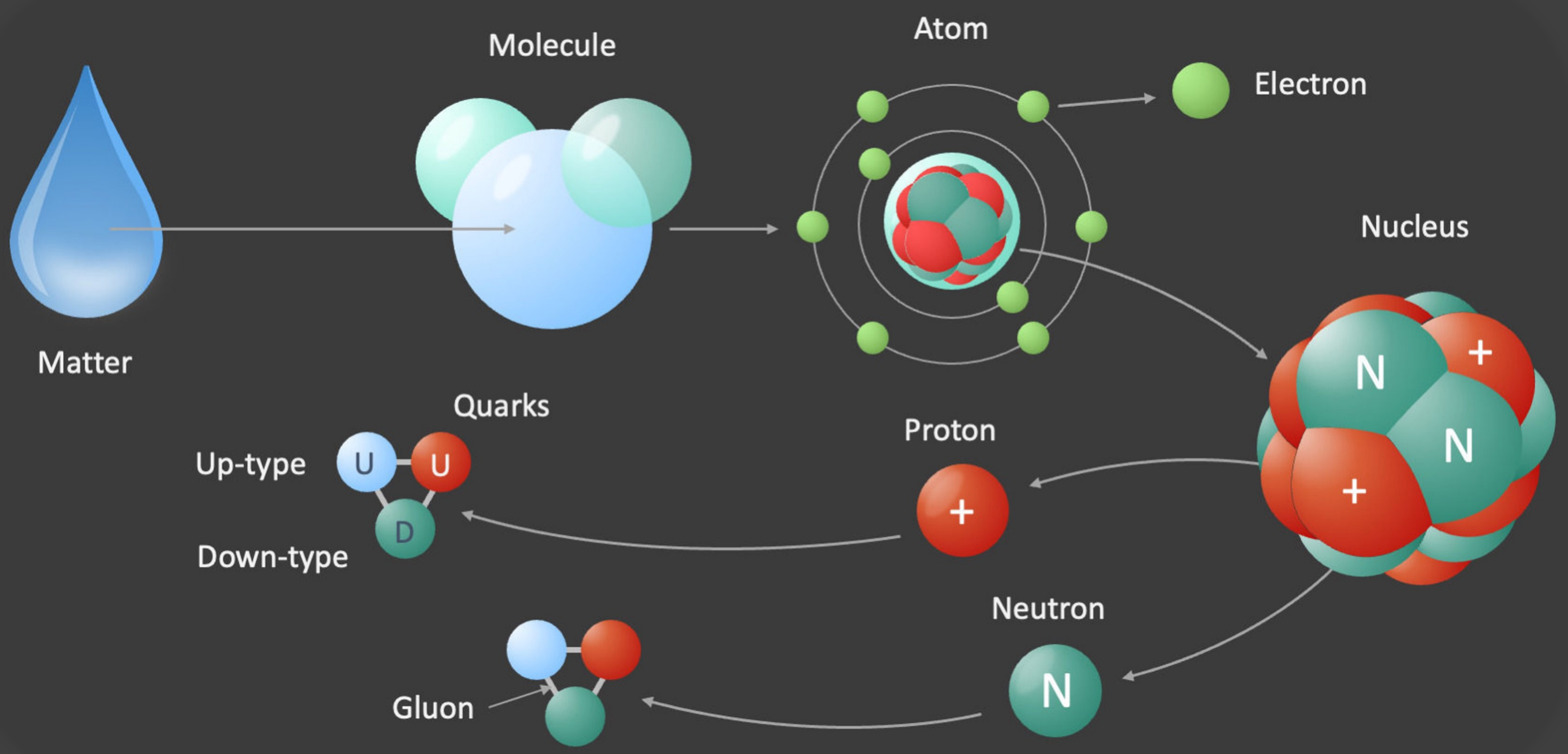
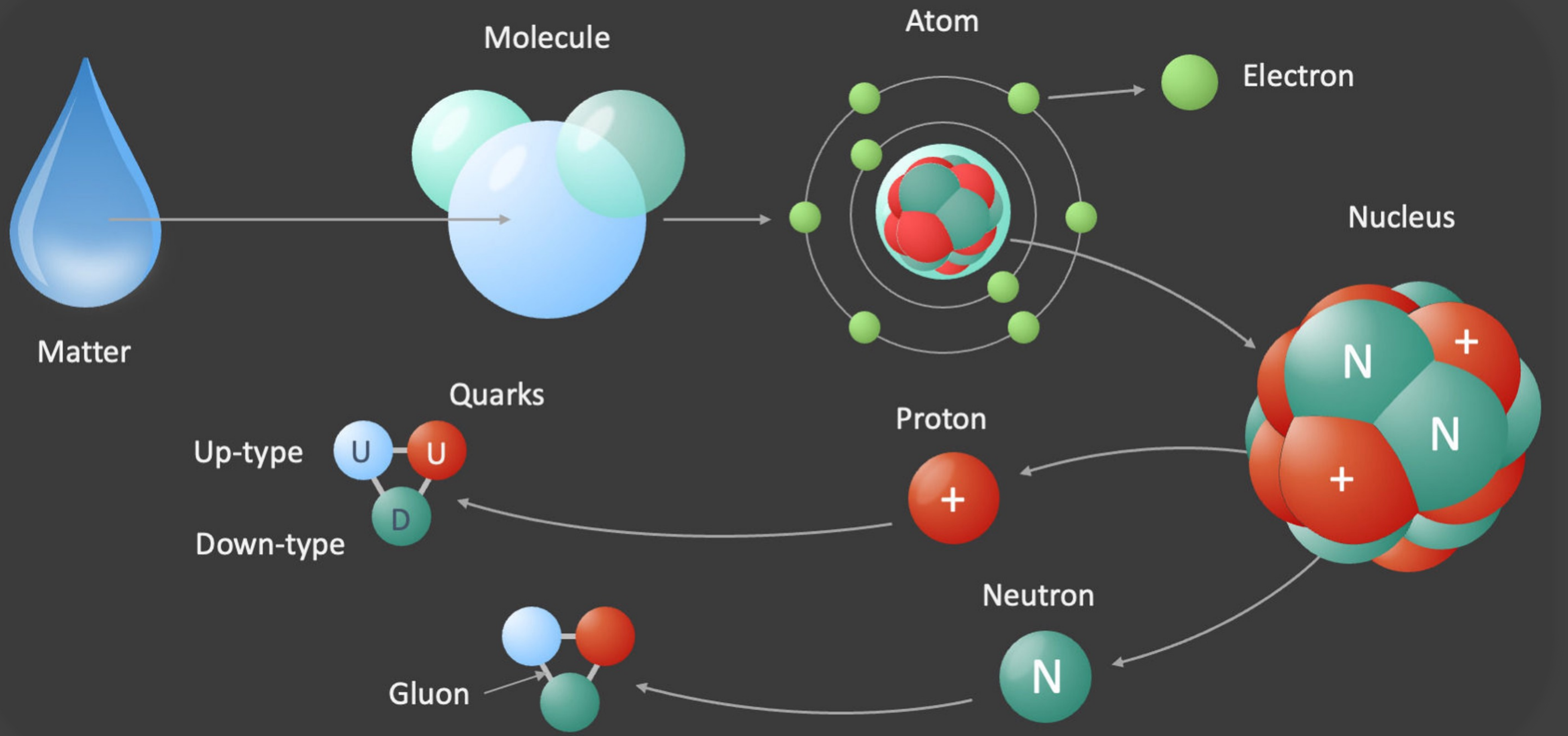
EIC Physics: Experimental Perspective (1)

