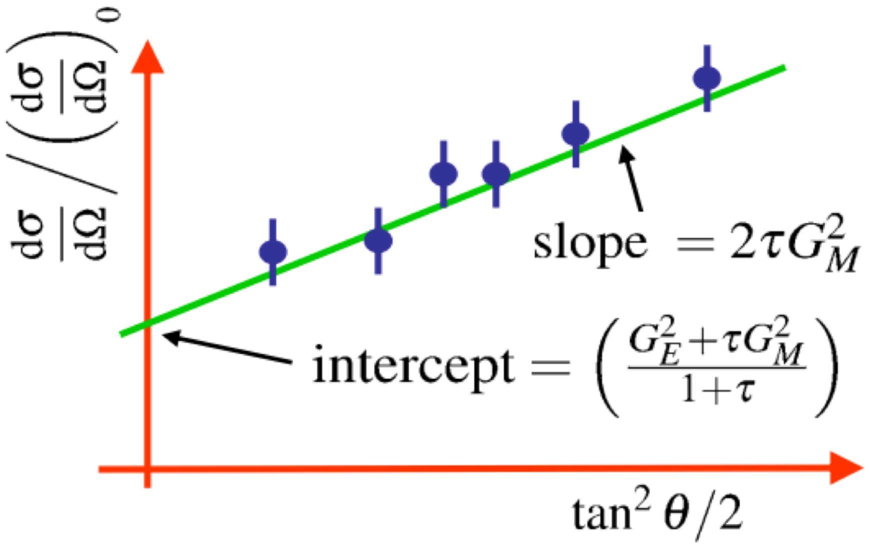
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 \left(\frac{G_E^2 + \tau G_M^2}{(1+\tau)} + 2\tau G_M^2 \tan^2\frac{\theta}{2}\right)$$

Where we have the Mott cross section including the proton recoil as:

$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{\alpha^2}{4E_1^2 \sin^4\theta/2}\frac{E_3}{E_1}\cos^2\frac{\theta}{2}$$

Experimentally, we can study the angular dependence of the cross section at fixed Q^2

Reduced cross section



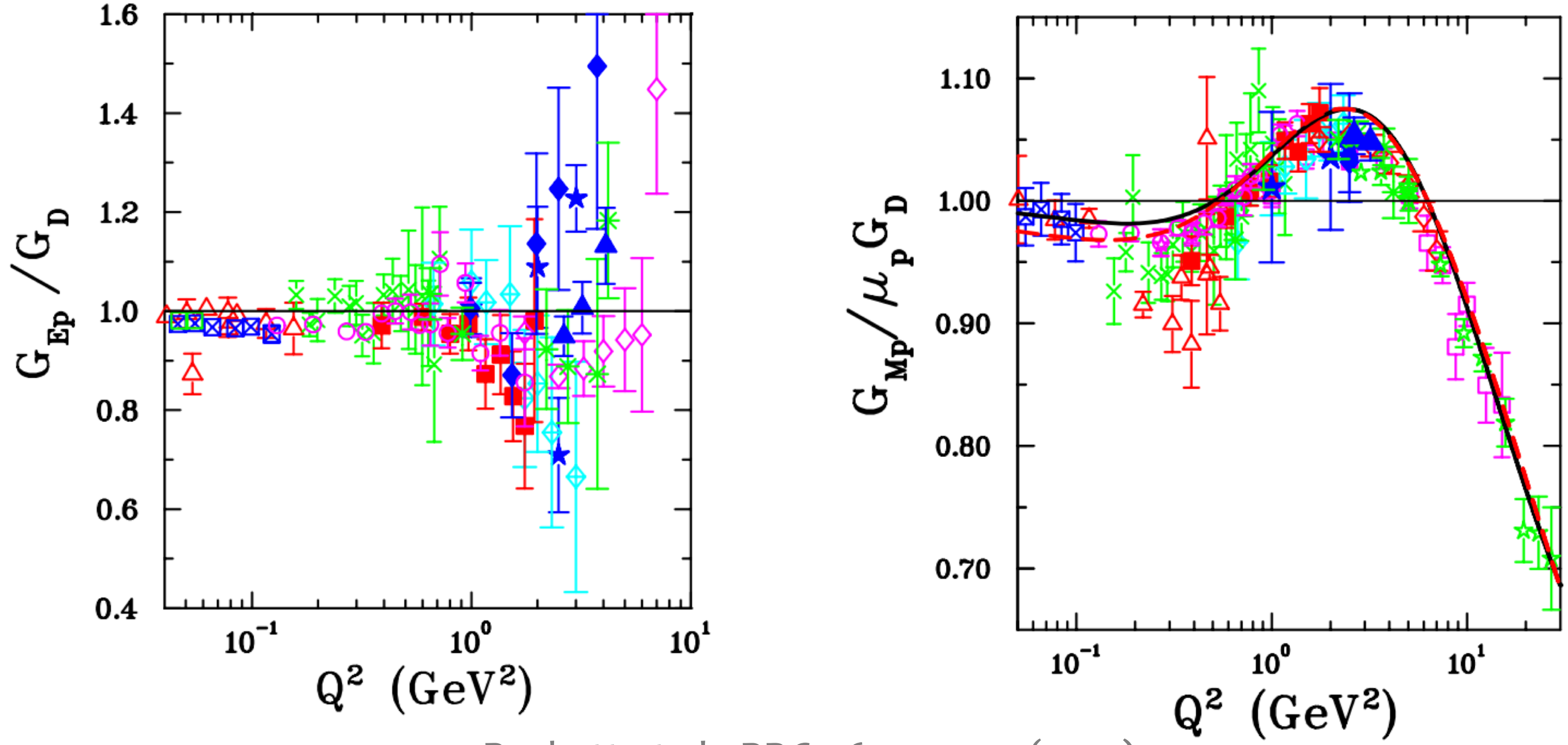
Rosenbluth separation, technique:
note the sensitivity is to the squares of the FFs

Form factor dependence

From elastic scattering on the proton, we determined the "dipole" form factor as:

$$G_D = \left(1 + \frac{Q^2}{0.71}\right)^{-2}$$

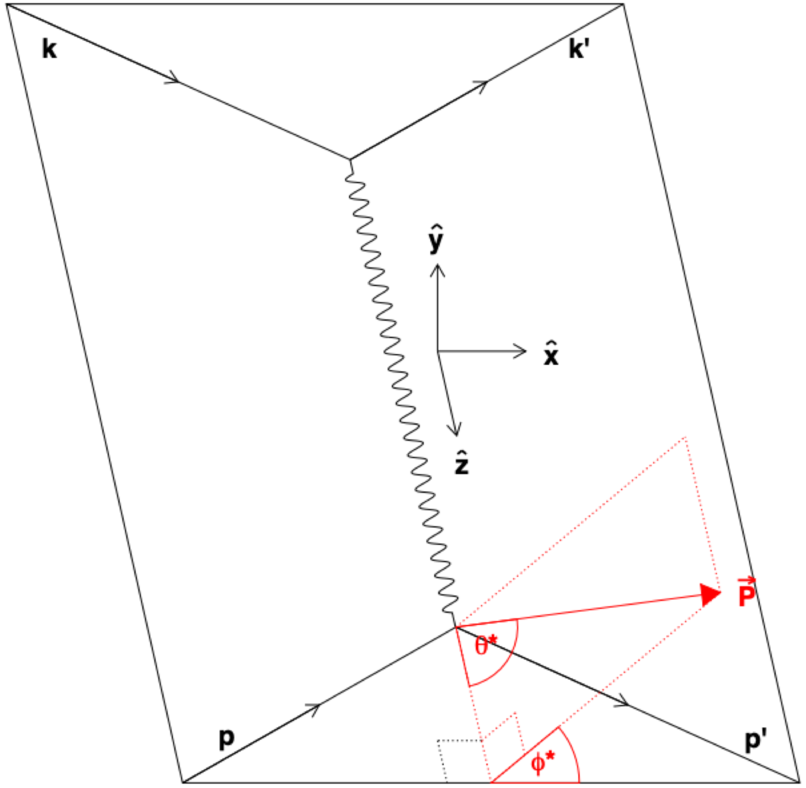
Proton form factors from Rosenbluth separations:



Puckett et al., PRC 96, 055203 (2017)

Improved sensitivity to the form factors

Longitudinally polarized beam and measuring the polarization transferred to the recoiling nucleon



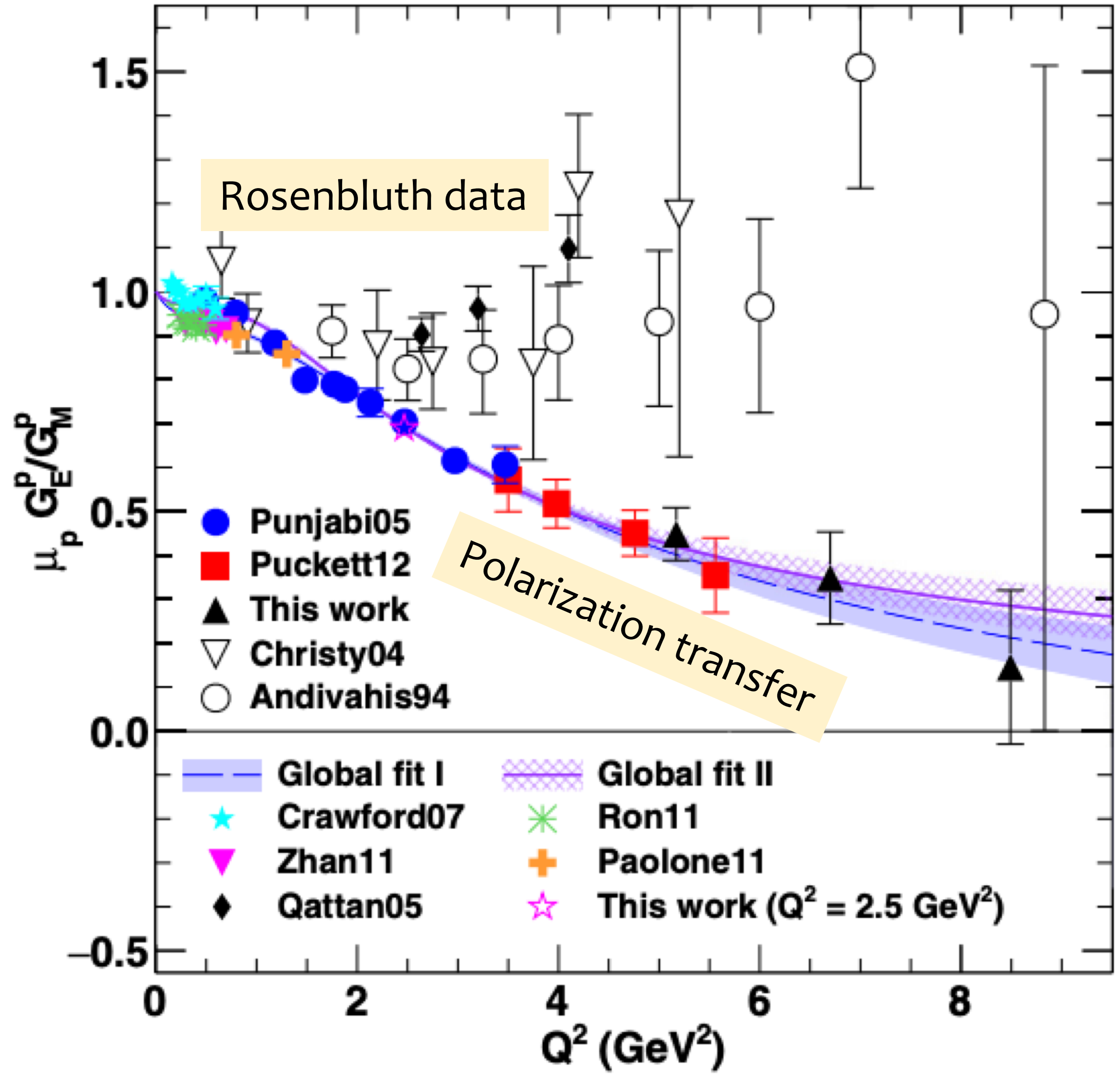
$$P_t = -hP_e\sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}}\frac{G_E G_M}{G_M^2 + \frac{\epsilon}{\tau}G_E^2},$$

$$P_\ell = hP_e\sqrt{1-\epsilon^2}\frac{G_M^2}{G_M^2 + \frac{\epsilon}{\tau}G_E^2},$$

$$\frac{G_E}{G_M} = -\frac{P_t}{P_\ell}\sqrt{\frac{\tau(1+\epsilon)}{2\epsilon}} = -\frac{P_t}{P_\ell}\frac{E_e + E'_e}{2M}\tan\left(\frac{\theta_e}{2}\right)$$

Enhanced sensitivity to the ratio ->
increased sensitivity to G_E for large Q^2 and G_M for small Q^2

Form factor ratio



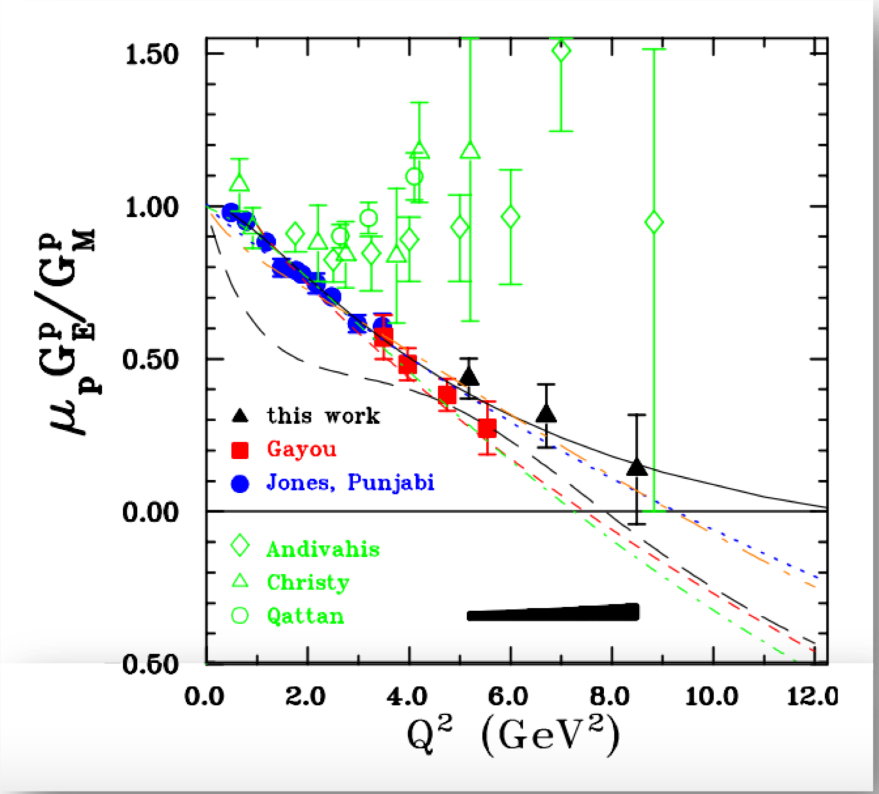
Large discrepancy between Rosenbluth-extracted data and polarization transfer measurements!

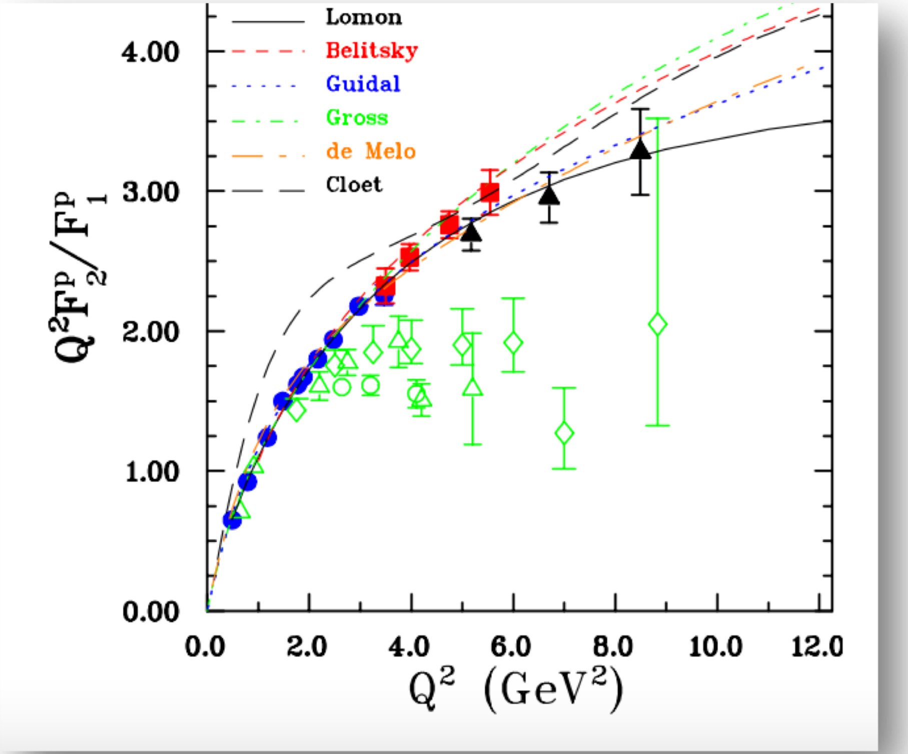
Two photon exchange correction neglected in Rosenbluth data is significant to the radiative corrections.

Puckett et al., PRC 96, 055203 (2017)

Scaling regime is unclear

pQCD predicts a plateau such that $F_2^p \propto F_1^p/Q^2$

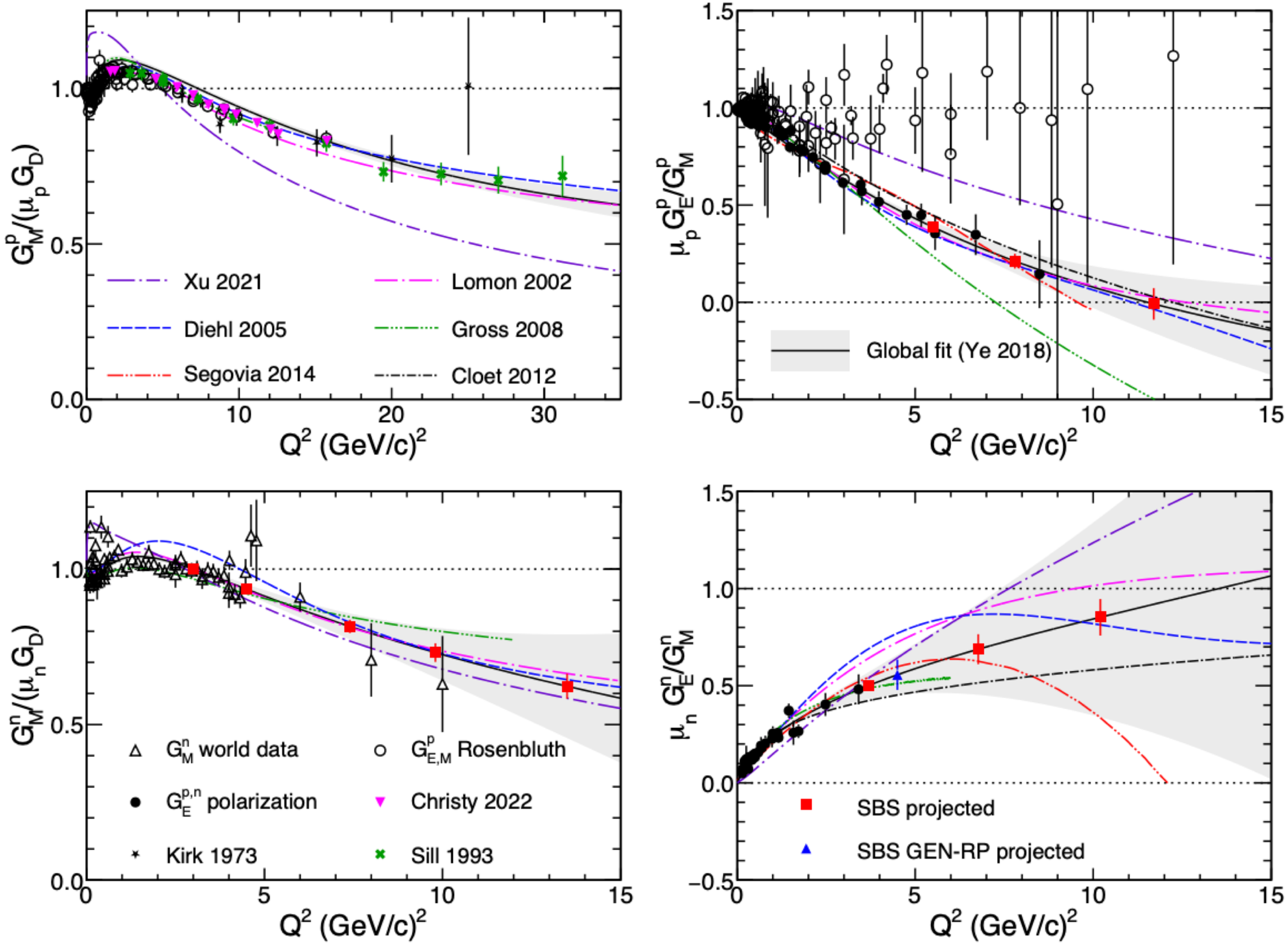




A.J.R. Puckett et al., Phys. Rev. Lett. 104, 242301 (2010).

Fear not-SBS is here!

Also integral to the CLAS12 experimental program!
G_M^n from Q^2 =3.5-13.5 GeV²

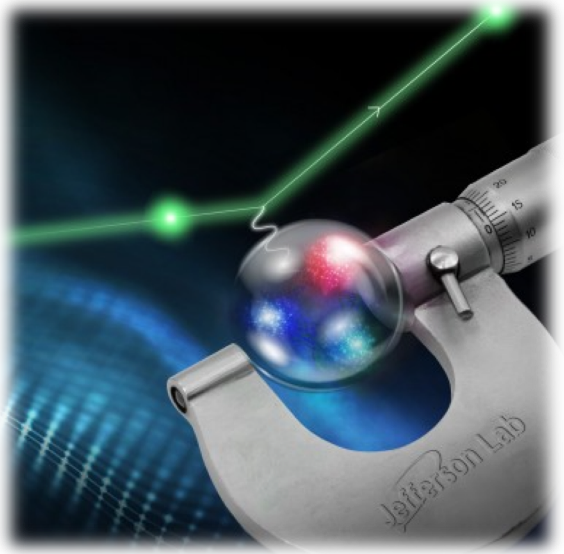


Proton charge radius

To measure the proton charge radius, we use the fact that as Q^2 goes to 0, the charge radius is proportional to the slope of G_E

$$G_E(Q^2) = 1 + \sum_{n\geq 1} \frac{(-1)^n}{(2n+1)!} \left\langle r^{2n} \right\rangle Q^{2n}$$

$$r_p \equiv \sqrt{\langle r^2 \rangle} = \left(-6 \left. \frac{\mathrm{d}G_E(Q^2)}{\mathrm{d}Q^2} \right|_{Q^2=0} \right)^{1/2}$$

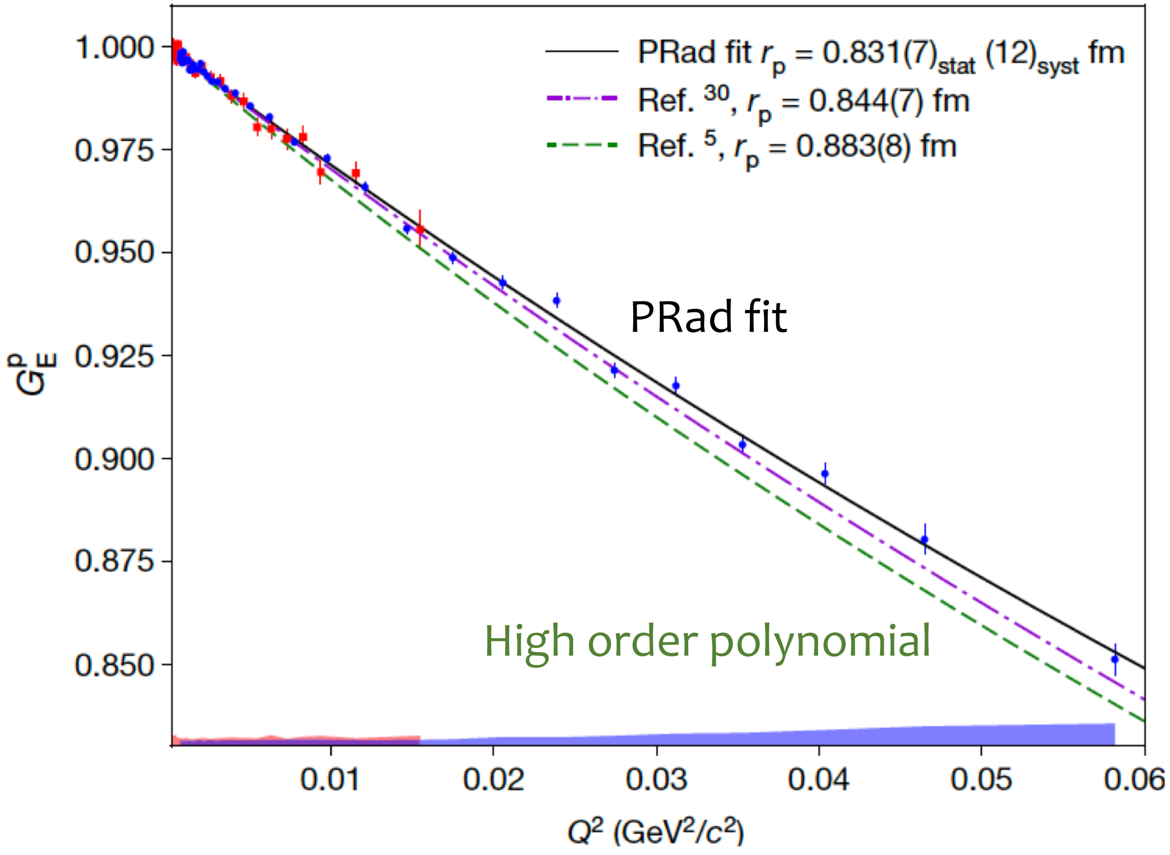


Since we don't measure Q^2 at 0, we have to extrapolate.

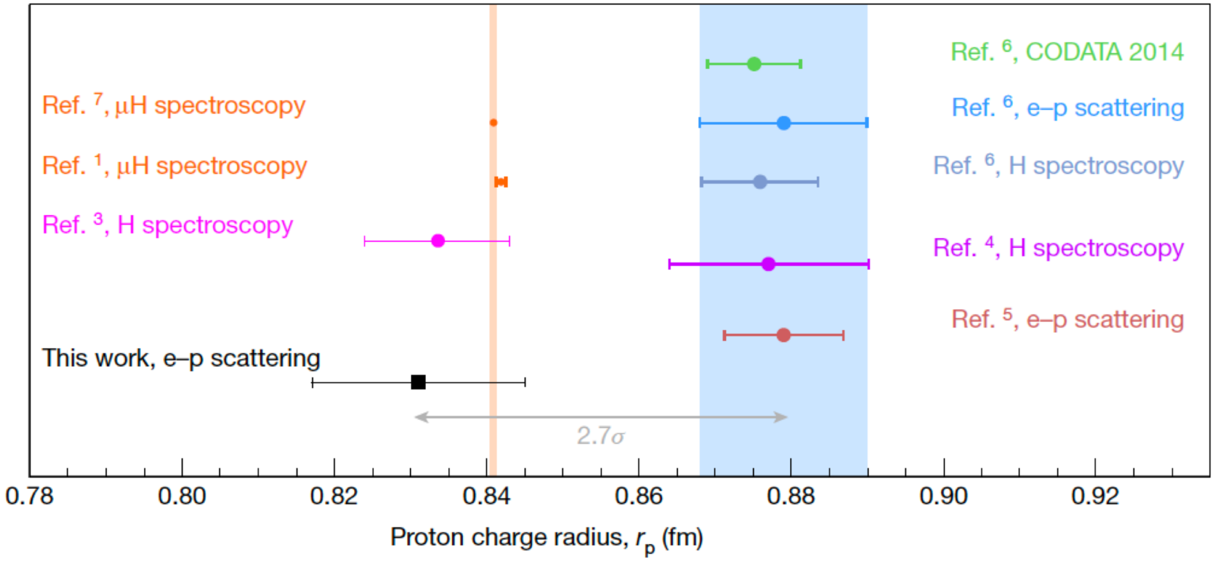
While the proton radius definition is the same whether done on muonic hydrogen or elastic electron-proton scattering, there is a historical division amongst the results.

PRad experiment in Hall B

W. Xiong et al, *Nature* 575, 147-150 (2019)

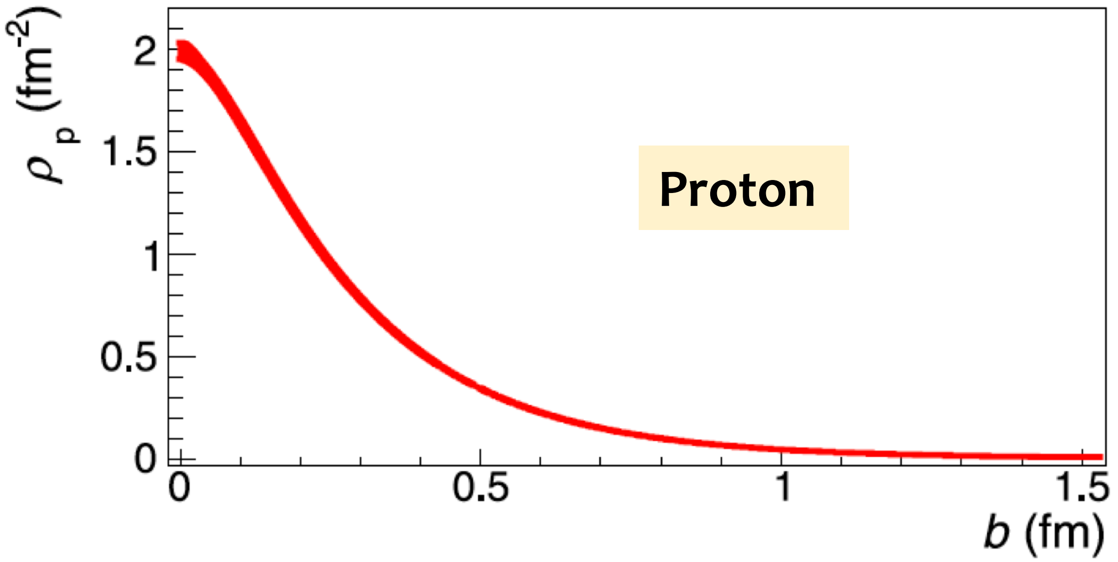


This recent proton radius measurement found agreement with the muonic hydrogen radius extractions.

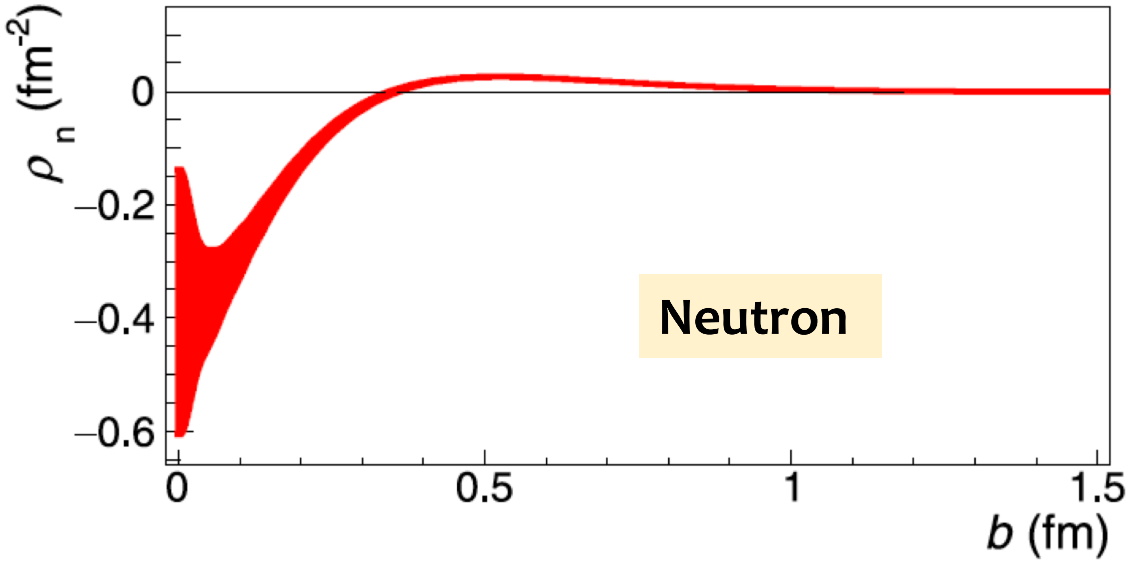


High precision, detailed e-p elastic scattering at small angle and small Q^2, thus G_M^p contribution was negligible (small systematic)

Going back to charge densities

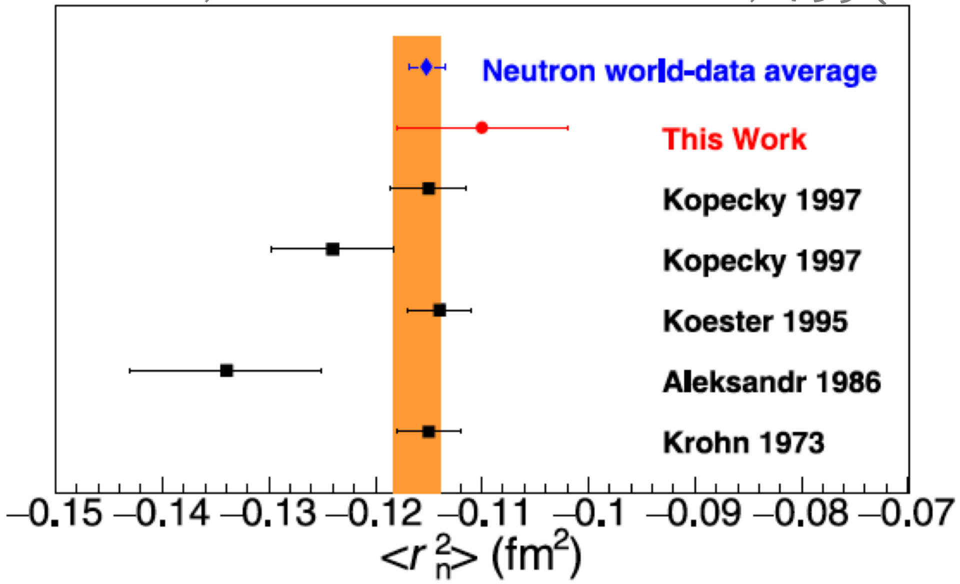


Proton peaks at low values of b but has a long positive tail -> long-ranged, positively charged pion cloud



Neutron is negative in the center and positive at the edge! Attributable to negatively charged down quarks.

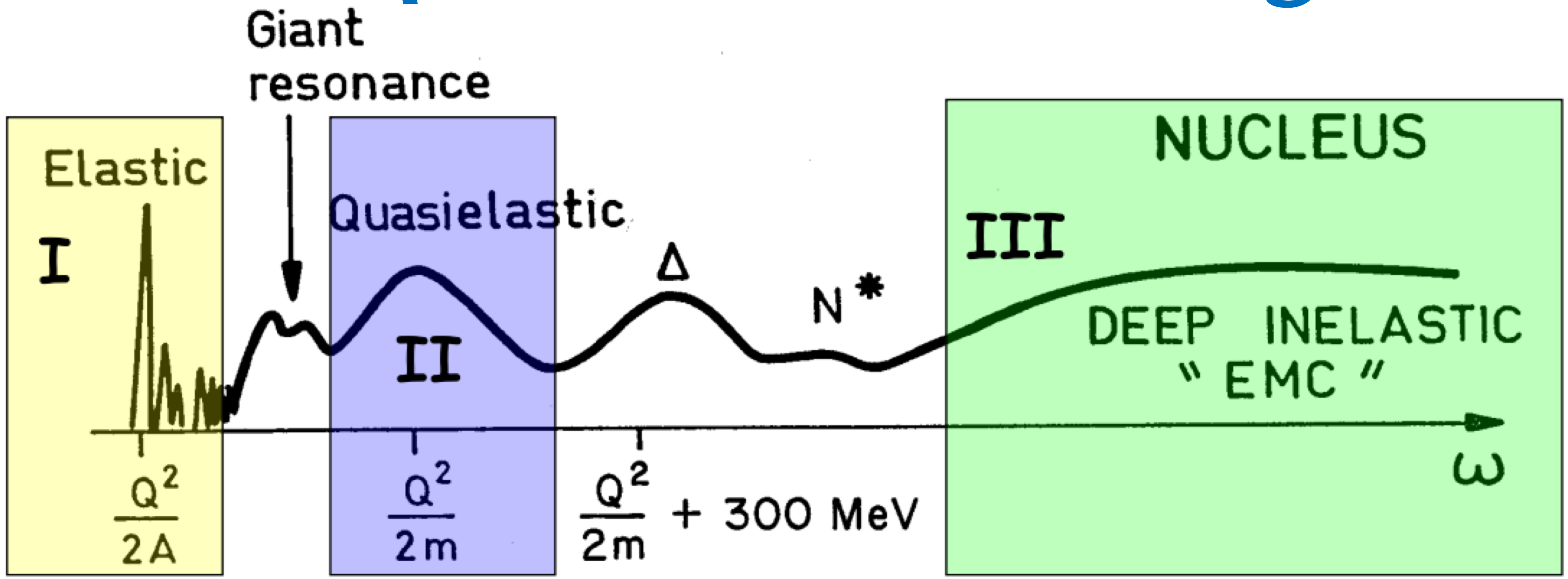
H. Atac et al, *Nature Communications* 12, 1759 (2021)

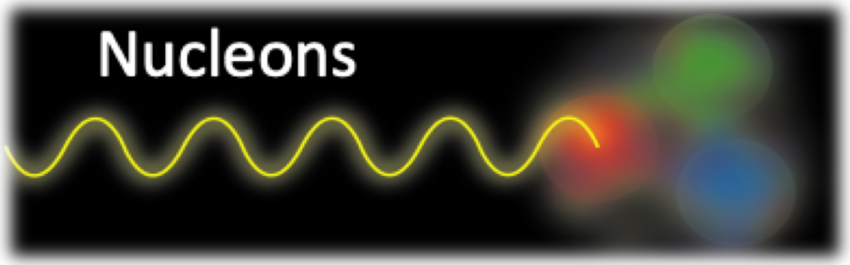


Elastic scattering summary

- We can measure things like the charge and magnetic moment distributions of the nucleons.
- These are described in terms of form factors (a Fourier transformation of the distributions).
- We can use form factors to extract the radius.
- This tells us about the structure of nucleons and nuclei.
- Nucleons are not point-like!