Or Hen
(MIT)

Fundamental Structure of Matter



Fundamental ~~Structure~~ of Matter *constituents*



Discovering the constituents of matter is often viewed as telling us about its structure

However, the emergence of structure is a complex process;

Its understanding goes beyond knowing its constituents and their interactions

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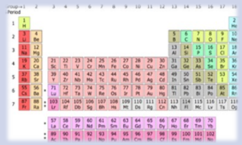
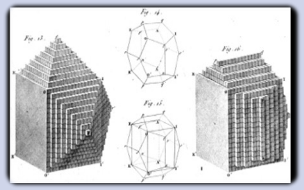
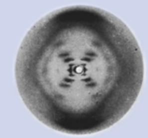
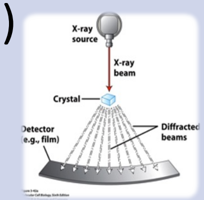
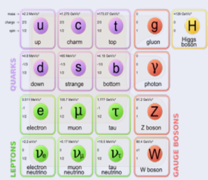
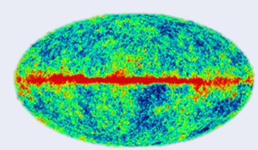
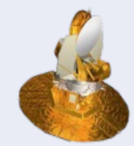
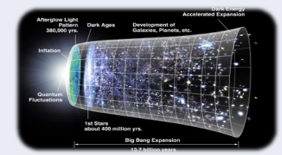
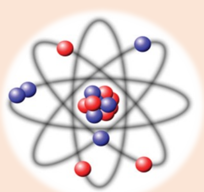
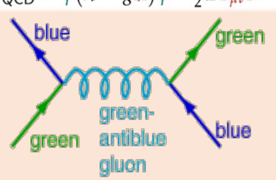
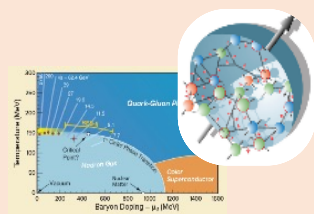
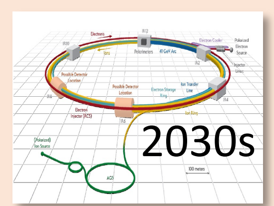
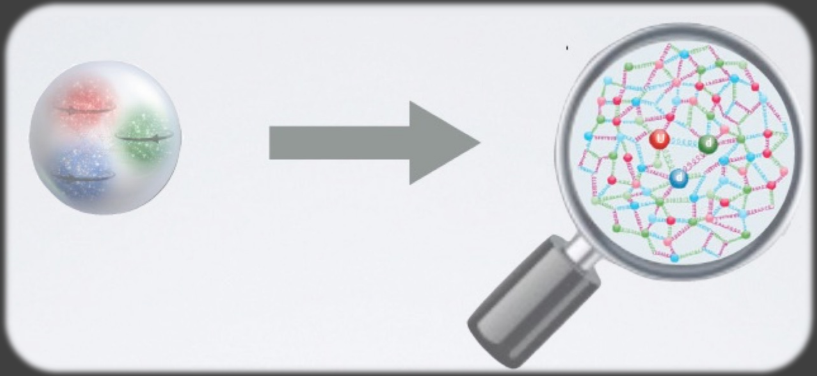
Structure Probes Lead to new Frontiers