Quasielastic scattering

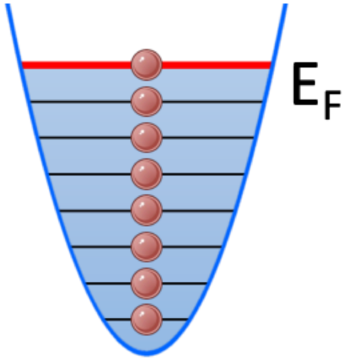




- Momentum distributions
- Shell structure and occupancies
- Short-range correlated pairs
- Transparency
- medium modification

THERE'S *NOTHING* MORE OBNOXIOUS THAN A PHYSICIST FIRST ENCOUNTERING A NEW SUBJECT.

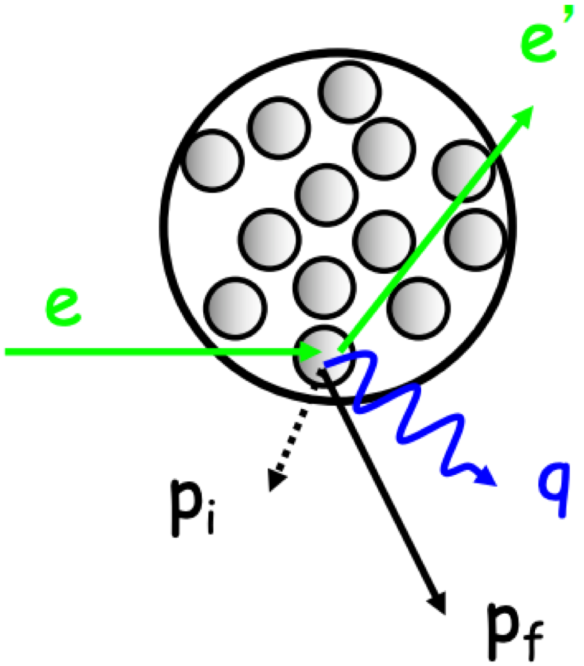
The nucleus as a Fermi gas



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



We can expect:

peak centroid of $\nu = q^2/2m_p + \varepsilon$

peak width is $2qp_{fermi}/m_p$

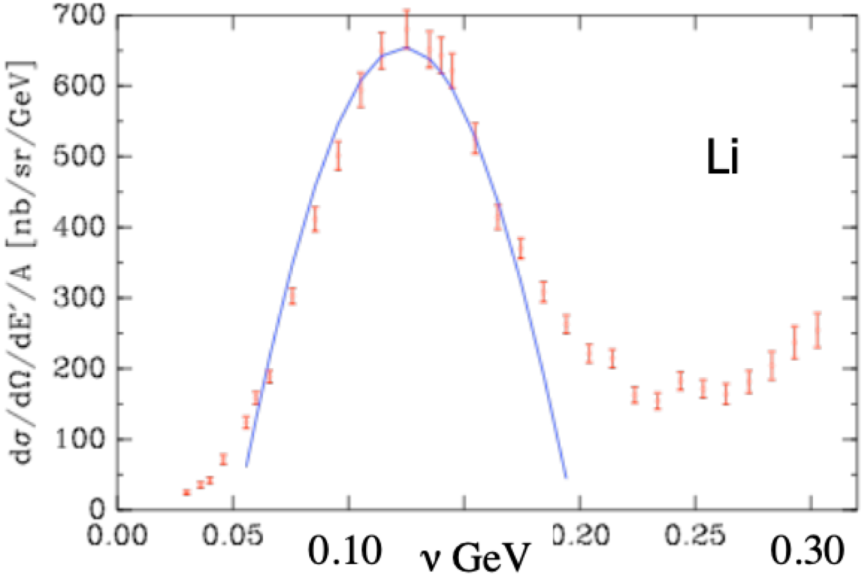
Total peak cross section would be $Z\sigma_{ep} + N\sigma_{en}$

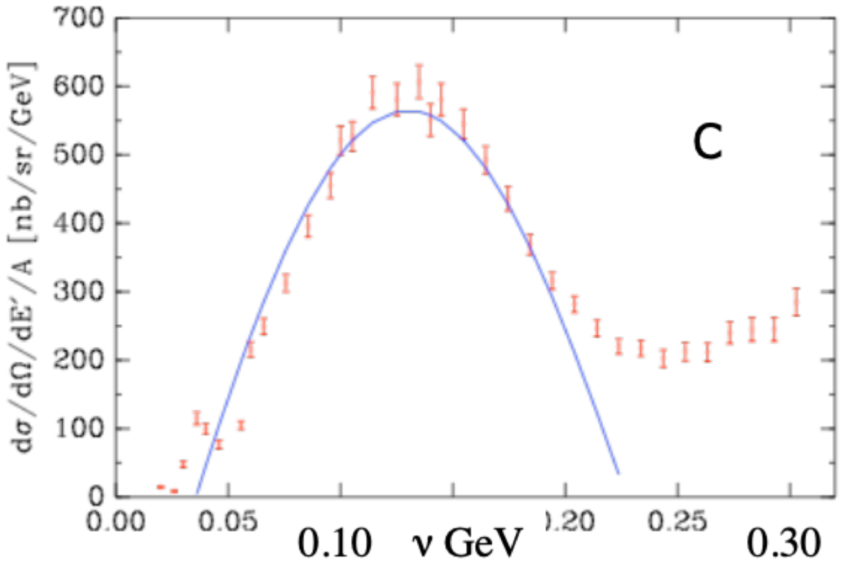
Good approximation of the cross section, but not descriptive of structure.

Early 1970s quasielastic data

500 MeV, 60 deg
q≈ 500 MeV/c

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

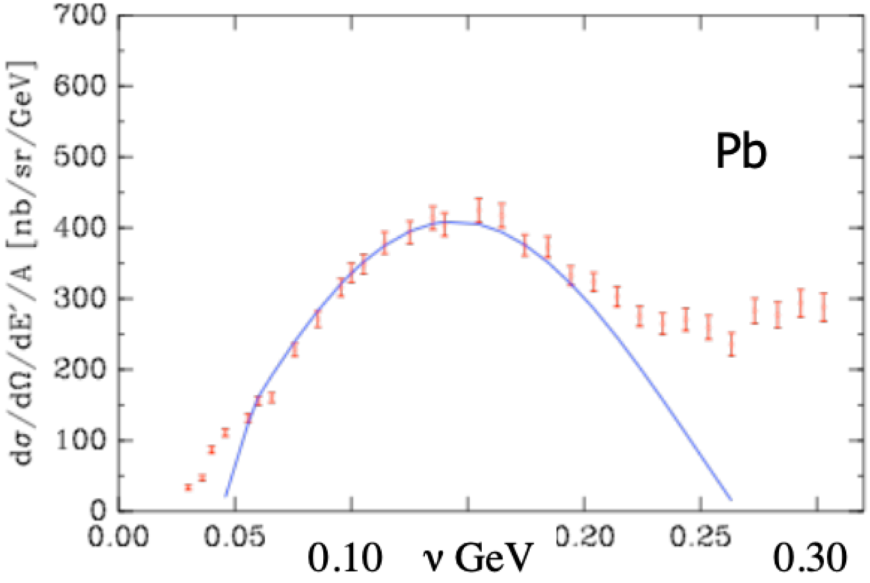




Width ~ k_F
(Fermi momentum)

Mean ~ ε
(separation energy)

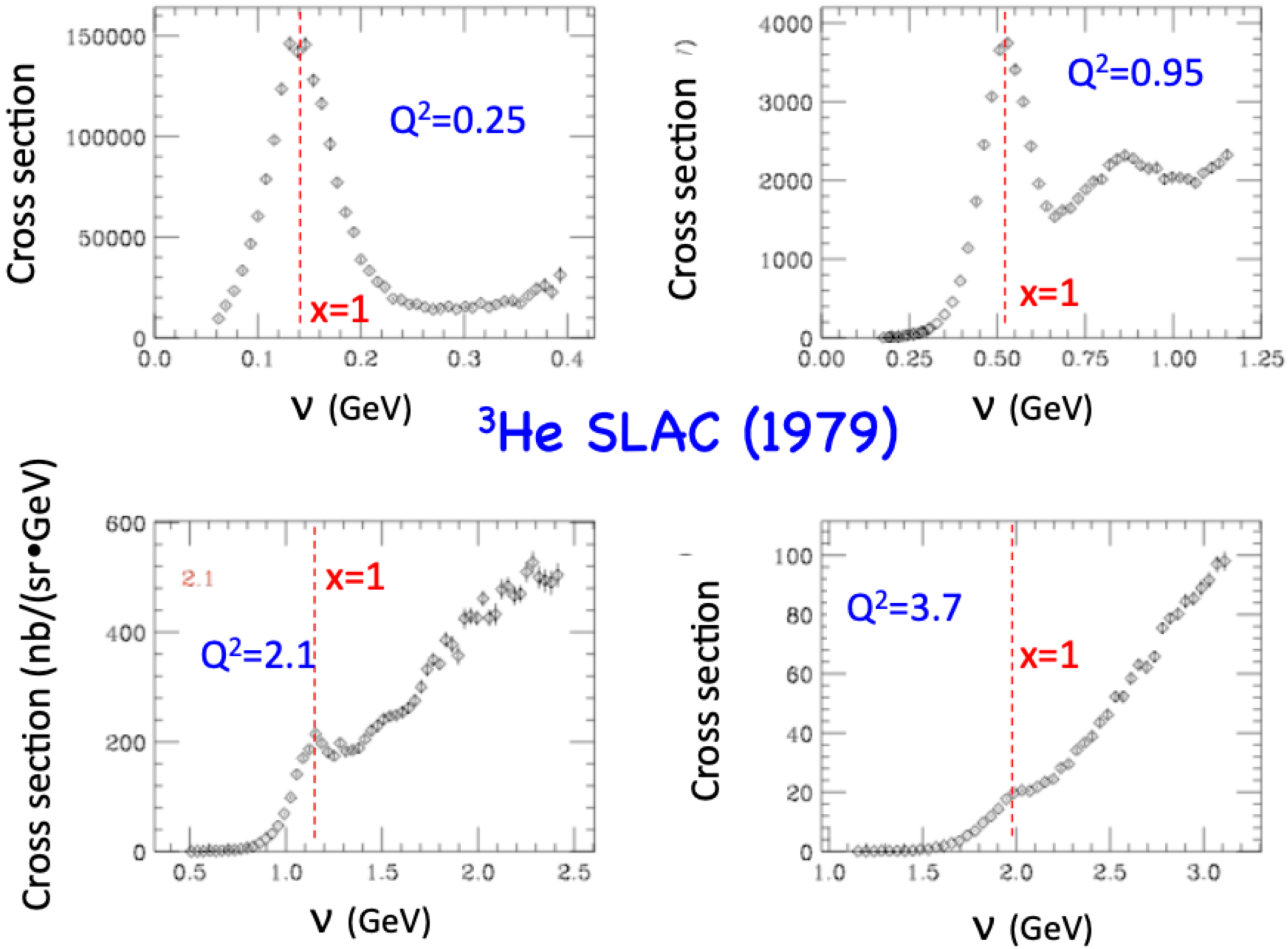
- Peak broadens with increasing A



Nucleus	k_F MeV/c	$\bar{\varepsilon}$ 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

Quasielastic peak



Inelastic scattering begins to dominate at $Q^2 \gg 1$ GeV²

y-scaling

Scaling refers to the dependence of a cross section on a single variable

- Scaling validates the scaling assumption
- Scale-breaking indicates something we don't understand

At moderate Q^2 and $x_B > 1$, we expect **y-scaling**:

- Electrons scatter from **quasifree nucleons**
- y = minimum momentum of the struck nucleon

At high Q^2, we expect **x-scaling**:

- Electrons are scattering from **quarks**
- $x_B = \frac{Q^2}{2m\nu} \equiv$ fraction of the nucleon momentum carried by the struck quark (in the infinite momentum frame)

y-scaling

Under certain assumptions, the cross section can be written as:

$$\frac{d^2\sigma}{d\Omega_e d\omega} \approx \bar{\sigma}_e(q,y) \cdot F(y)$$

quantity related to the elementary electron nucleon cross section

F(y) = probability to find in the nucleus a nucleon of momentum component y parallel to **q**

y-scaling in quasielastic scattering reveals the nucleon momentum distribution in the nucleus.

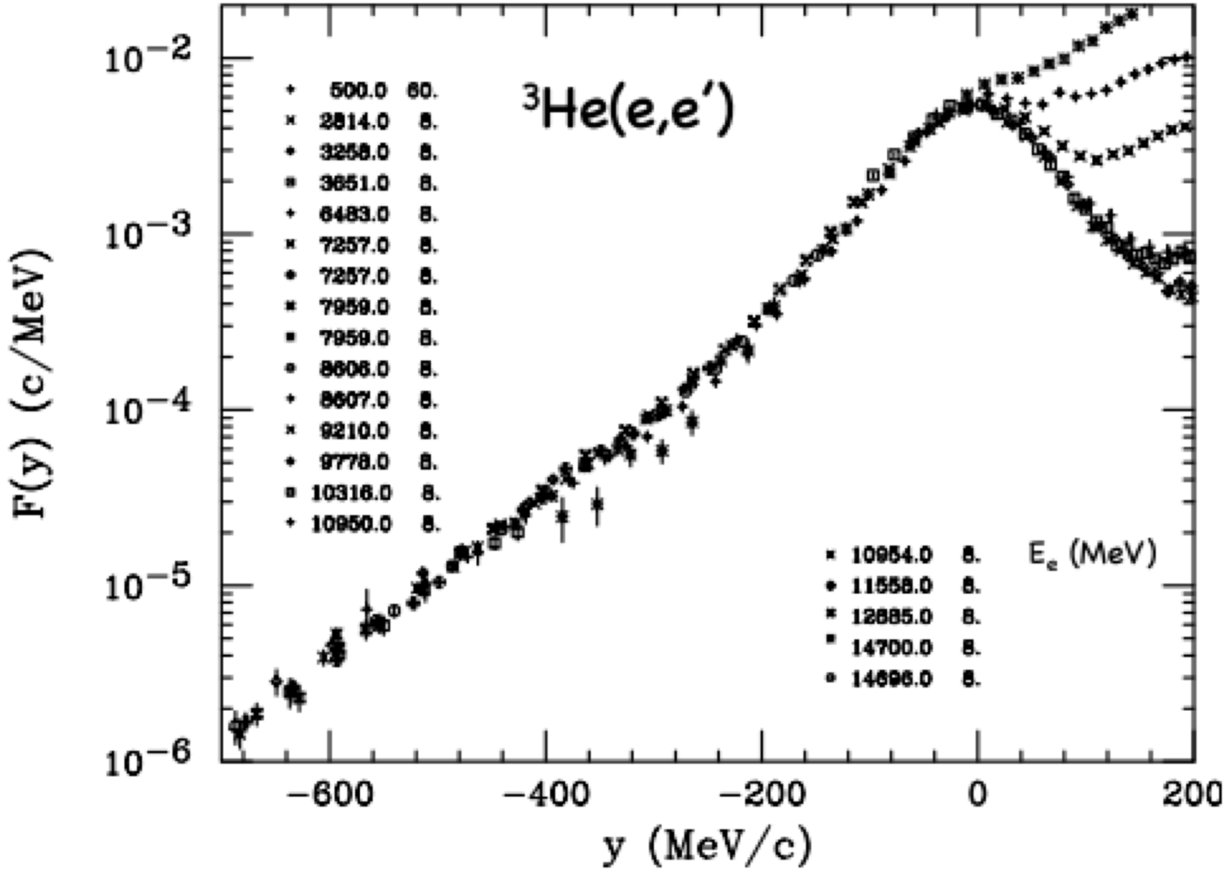
Deviation of the cross section from scattering from free nucleons scales to y.

$$F(y) = \frac{\sigma(q,\omega)}{Z\sigma_{ep} + N\sigma_{en}} \cdot \frac{d\omega}{dy}$$

D.H. Lu, et al., Nucl. Phys. A 634, 443 (1998); O. Benhar, D. Day, I. Sick, Rev. Mod. Phys. 80, 189 (2008)

y-scaling in inclusive 3He scattering

Evidence of y-scaling over range of energy transfer

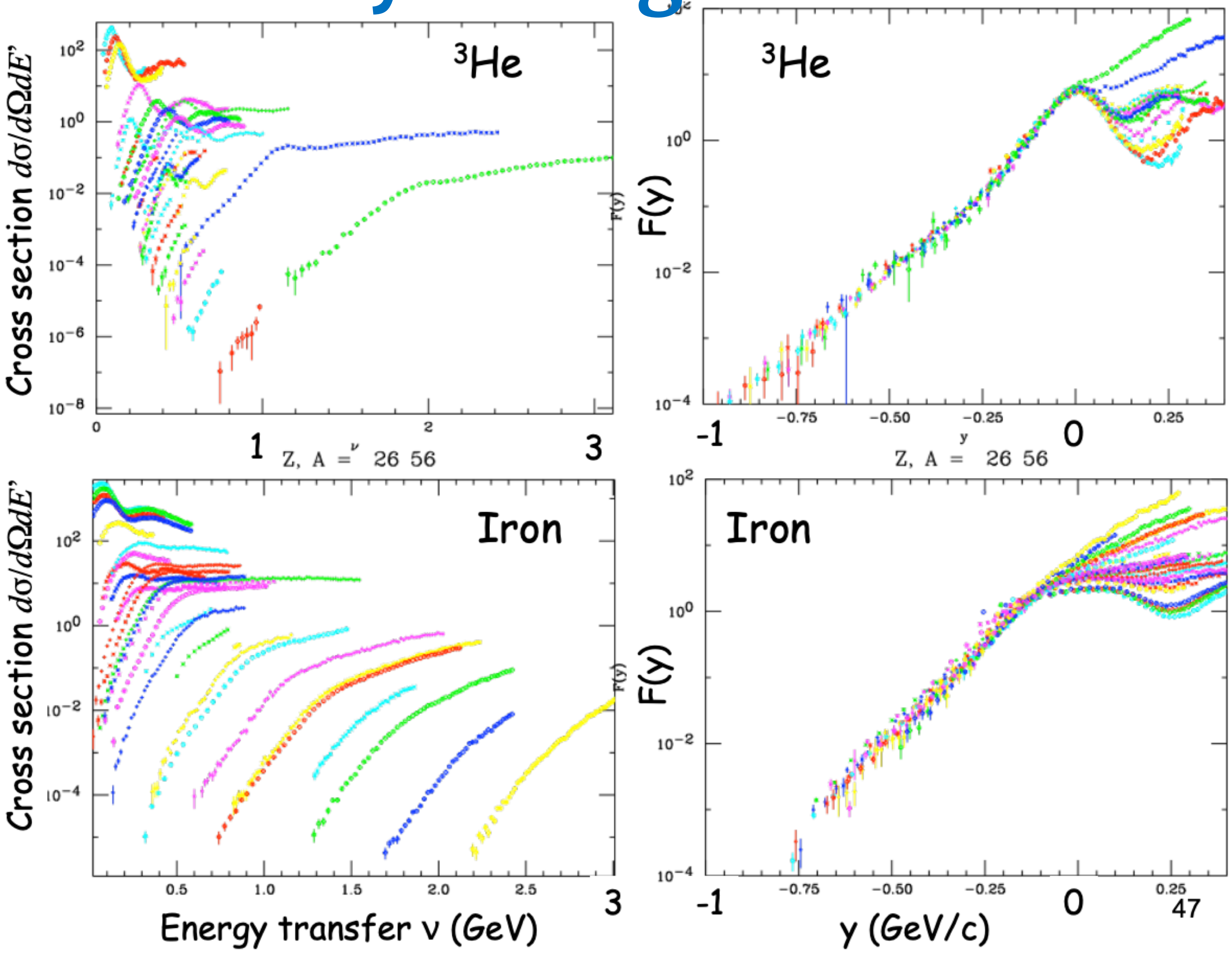


Assumptions in y-scaling:

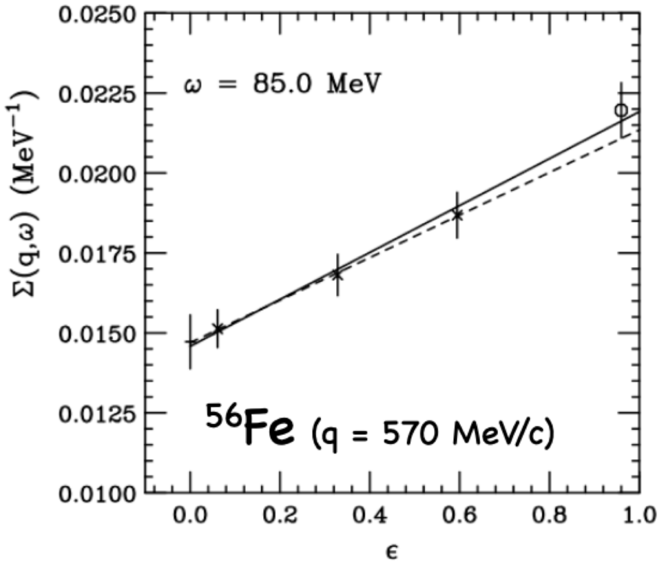
- No final state interactions (FSI)
- No internal excitation
- No medium modifications
- No inelastic processes (only y<0)
- Full strength of the spectral function can be integrated for finite q

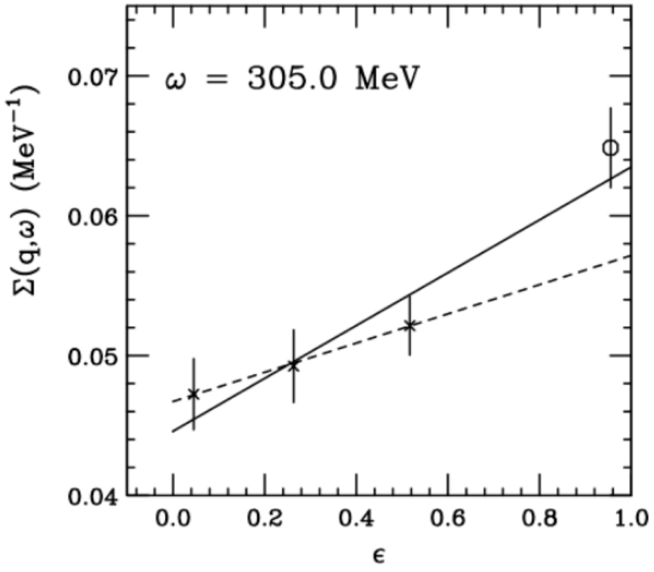
I. Sick, D. Day and J.S. McCarthy, Phys. Rev. Lett. 45, 871 (1980)

y-scaling works!