Dynamical System	Fundamental Knowns	Unknowns	Breakthrough Structure Probes	New Sciences, New Frontiers
Solids 	Electromagnetism and Atoms 	*Structure* 	X-ray Diffraction (~1920)  	Solid state physics Molecular biology 
Universe 	General Relativity Standard Model 	Quantum Gravity, Dark matter, Dark energy. *Structure* 	Large Scale Surveys CMB Probes (~2000)  	Precision Cosmology 
Nucleons and Nuclei 	Perturbative QCD Quarks and Gluons $\mathcal{L}_{QCD} = \overline{\psi}(i\partial\!\!\!/ - gA\!\!\!/)\psi - \frac{1}{2}\mathrm{tr}\, F_{\mu\nu}F^{\mu\nu}$ 	Non-perturbative QCD. *Structure* 	DIS (1970s) ➔ Electron-Ion 	Structure & Dynamics in QCD 

Special Challenge as QCD Matter is Unique

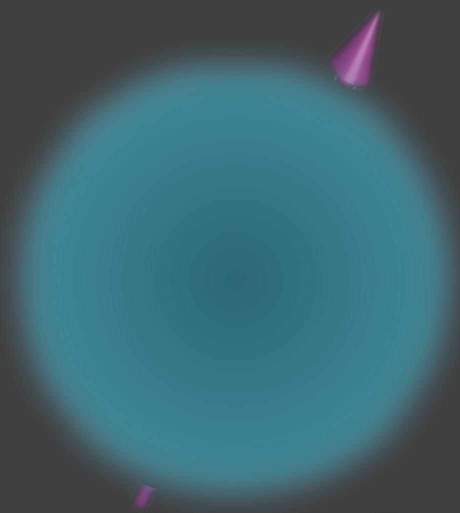
Interactions & structures inextricably mixed

Observed properties such as mass & spin, *emerge* out of this complex system



To understand QCD matter we need to Image it

First Elastic scattering show protons are not point particles



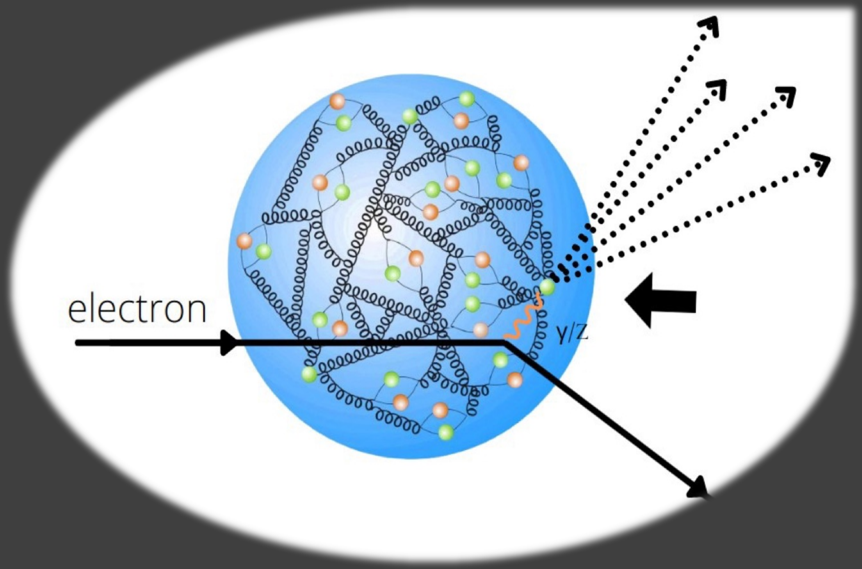
The Proton
(early 1900s)

1961

Deep Inelastic Scattering reveal point like constituents!