Rosenbluth technique on quasielastic A(e,e')





Rosenbluth technique allows us to write:

$$\Sigma(q,\omega,\epsilon) = \frac{d^2\sigma}{d\Omega\, d\omega}\frac{1}{\sigma_{\text{Mott}}}\epsilon\left(\frac{q}{Q}\right)^4$$
$$= \epsilon R_L(q,\omega) + \frac{1}{2}\left(\frac{q}{q}\right)^2 R_T(q,\omega)$$

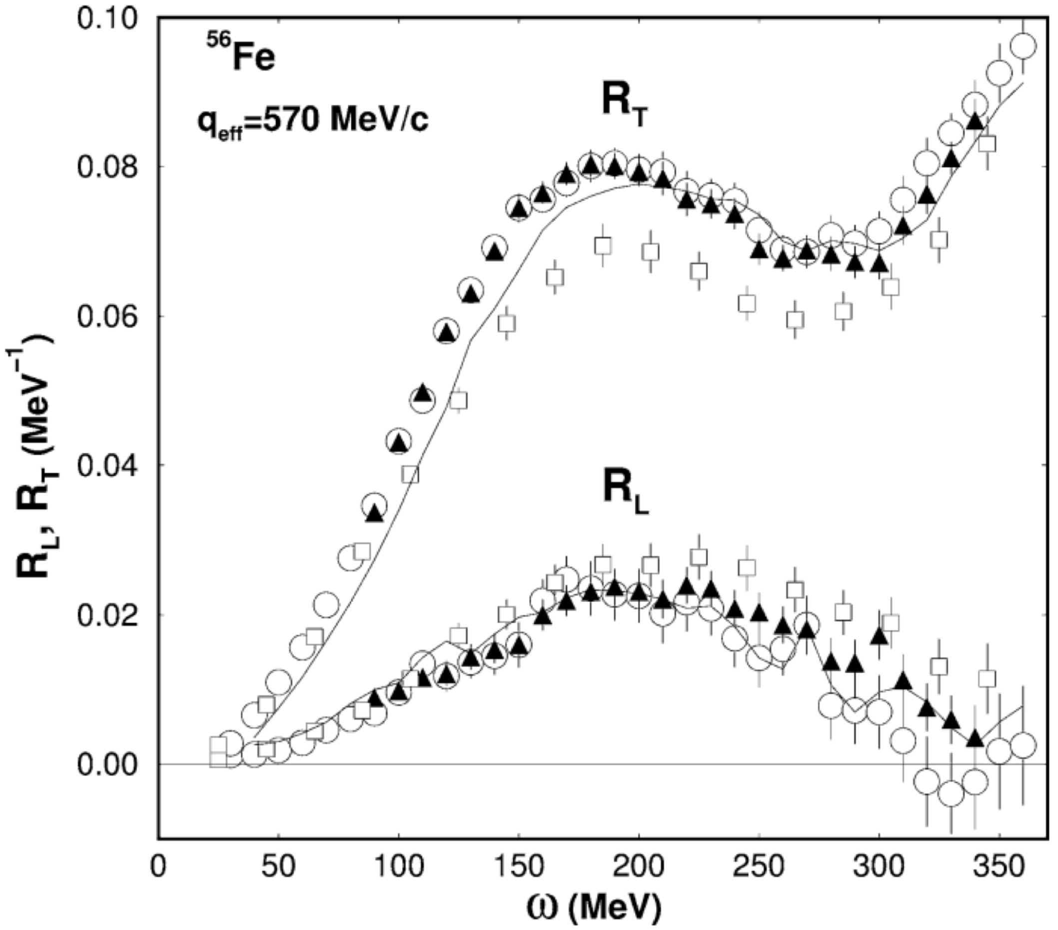
Where, the longitudinal virtual photon polarization is $\epsilon = \left(1 + \frac{2q^2}{Q^2}\tan^2\frac{\vartheta}{2}\right)^{-1}$

Here we assume the plane wave born approximation. Data must be corrected for Coulomb distortions.

We fix q and vary θ.

J. Jourdan, Nucl. Phys. A 603, 117 (1996)

Coulomb Sum Rule



L/T separation:

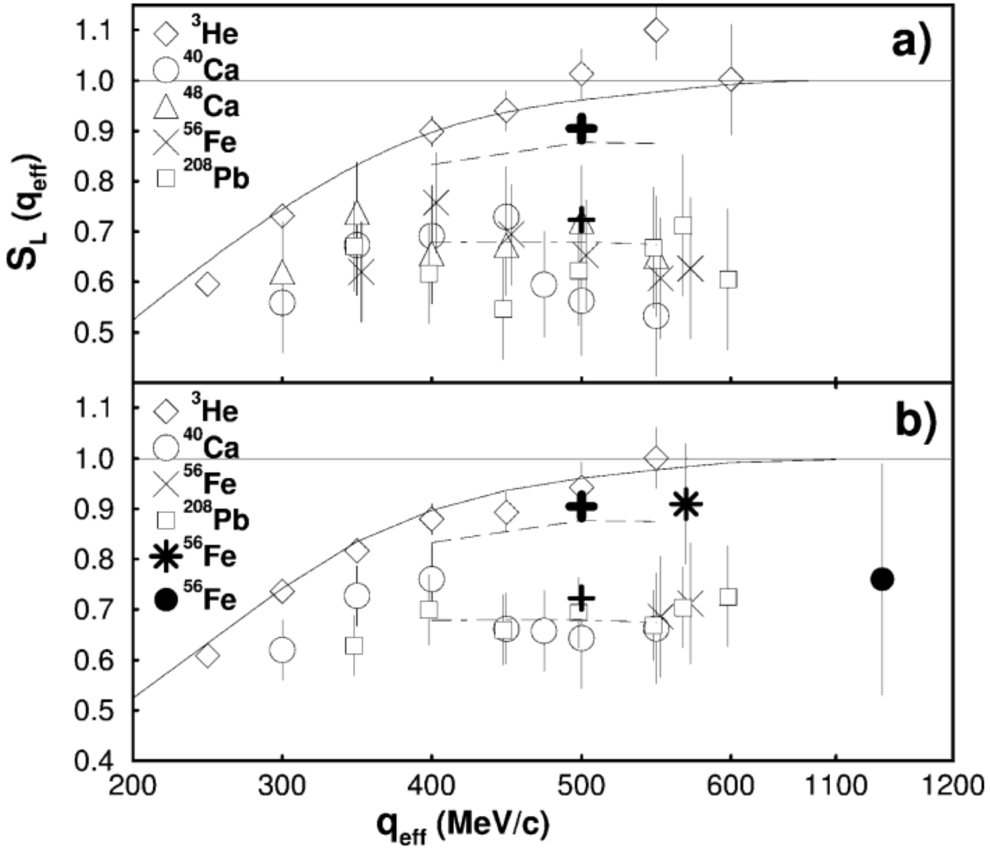
- Transverse response: contributions from meson exchange currents and Δ excitation
- Longitudinal response: expected to obey the **Coulomb Sum Rule**:

$$S_L(q) = \frac{1}{Z} \int_{0+}^{\infty} \frac{R_L(q,\omega)}{\widetilde{G}_E^2} d\omega \quad \longrightarrow 1$$

We expect that integrating the quasielastic R_L over the full range of energy loss at large enough q (>2p_f), we can count the number of protons in the nucleus (nonrelativistic assumption).

J. Morgenstern, Z.-E. Meziani, Phys. Lett. B 515, 269 (2001)

Coulomb Sum Rule: evidence for QCD effects in nuclei?



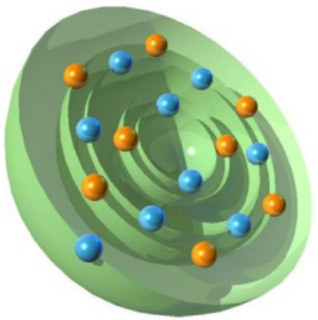
Experimental findings are controversial

- No quenching [1]
- Quenching [2]
- Jury is still out

Good agreement for 4He using free-nucleon form factors

[3] Suggests evidence for modification of the form factors in nuclei due to medium modifications (quark-level)

[1] J. Jourdan, Nucl. Phys. A 603, 117 (1996)
[2] J. Morgenstern, Z.-E. Meziani, Phys. Lett. B 515, 269 (2001)
[3] I. Cloet, Phys. Rev. Lett. 116, 032701 (2016)

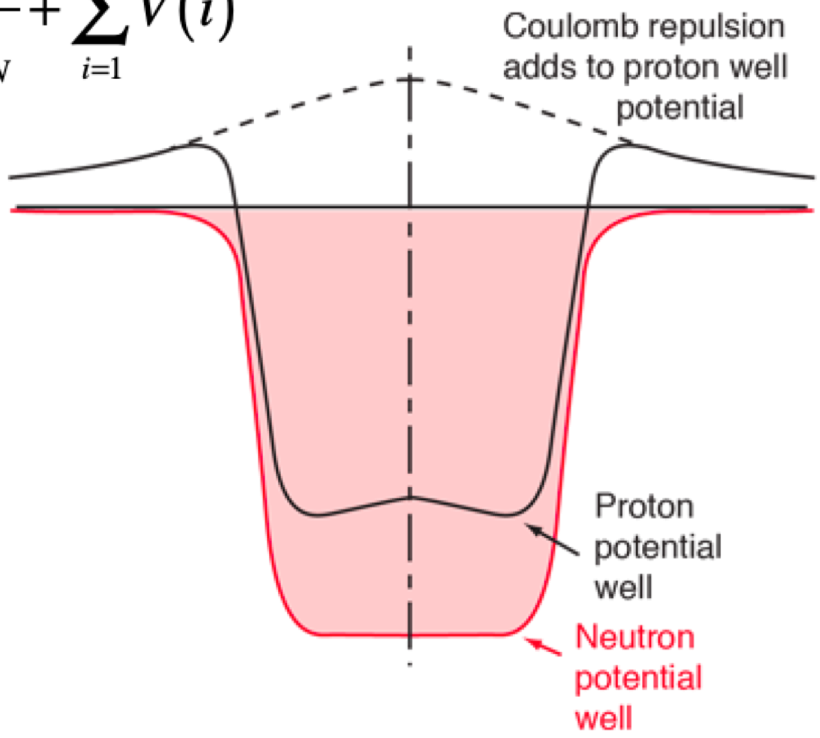


Independent particle shell model

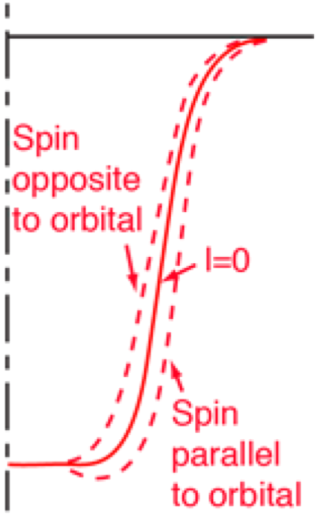
Nucleon moves in an effective, attractive potential formed by the other nucleons (mean-field)

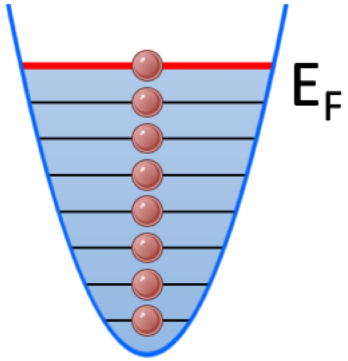
No interaction at short distance

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



Correction due to spin-orbit interaction





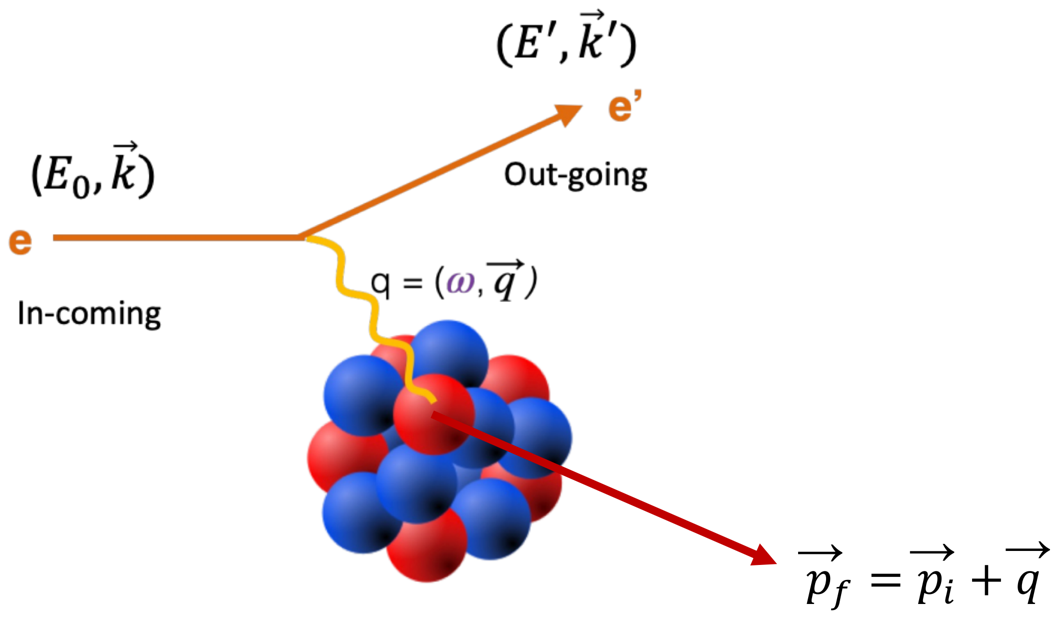
Works decently up to k_f

1963 Nobel Prize to Wigner, Mayer, and Jenson

Plane wave impulse approximation (PWIA)

Assumptions:

- Virtual photon is absorbed by one nucleon
- Nucleon does not interact further
- Thus, in measuring the knocked out nucleon, the missing momentum of the reaction = initial nucleon momentum in the nucleus



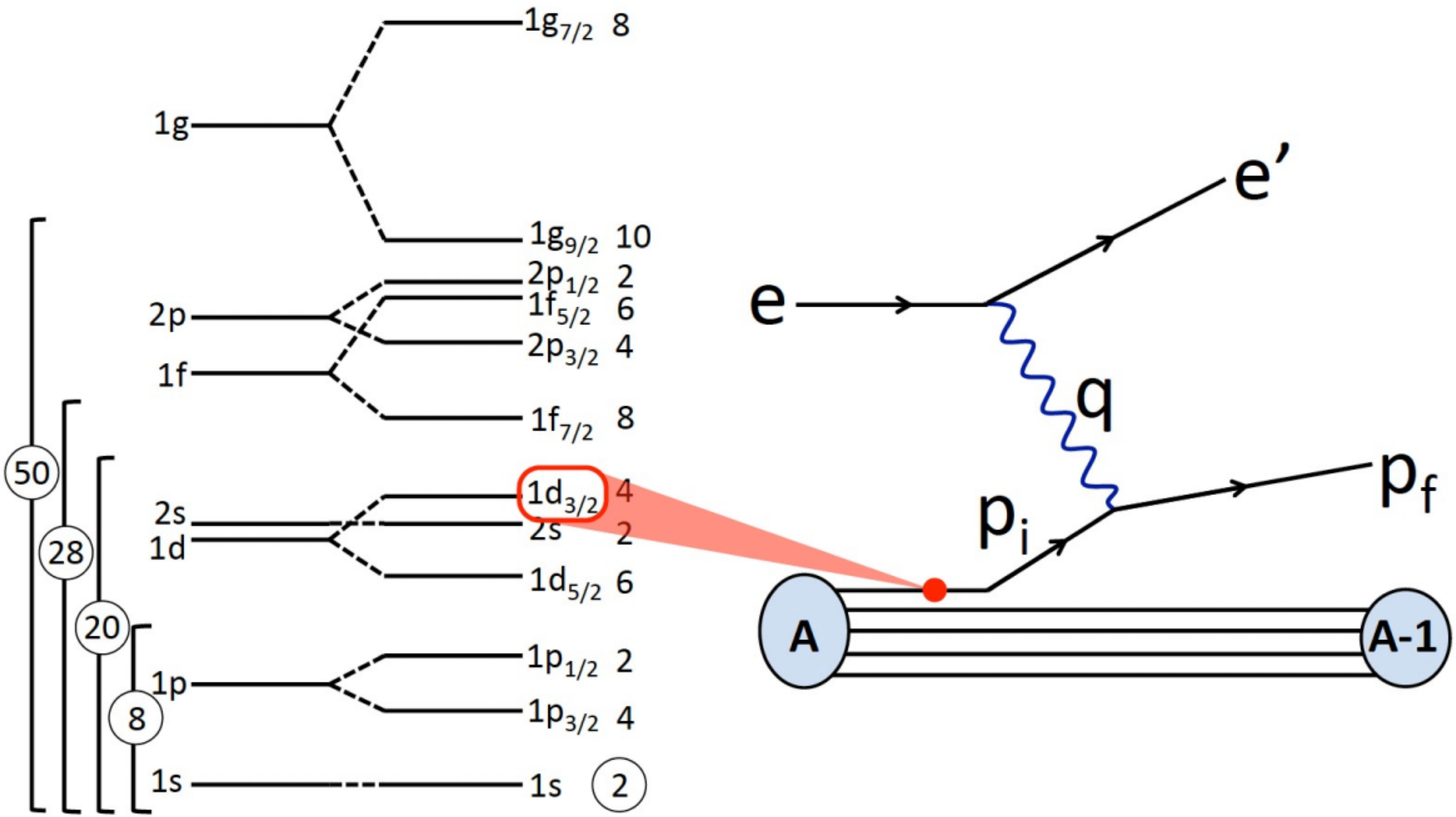
In (e,e'N), detect the scattered electron and knocked out nucleon:

- Missing energy, $E_m = \nu - T_{pf} - T_{A-1}$
- Missing momentum, $\vec{p}_m = \vec{q} - \vec{p}_f$

PWIA implies: $\vec{p}_i = -\vec{p}_m$, $|E| = E_m$

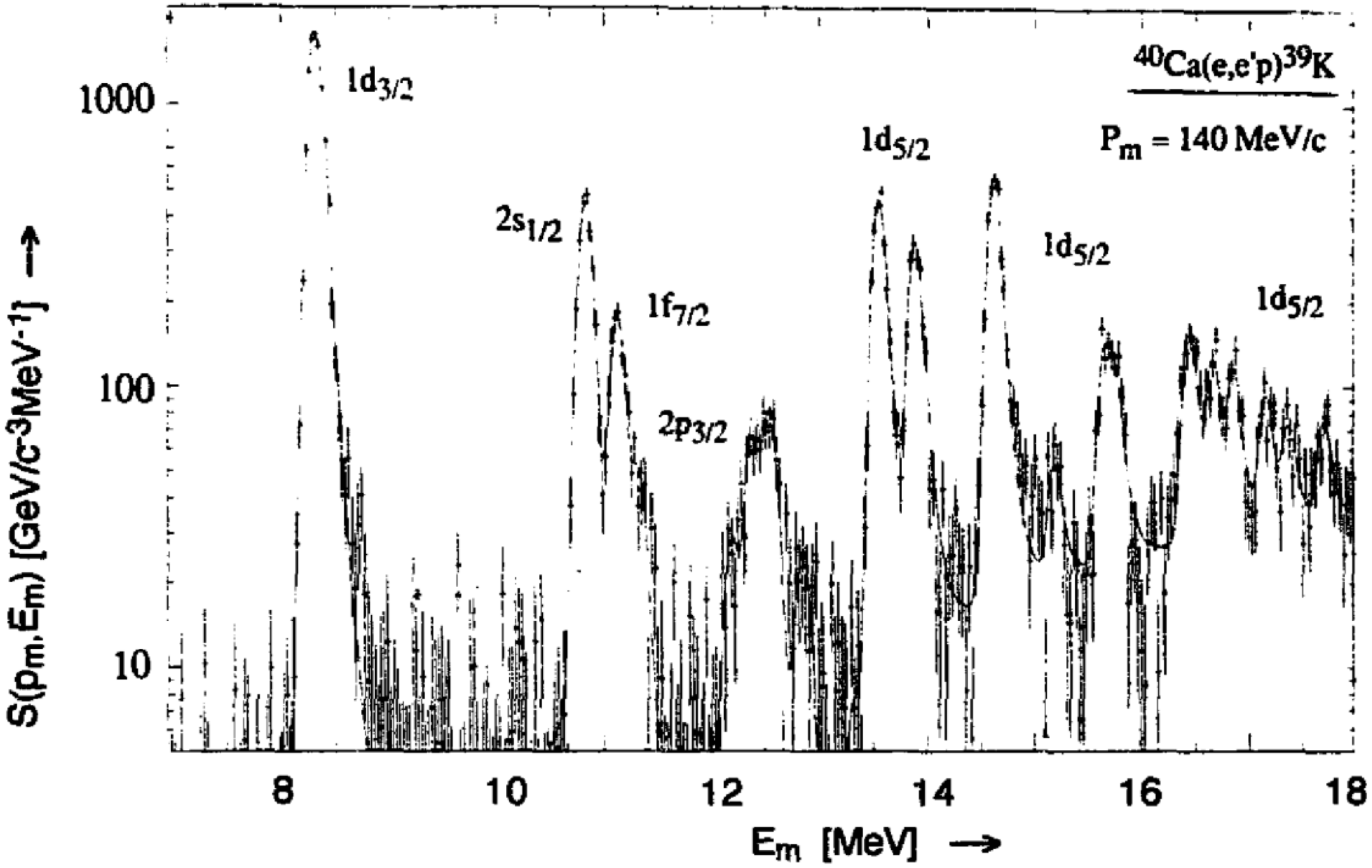
Cross section: $\sigma = K\, \sigma_{ep}\, S(|\vec{P}_i|, E_i)$

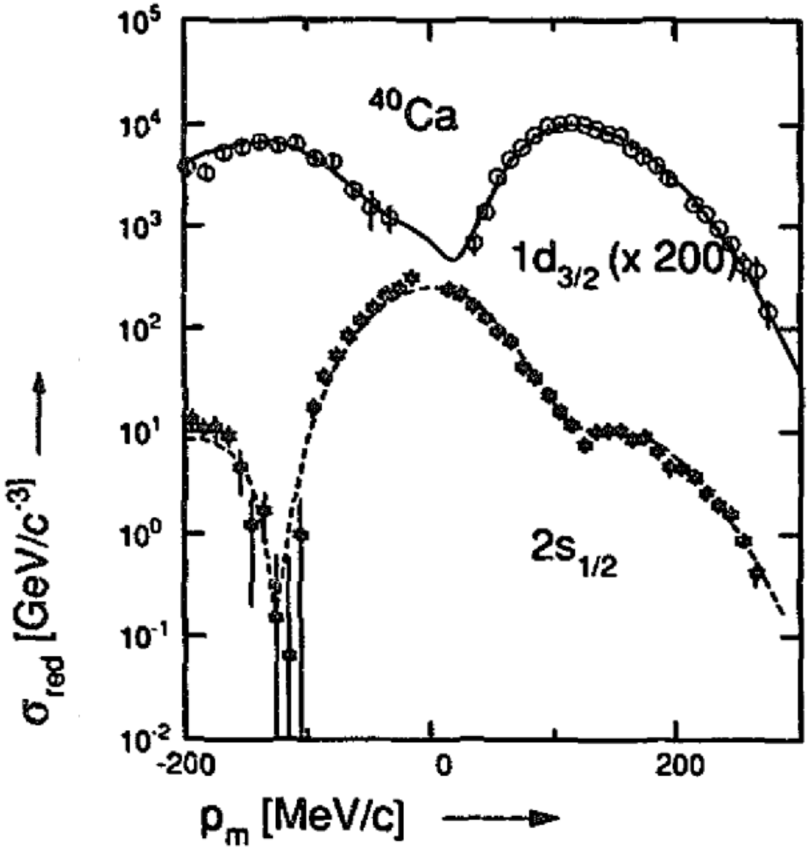
A(e,e'p) scattering from shell orbitals



Scattering from shell orbitals

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

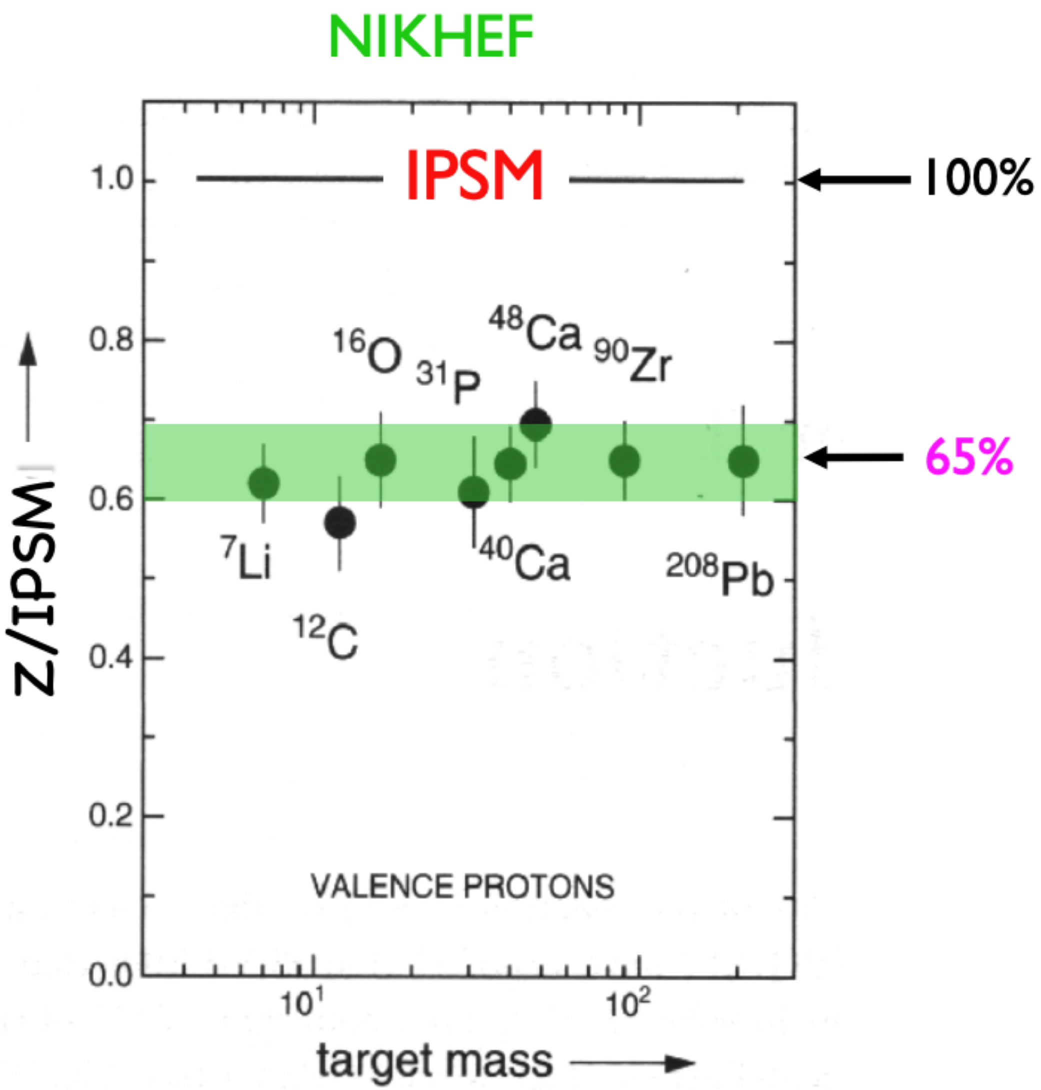




We can "see" the orbitals. The shapes are reasonably described.

Scattering from shell orbitals

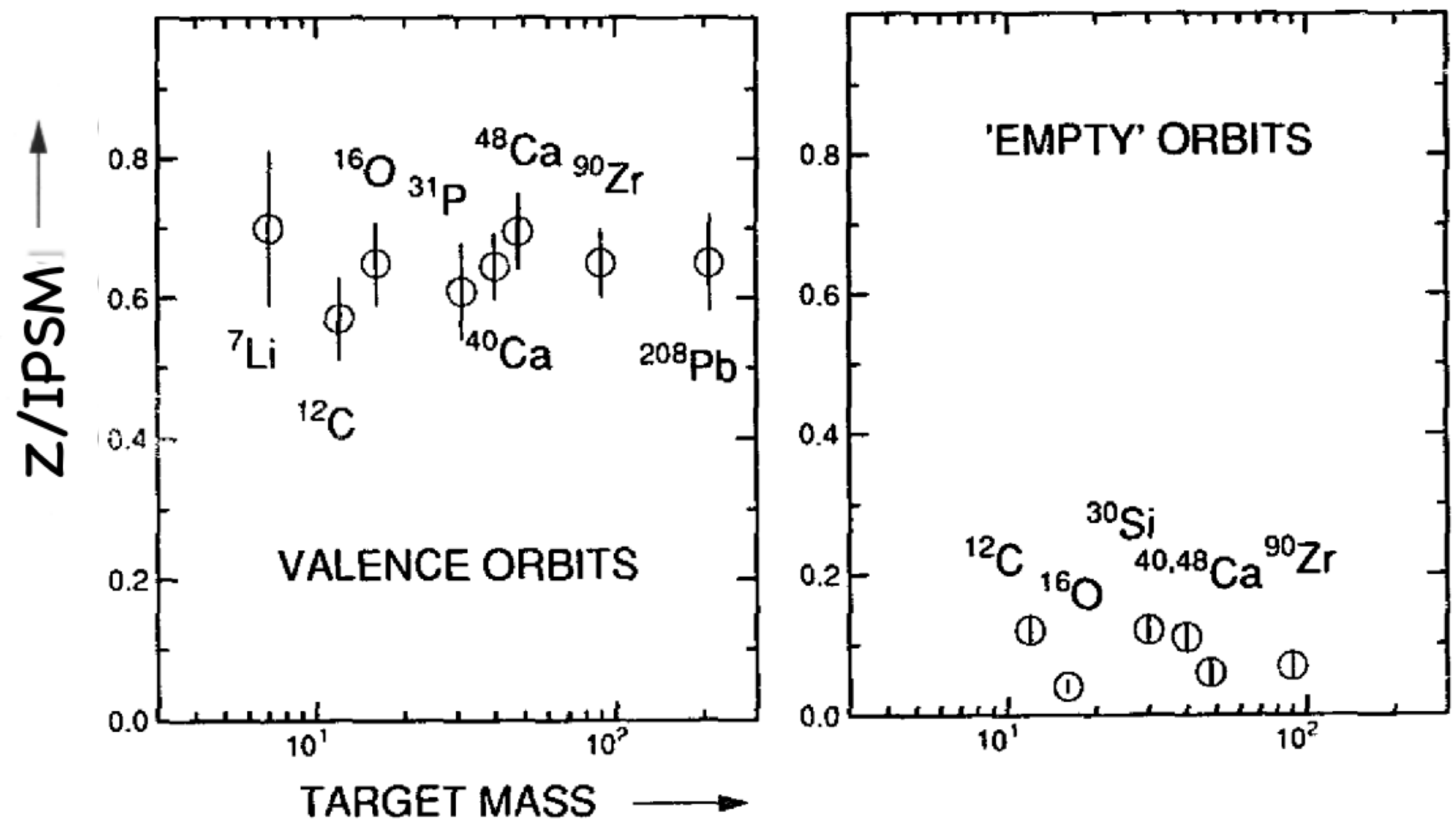
But the strengths (or "occupancies") are not as predicted...

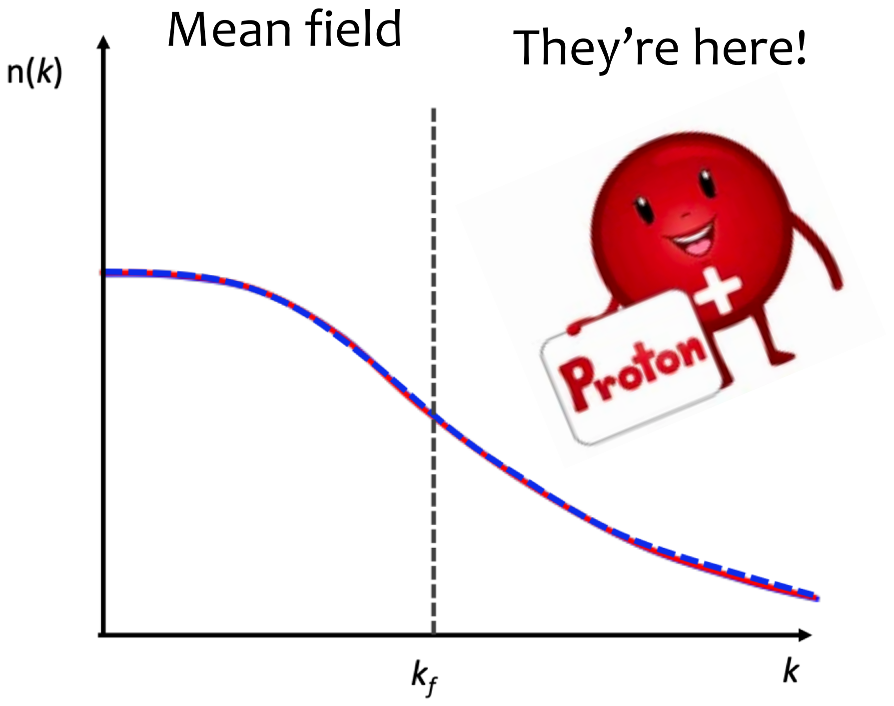


We don't see enough protons!

Where did they go?

Protons found above the Fermi momentum!





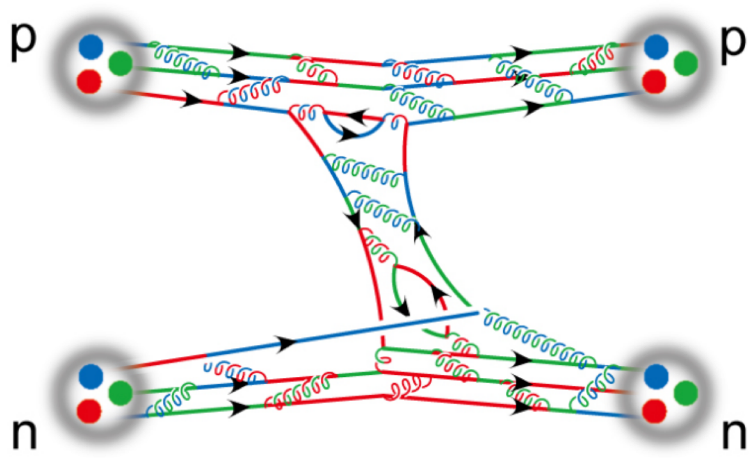
L. Lapikas, Nuclear Phys. A553, 297c (1993)