e + p → e' + X

Golden process, utilizing unmatched precision of electromagnetic interactions



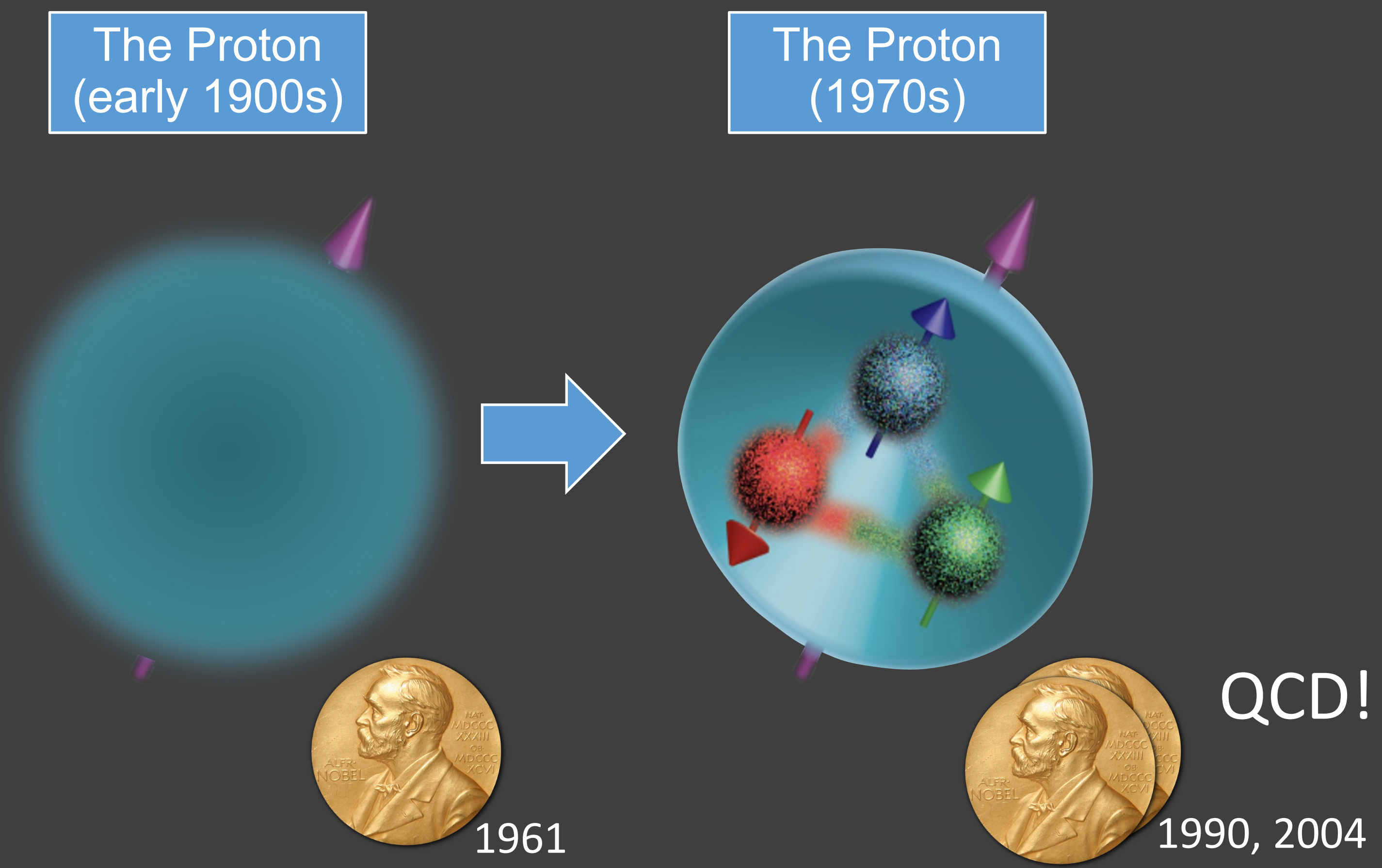
Q^2 – resolution power (virtuality of the photon)

s – center-of-mass energy squared

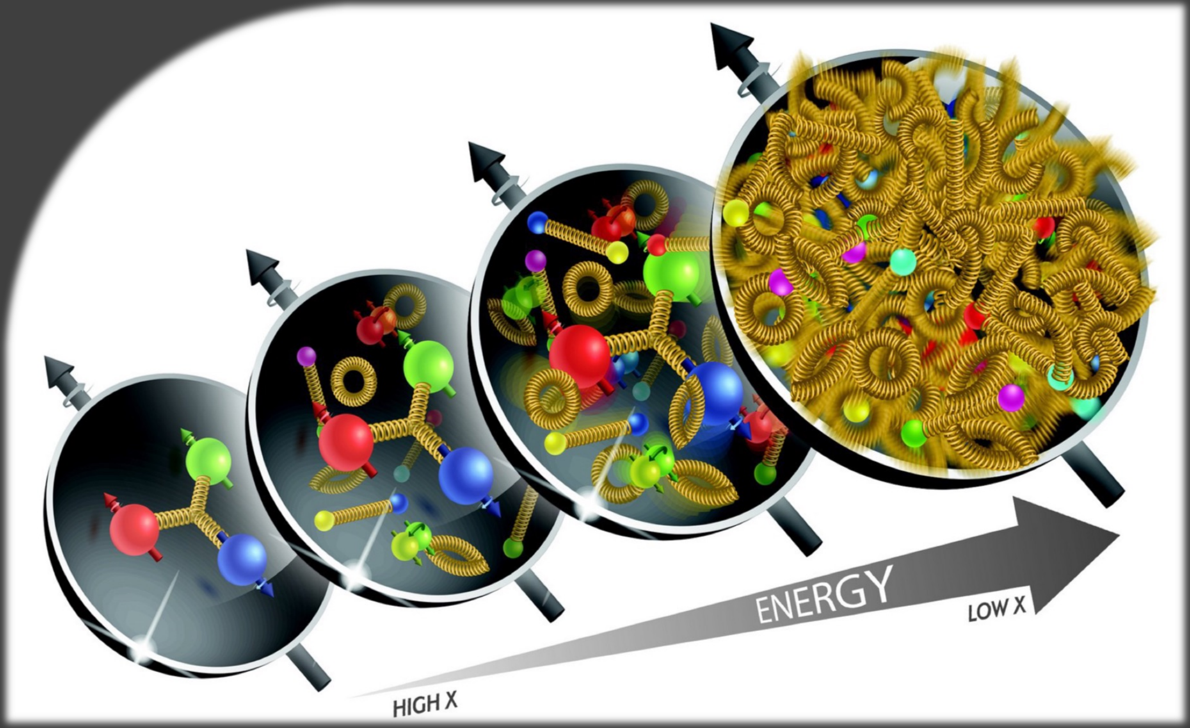
x – the fraction of the nucleon's momentum carried by the struck quark

y – inelasticity

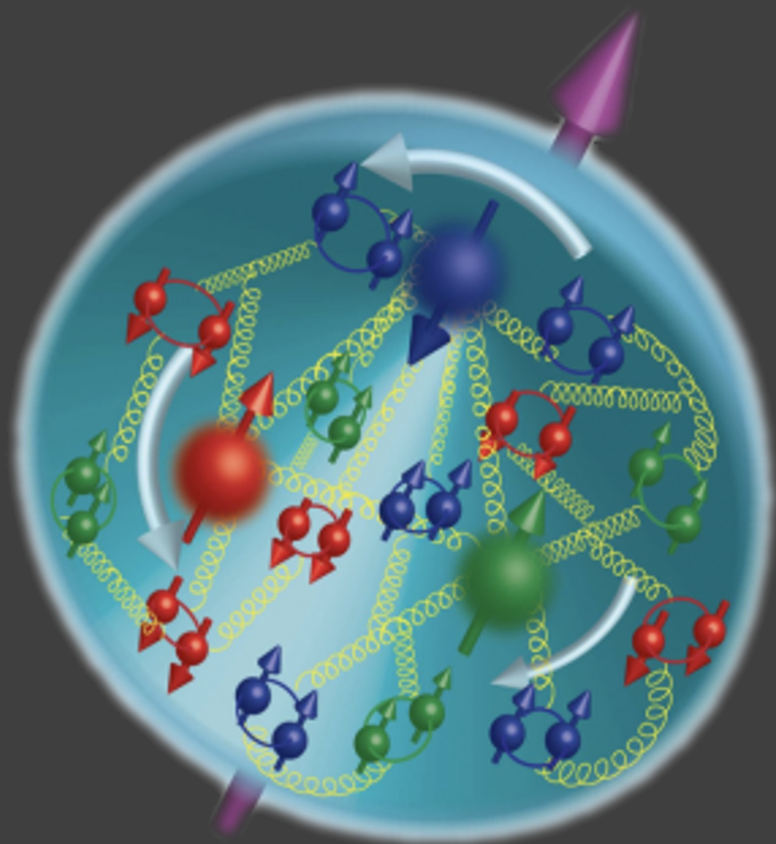
→ Imaging the subatomic world was key for gaining new understanding



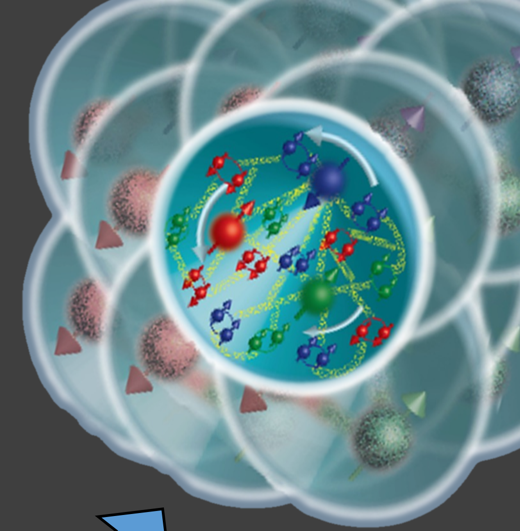
Improved measurements, incl. polarization observables, led to new insights!