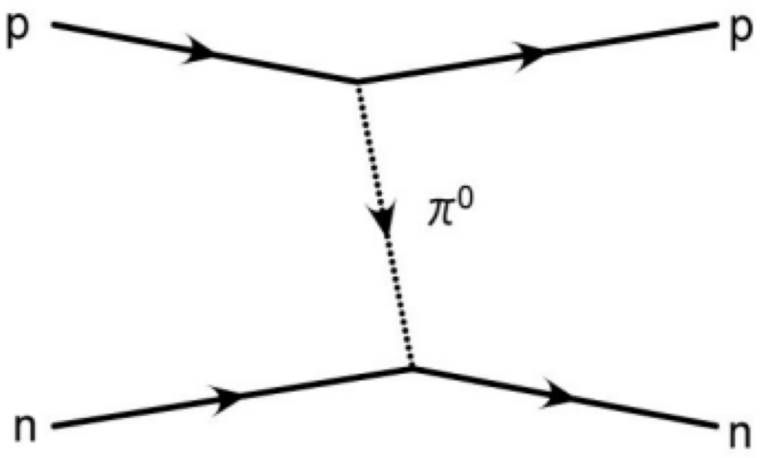
Nuclear picture is a many body problem

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

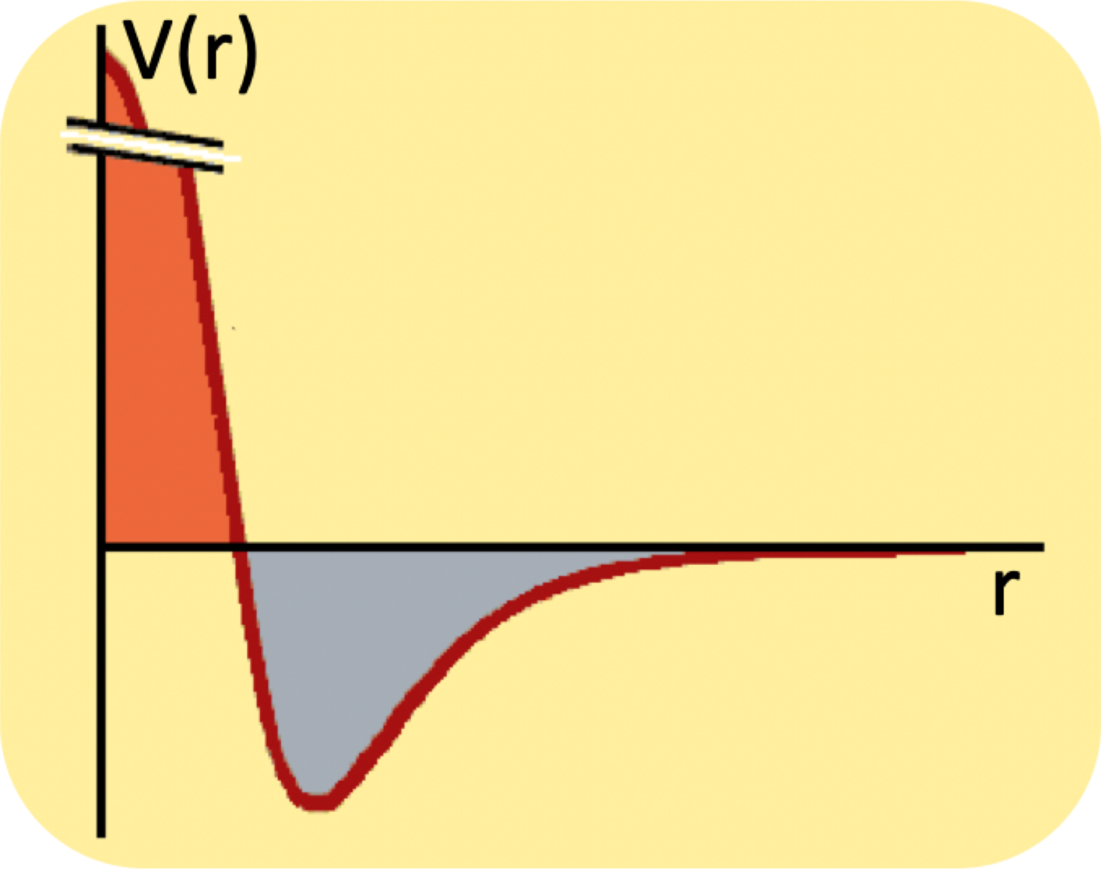
From elastic scattering, we already know that quarks and gluons compose the nucleons…

We simplify by describing the effective NN interaction as:

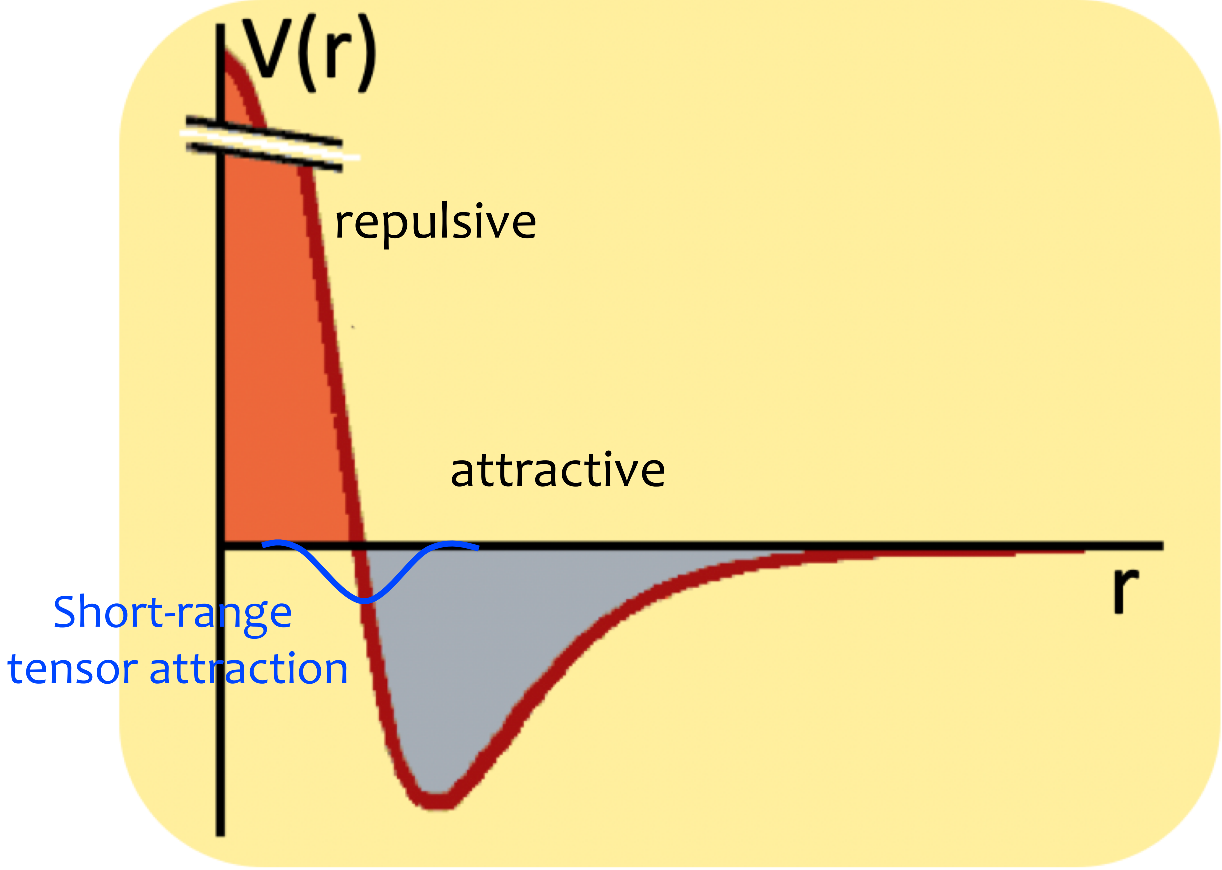




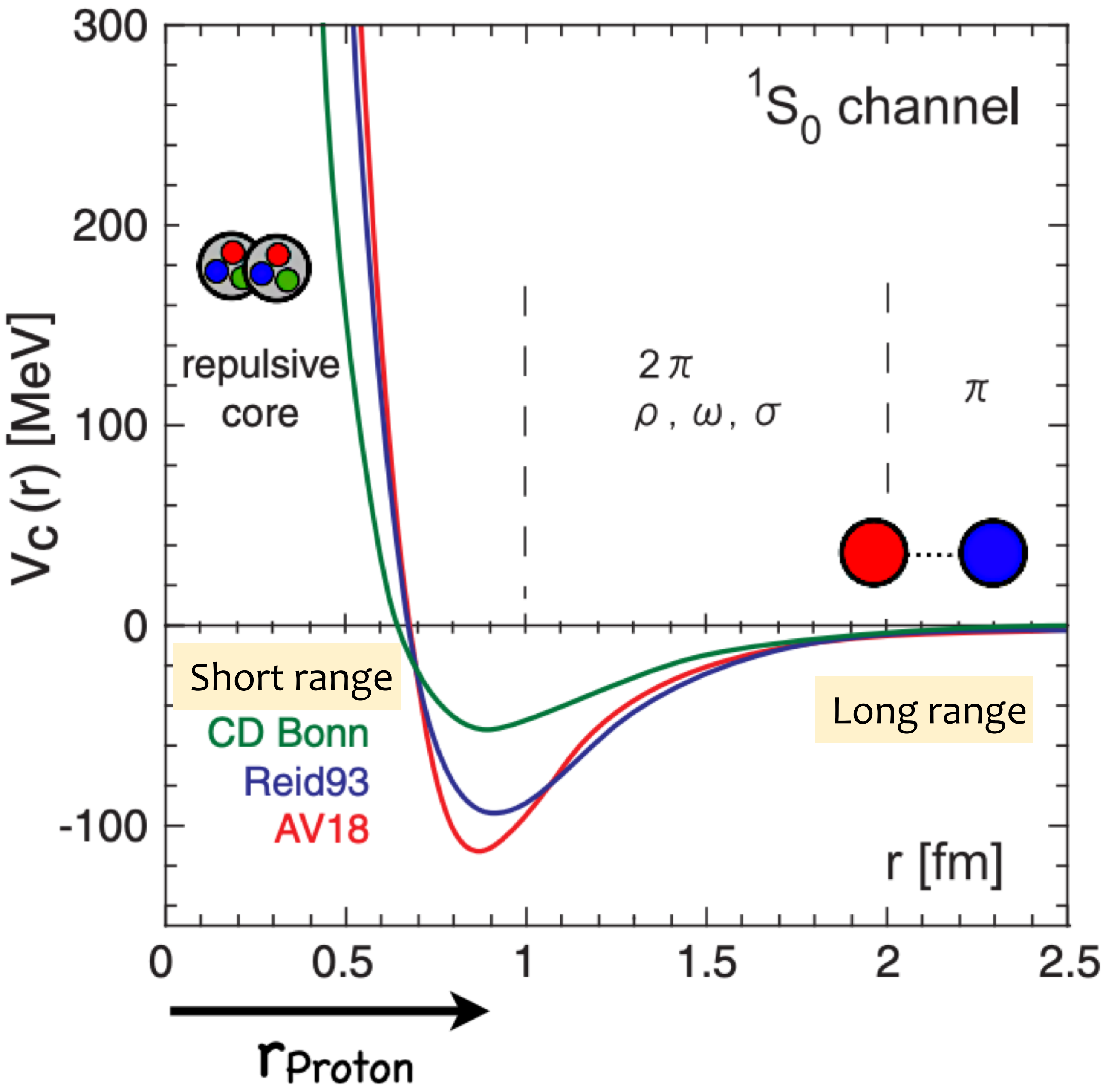
NN potential



NN potential



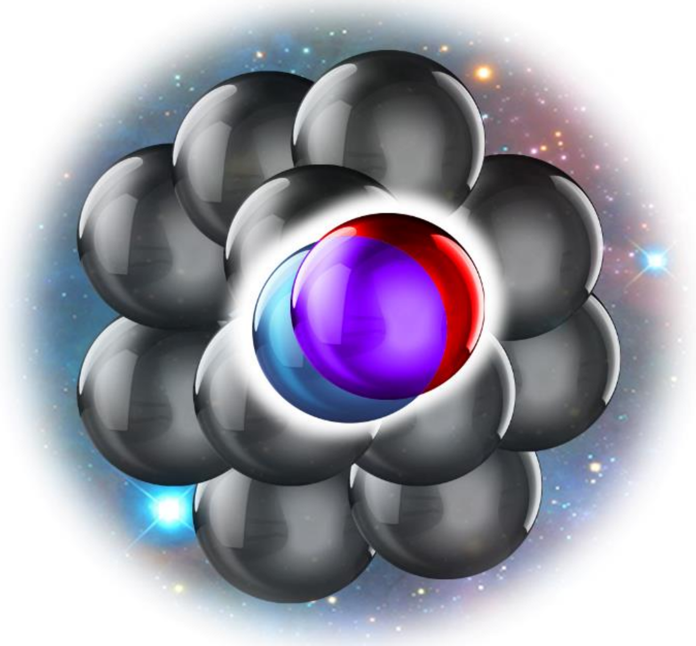
NN interaction



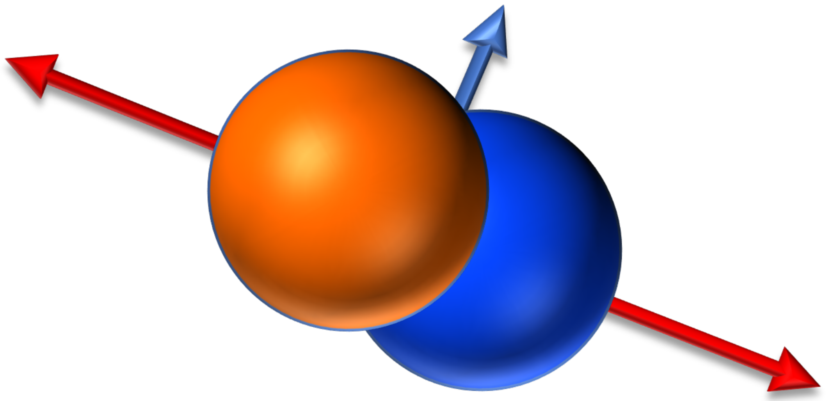
NN short-range correlated pairs

Nucleon pairs that are close together (overlapping) in the nucleus

High relative momentum and low center of mass momentum (as compared to k_f)



r-space

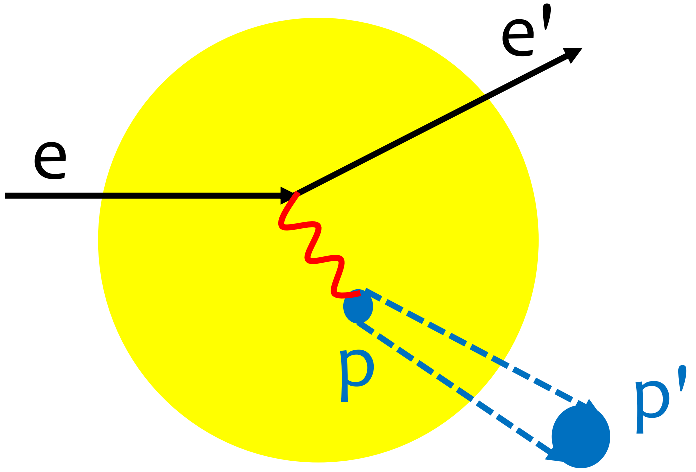


k-space

More on this tomorrow…

Nuclear transparency

If we are going to learn anything about nucleons in the nucleus, we have to know something about transparency



Hadron propagation in the nucleus is dominated by a reduction of flux at high energies.

Transparency refers to the probability that a knocked out nucleon is deflected or absorbed.

$$T_A = \frac{\sigma_A}{A\,\sigma_N}$$

σ_A (nuclear cross section)

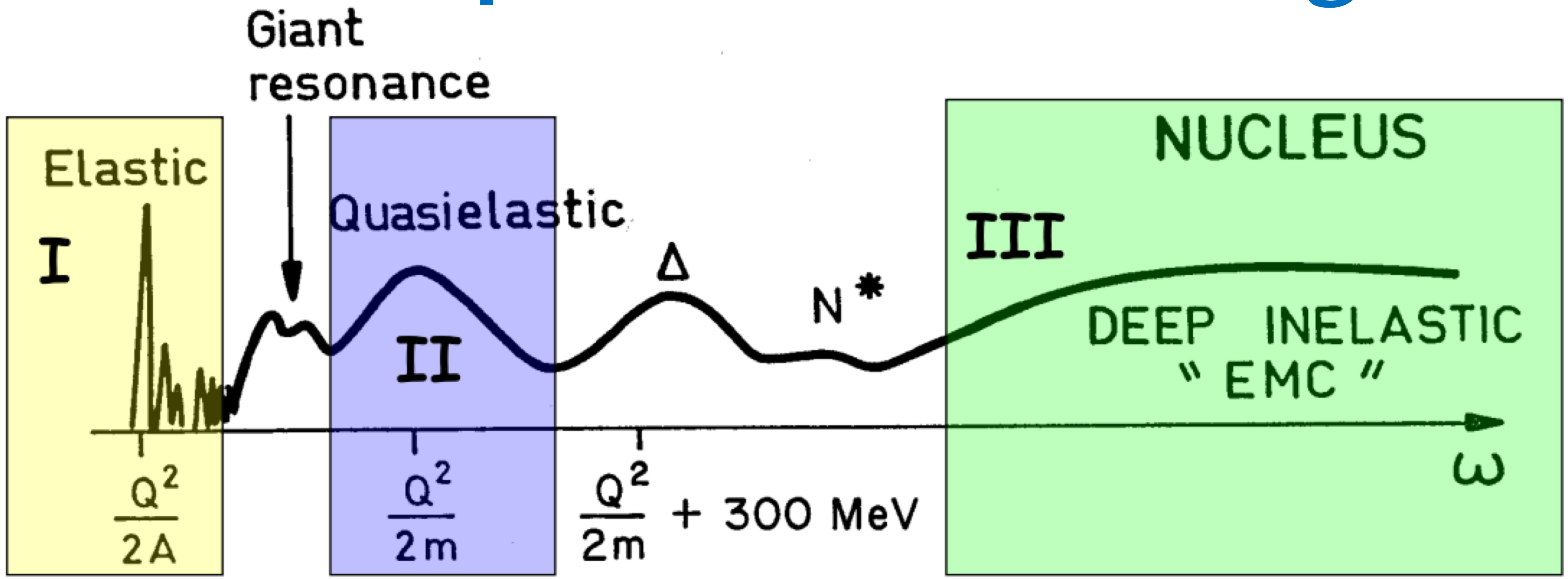
σ_N (free nucleon cross section)

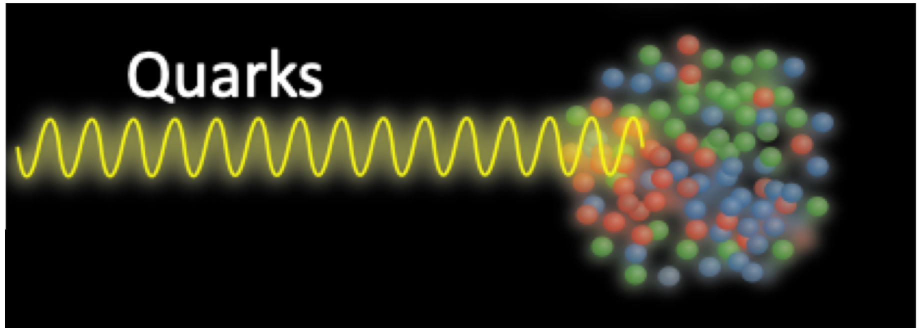
More on this tomorrow…

Quasielastic scattering summary

- Nuclei are complicated systems that we model with different assumptions.
- Fermi gas model gives us a good idea about the cross section.
- Scaling refers to the dependence of a cross section on a single variable
  - y-scaling can tell us about the nucleon momentum distributions in the nucleus.
- Indications that nucleons are not truly quasifree (but modified in the nucleus) from the Coulomb Sum Rule and the loss of spectroscopic strength in orbitals.
- Can study NN interaction and nuclear transparency

Deep inelastic scattering



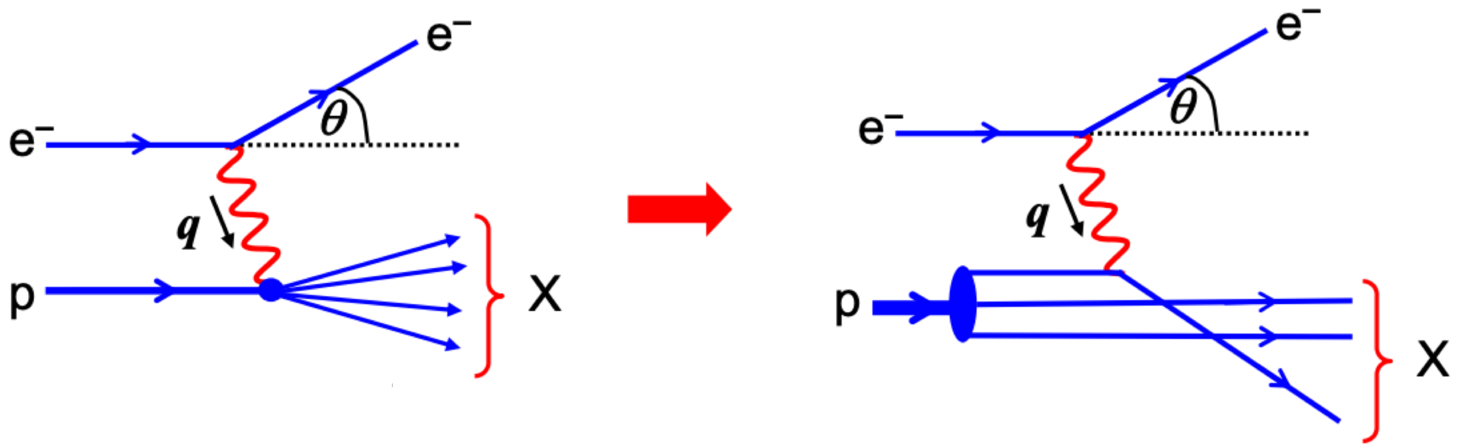


Proton breaks up resulting in many particle final state.