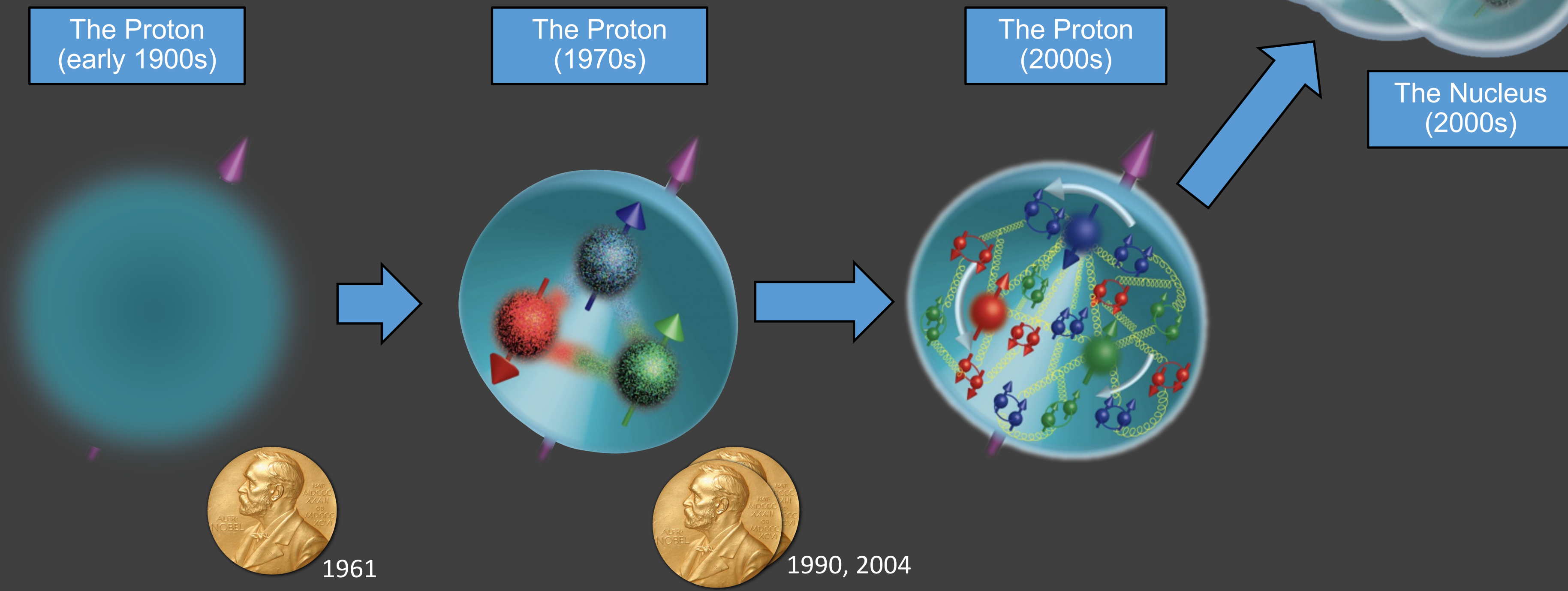


"Today's" proton is one of the most complex QM systems we know

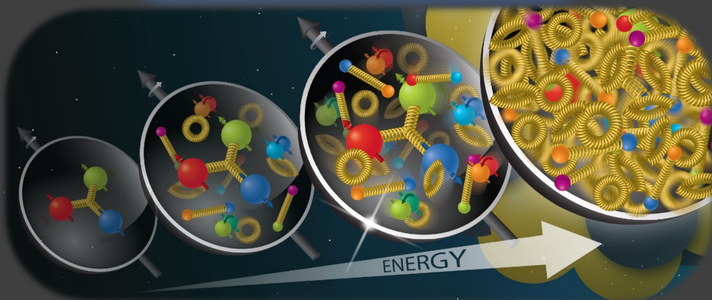


The Electron-Ion Collider: Imaging Nucleons and Nuclei





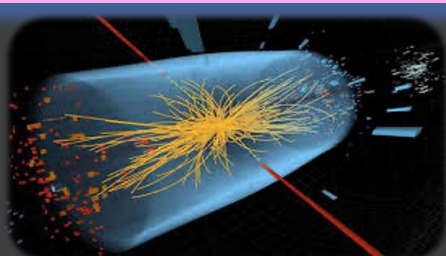
Dense Gluons



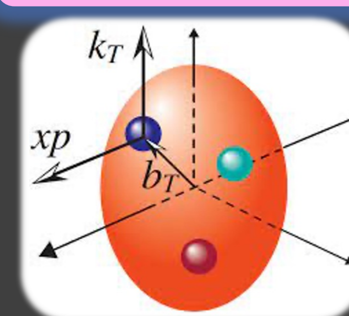
Nuclei

QCD Science

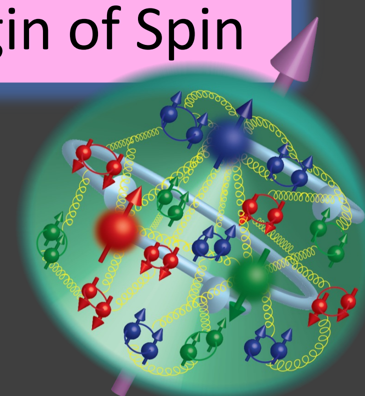
Standard Model



Femtography



Origin of Spin



Origin of Mass

Back to basics: Electon Scattering

Electron Scattering: Nuclear Microscope

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

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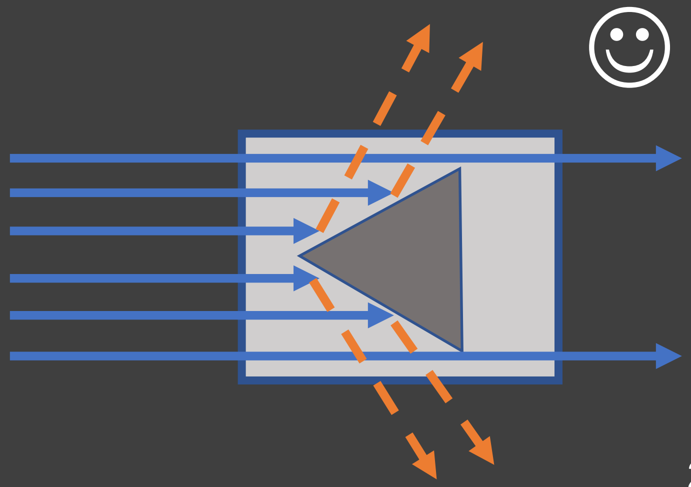
Means: using high energy lepton scattering



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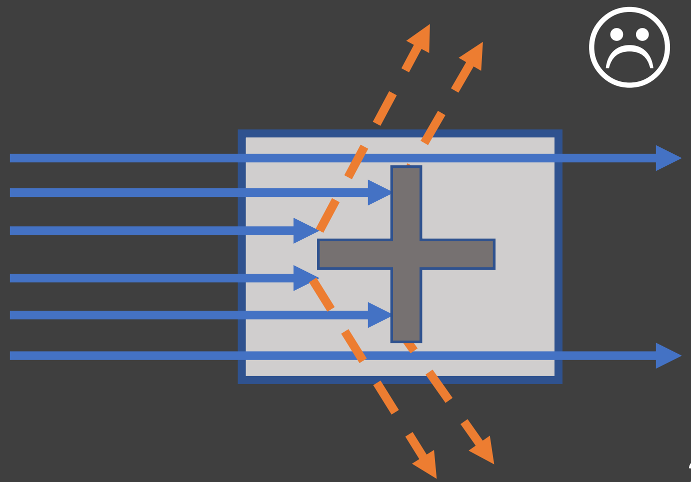

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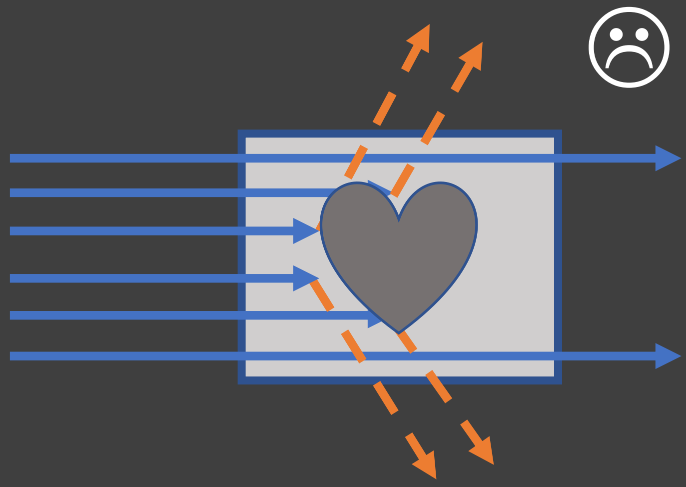