- Structure functions
- EMC effect

Quark-parton model

DIS is dominated by the scattering of a single virtual photon from point-like spin-half constituents of the proton



Scattering from a proton with structure functions

Scattering from a point-like quark in the proton

Elastic scattering from a quasifree quark!

Note: Frame where the proton has very high energy → “infinite momentum frame”

Structure functions

Form factors are replaced by structure functions with a dependence on Q^2 and x_B.

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

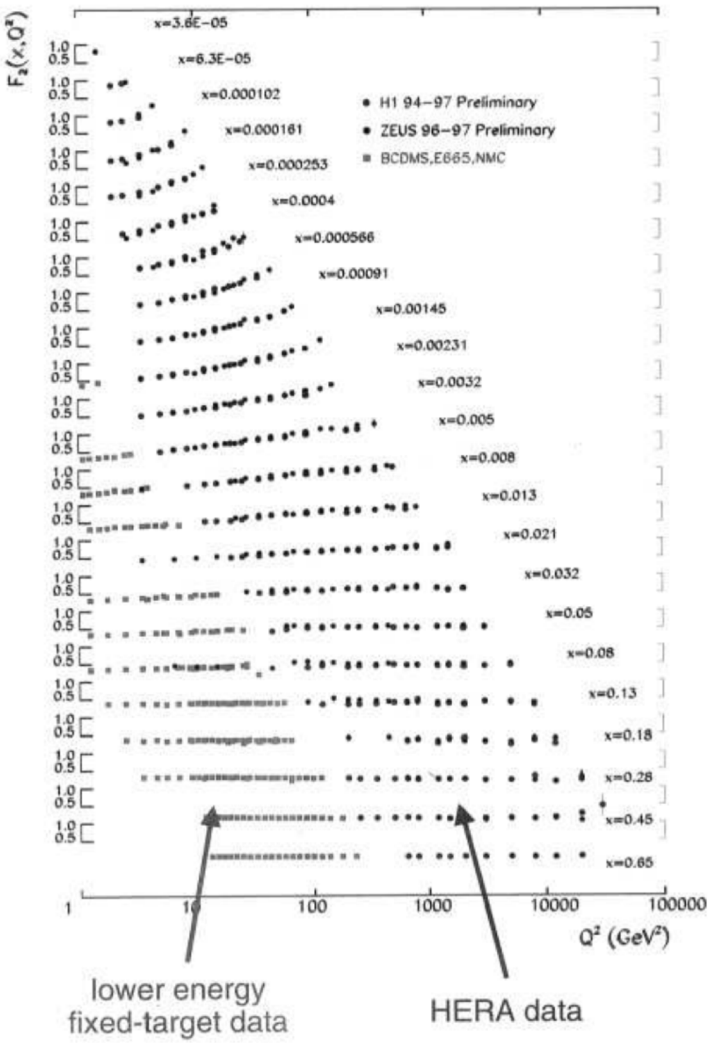
Interpreted as the momentum distribution of the quarks in the proton.

$F_1(x, Q^2)$ ~ pure magnetic structure function

$F_2(x, Q^2)$ ~ electromagnetic structure function

Bjorken scaling

F$_2$ (x,q^2) from HERA



- Experimentally, F_1 and F_2 are determined with measurements varying both the scattering angle and beam energy.

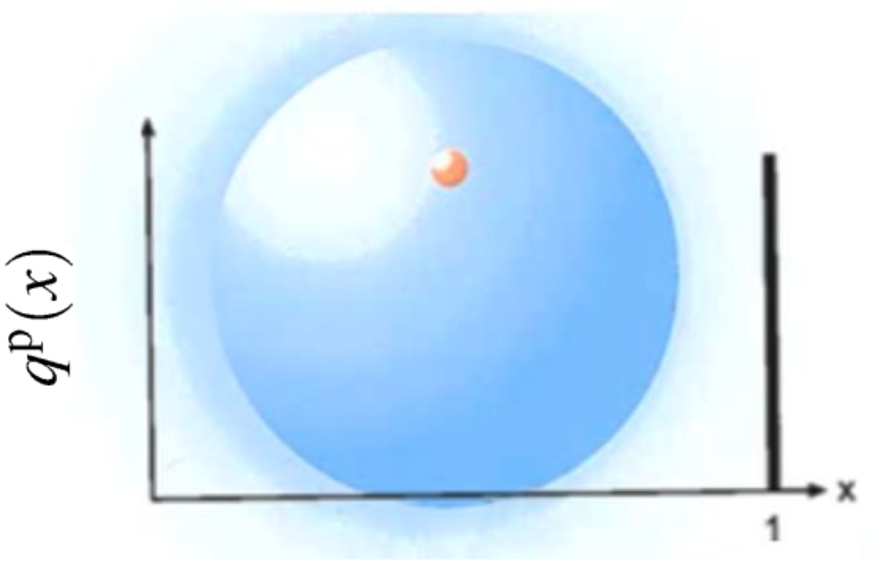
- We observe that F_1 and F_2 are nearly independent of Q^2. Thus, a reliance only on x_B…

$$F_1(x, Q^2) \rightarrow F_1(x) \qquad F_2(x, Q^2) \rightarrow F_2(x)$$

"Bjorken scaling" → implies scattering from point-like objects in the proton

Partons in nucleons

x_B is the fraction of the proton momentum carried by the struck quark (in the infinite momentum frame)



Single proton

Parton distribution functions:

$q^{p}(x)\mathrm{d}x$ — the number of quarks of type *q* within a proton with momenta between *x* and *x+dx*

Structure functions related to the quark distributions as:

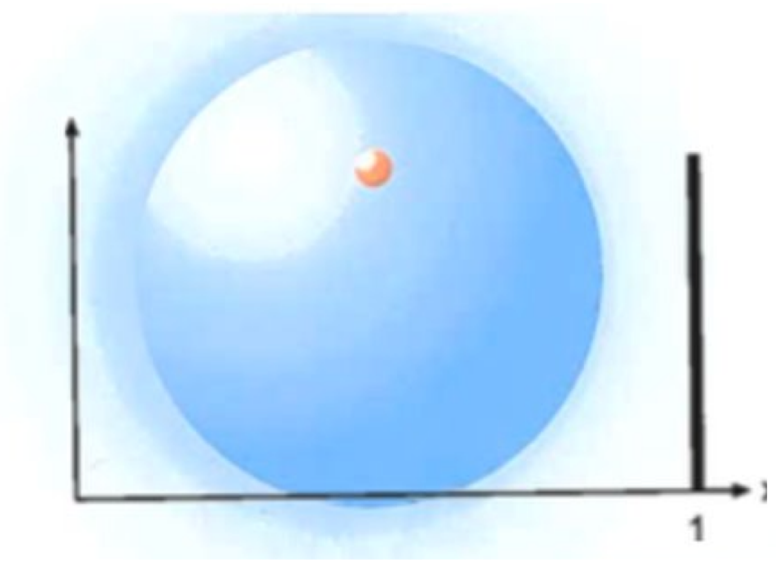
$$F_2^{p}(x,Q^2) = 2xF_1^{p}(x,Q^2) = x\sum_q e_q^2 q^{p}(x)$$

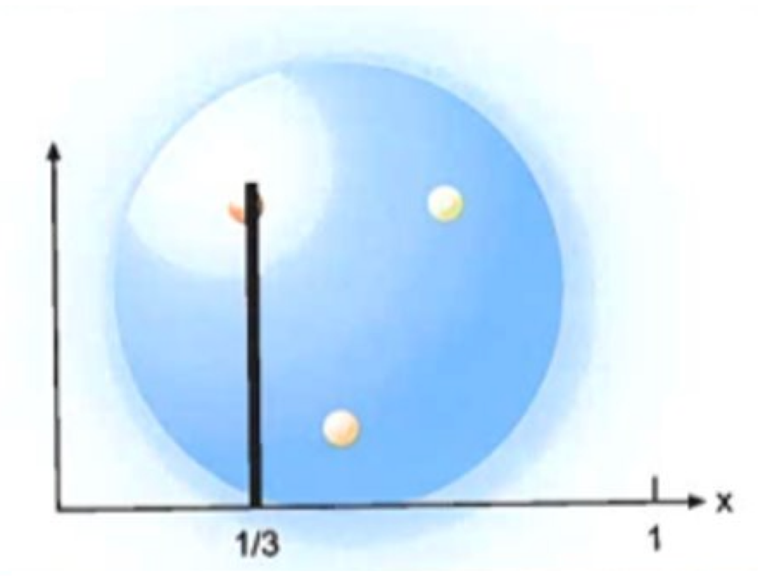
(Callan-Gross relation)

Partons in nucleons

x_B is the fraction of the proton momentum carried by the struck quark (in the infinite momentum frame)

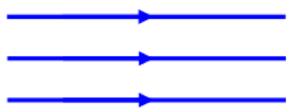
$q^p(x)$





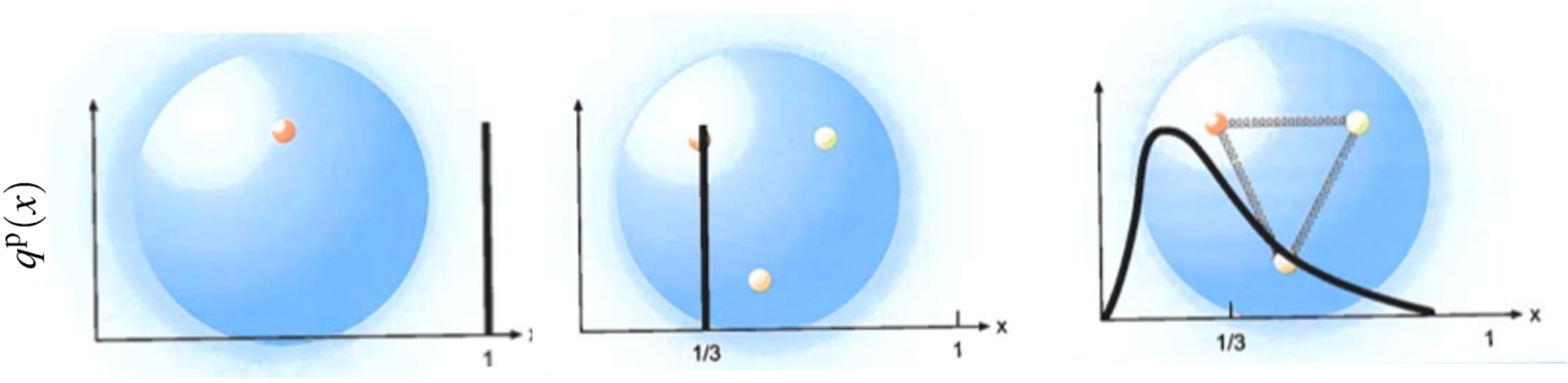
Single proton

3 static quarks (valence)



Partons in nucleons

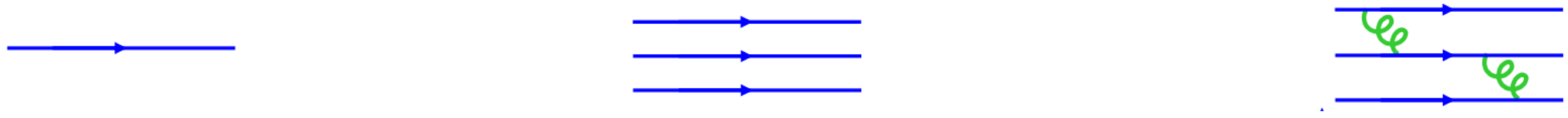
x_B is the fraction of the proton momentum carried by the struck quark (in the infinite momentum frame)



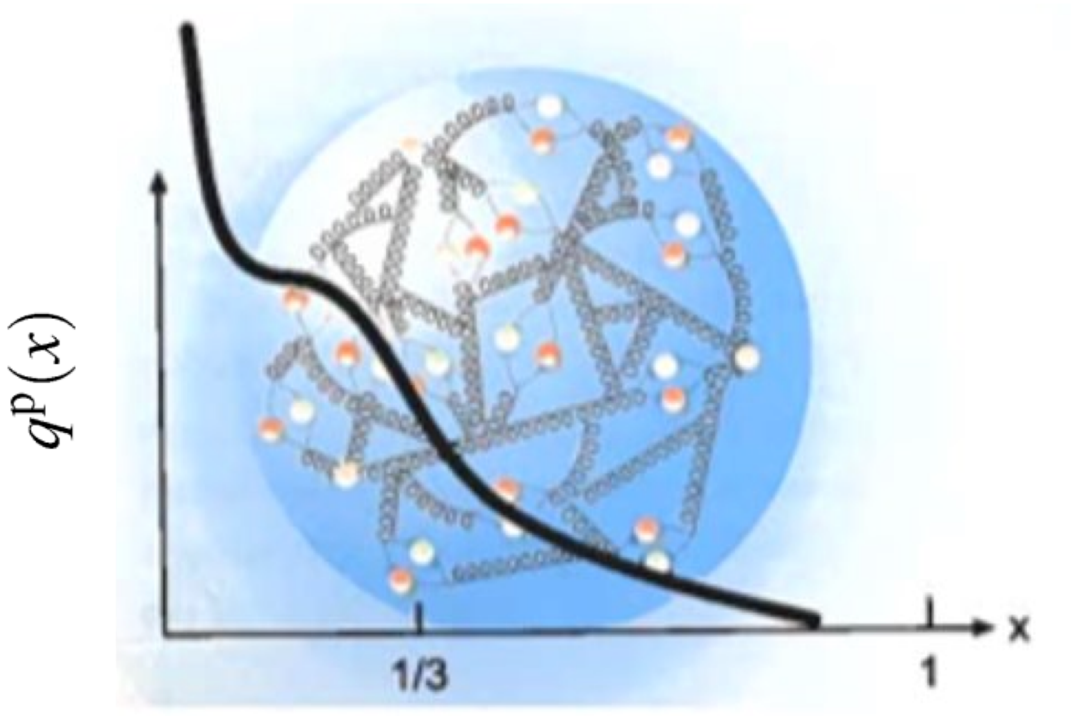
Single proton

3 static quarks (valence)

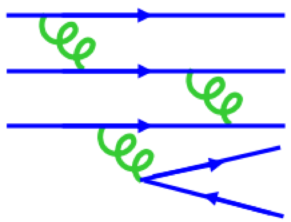
3 interacting quarks

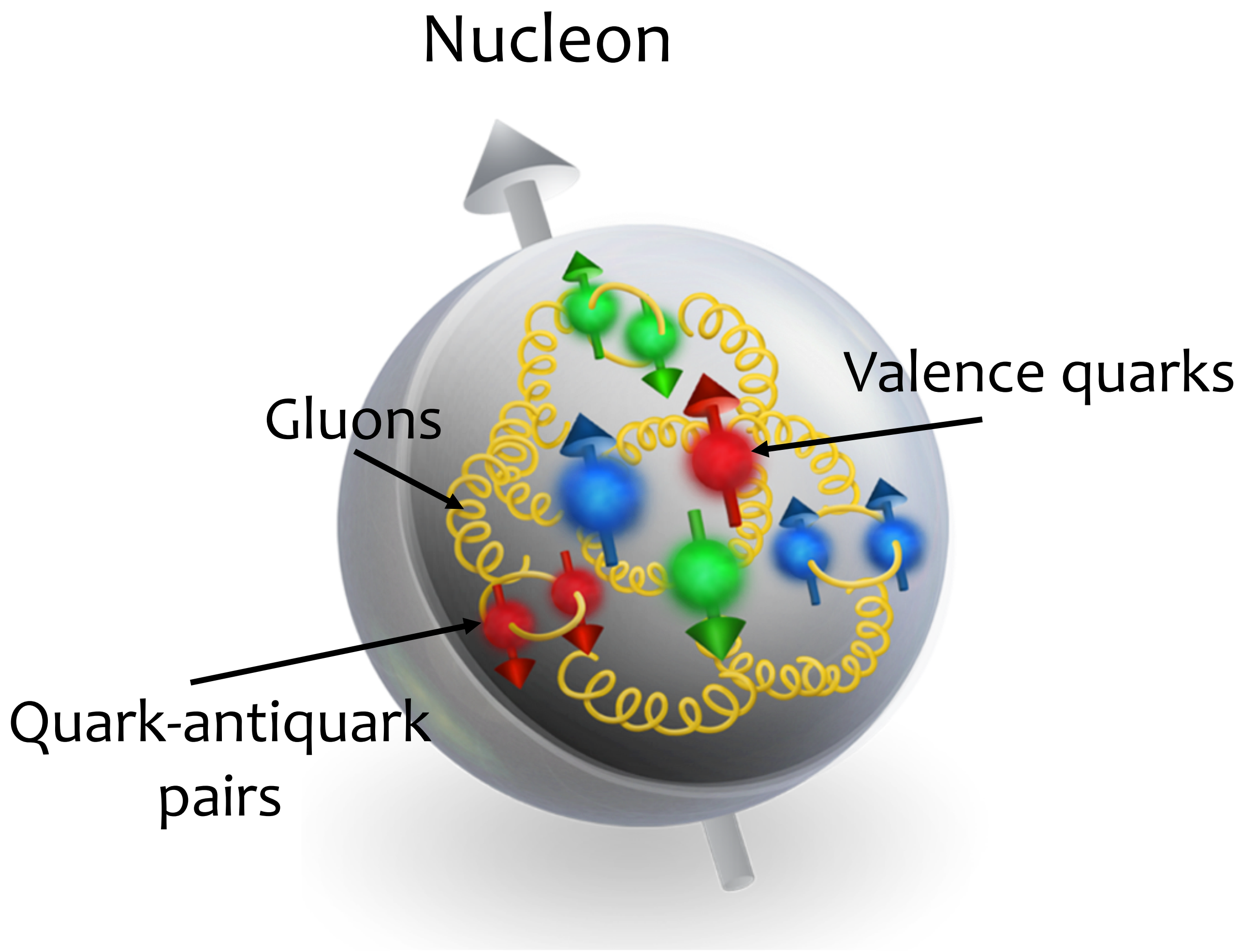


Quarks and gluons

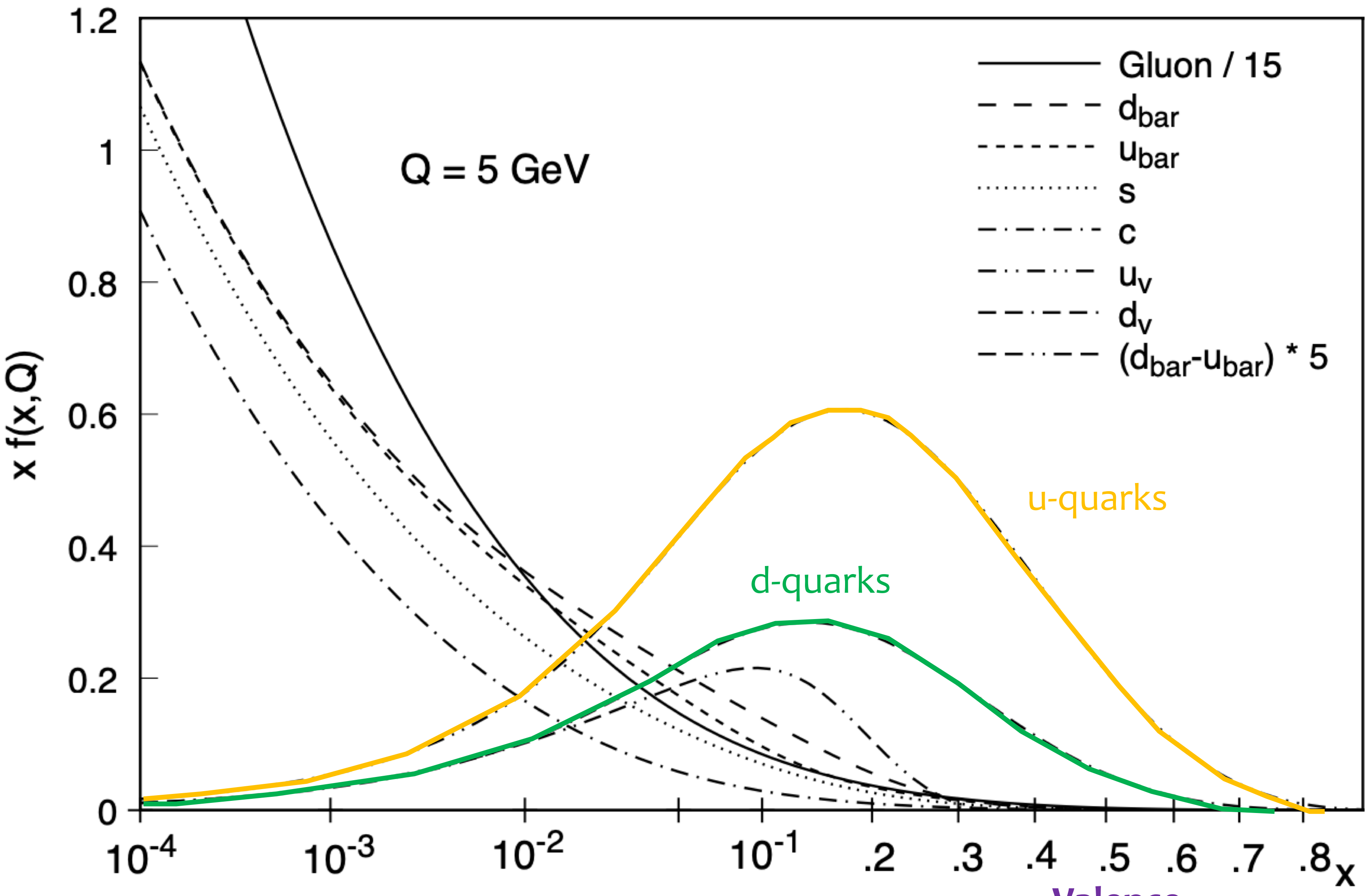


Valence quarks & sea quarks,
higher order interactions





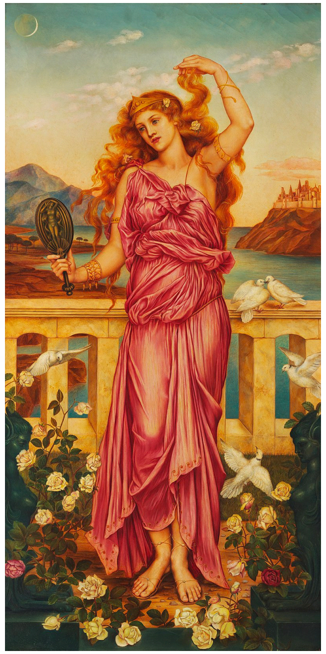
Quark distributions



Valence quarks dominant at intermediate to large x

H.L. Lai, Eur. Phys. J. C 12, 275 (2000)

EMC Effect



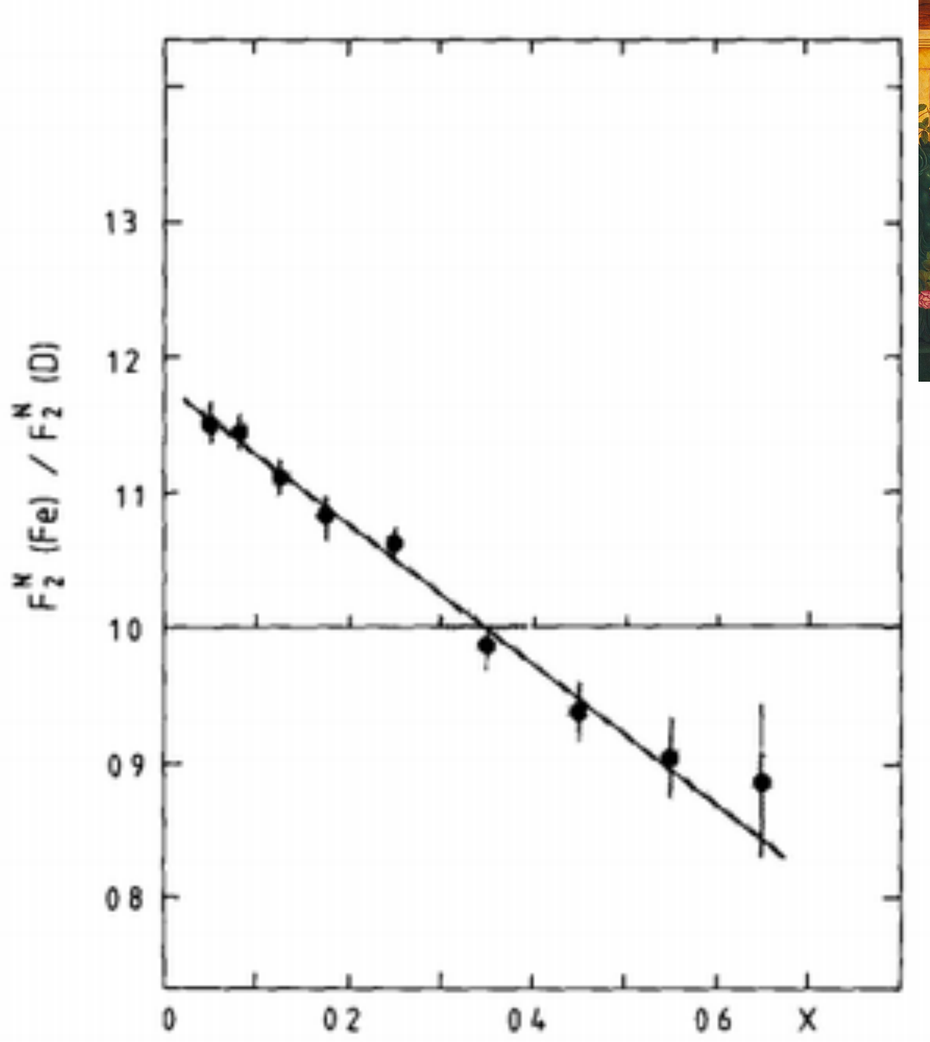
Recall that in DIS, we describe the **cross section** in terms of the **structure functions**.

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

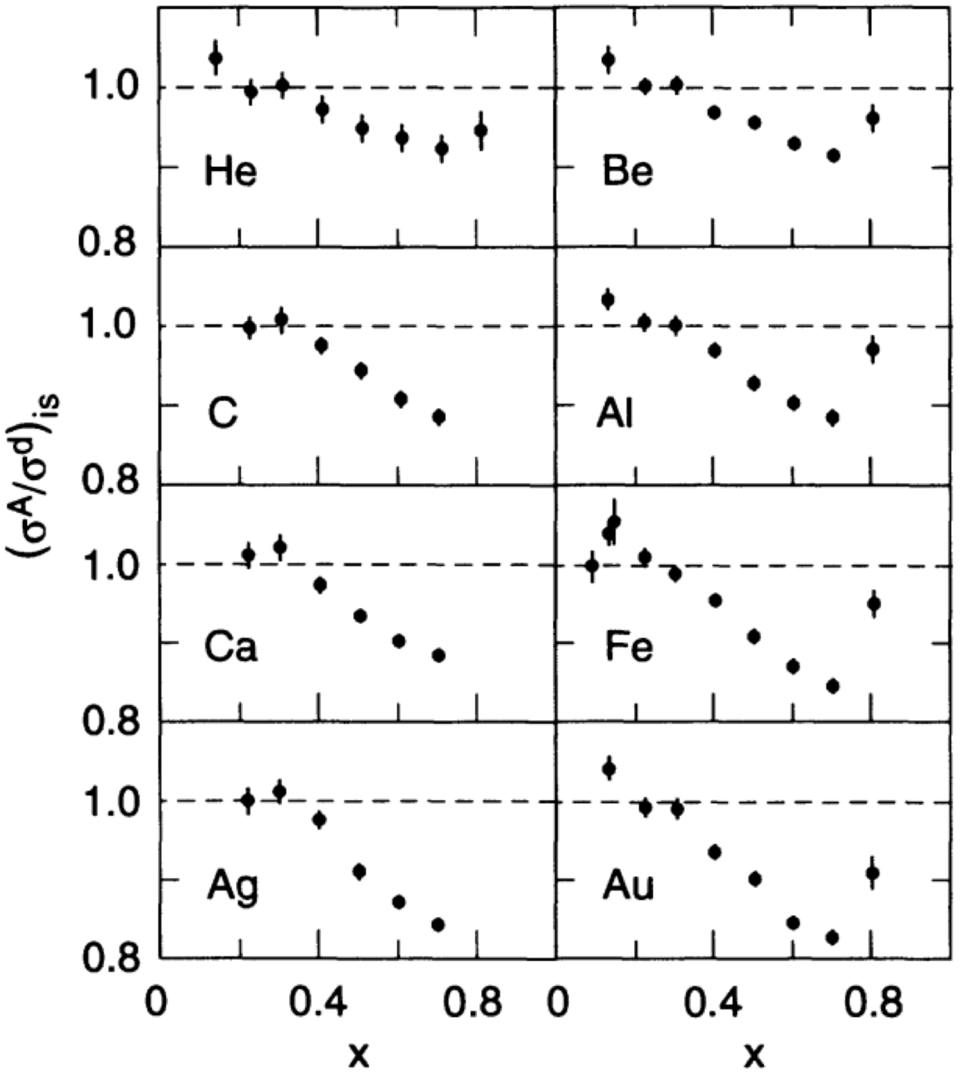
These **structure functions** describe the **quark momentum distributions.**

$$F_2^{\mathrm{p}}(x,Q^2) = 2xF_1^{\mathrm{p}}(x,Q^2) = x\sum_q e_q^2 q^{\mathrm{p}}(x)$$

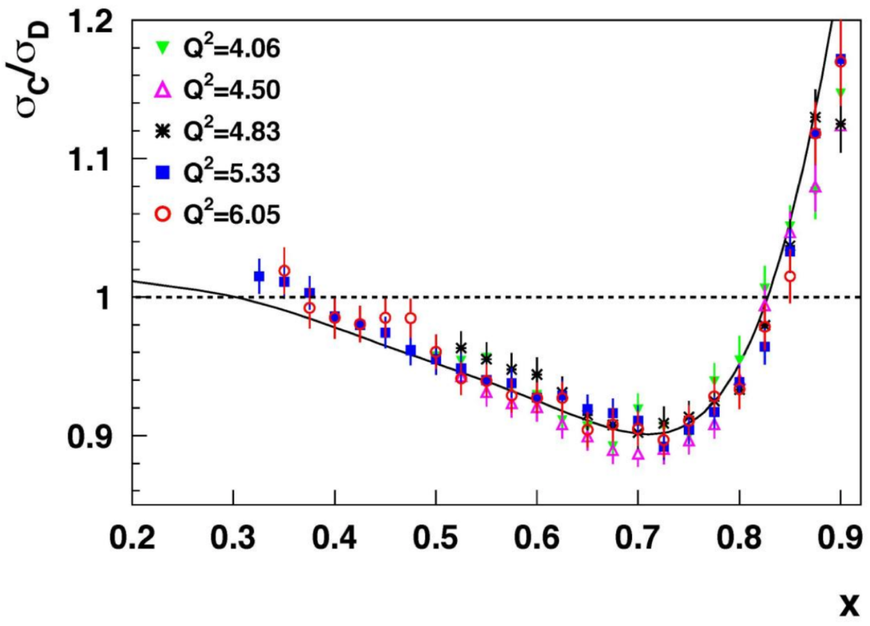
The European Muon Collaboration first observed that the DIS cross section ratio of a heavy nucleus relative to deuterium, per nucleon, is not 1 (where we expect to be scattering from the valence quarks).



Universal shape



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



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

- The effect increases with A
- It's Q^2 independent
- Region is 0.3<x<0.7

A thousand ships…

The parton model interpretation is that the valence quarks of a nucleon bound in a nucleus carry less momentum than those of free nucleons.

EMC Effect is not described by conventional nuclear physics only.

Many theories, but no universally agreed upon model:

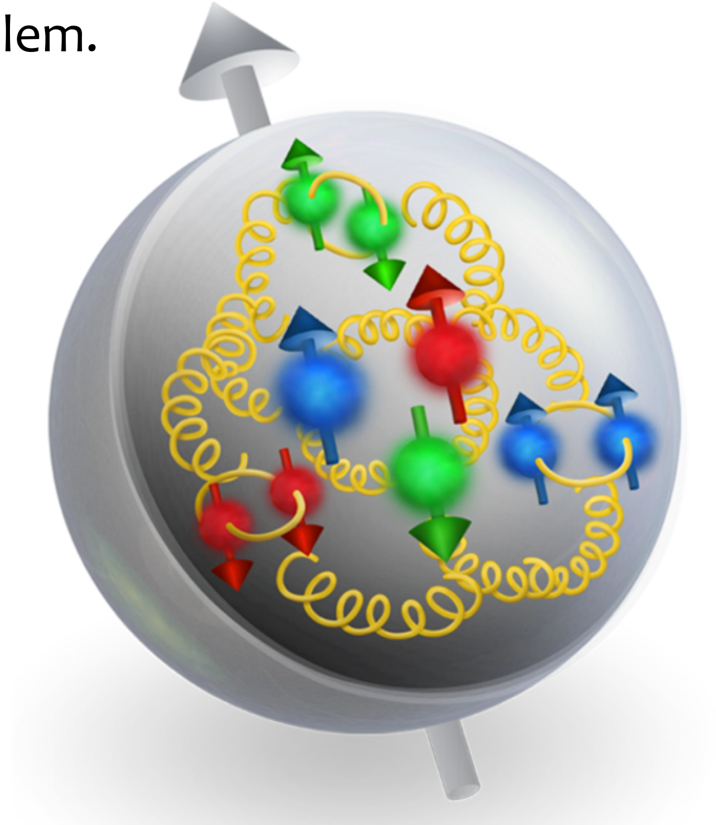
- Single nucleons
- Pion enhancement
- Multiquark clusters
- Dynamical rescaling
- Medium effects
- Short range correlations
- …..

Many experiments, theories, and papers!

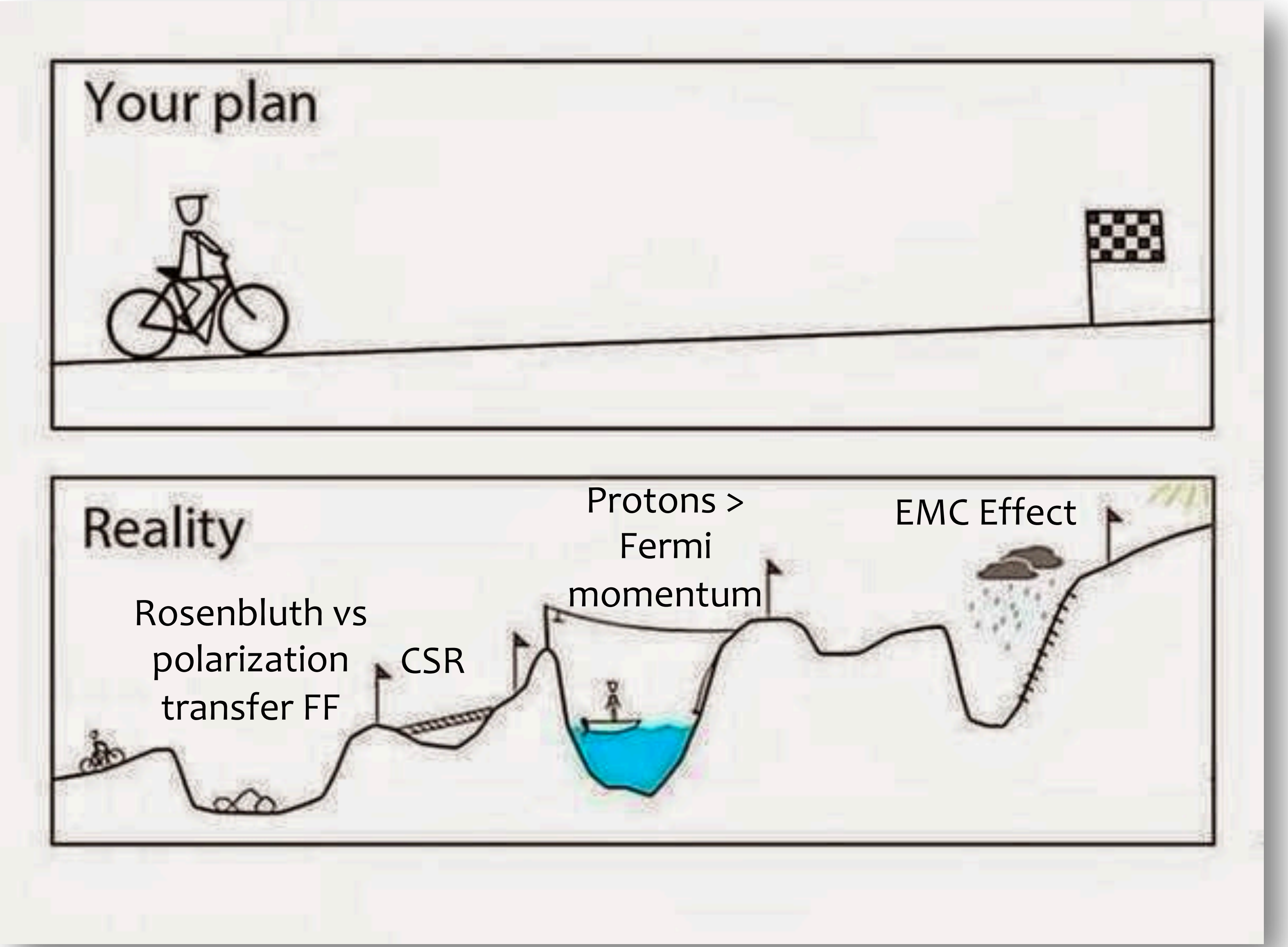
More on this tomorrow…

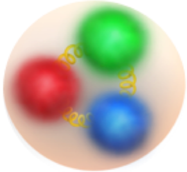
Deep inelastic scattering summary

- Structure functions contain the quark momentum density information.
- In the quark-parton model, DIS is scattering from a quasi-free quark.
- EMC Effect: There's a loss of momentum carried by the valence quarks in a bound nucleon vs that of a free nucleon. Many models try to explain the data. Many experiments try to understand the problem.



Summary of the physics





Summary of the physics

- Nuclear strong interaction that binds nuclei is the residual from the strong interaction between quarks.

- Elastic scattering:
  - Form factors describe the nuclear and nucleon structure in terms of charge and magnetic moment
- Quasielastic scattering:
  - Shell structure, momentum distributions, correlations
- Deep inelastic scattering:
  - Quark-parton picture, structure functions describe quark momentum distributions