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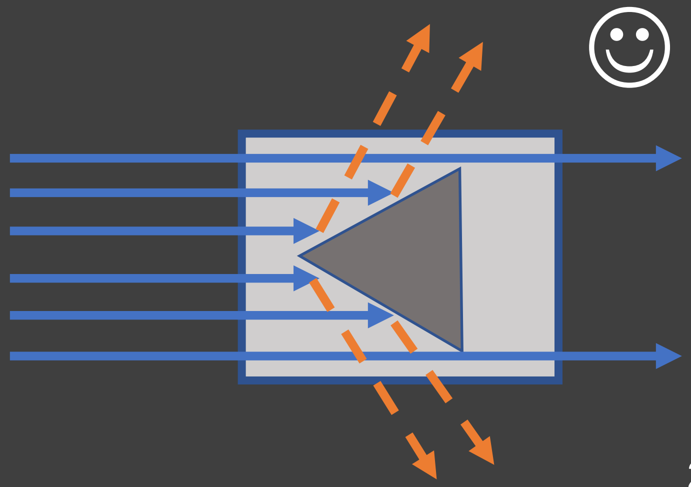

Electron Scattering: Nuclear Microscope

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

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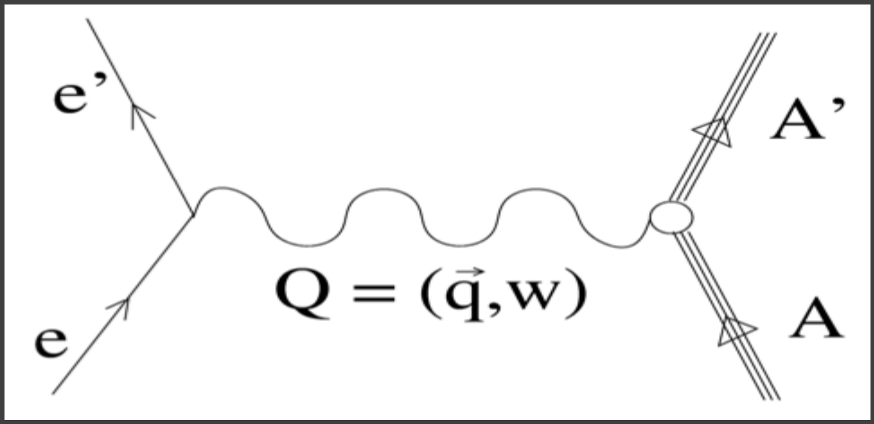
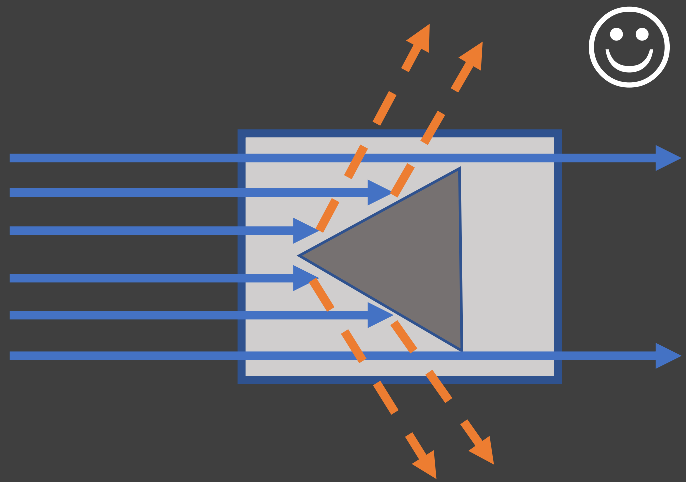
Reaction determined by two variables:

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



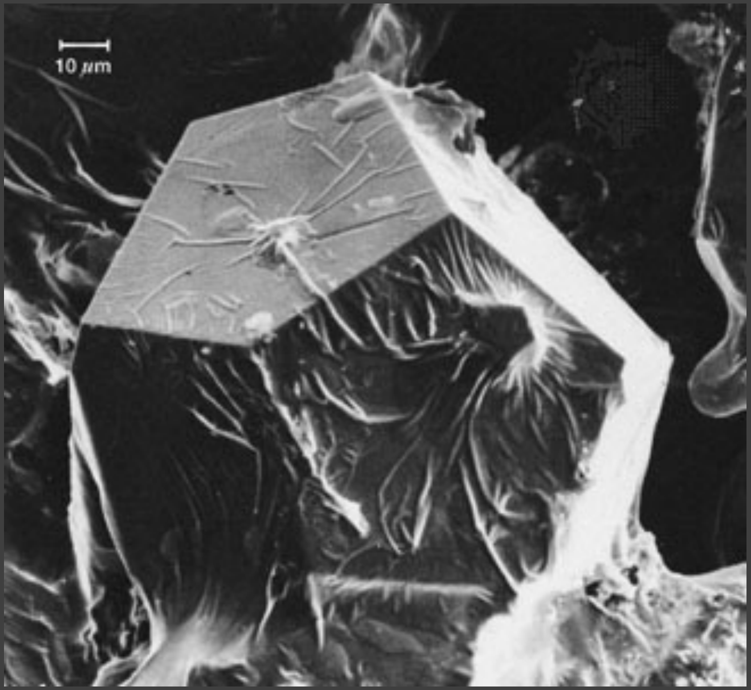


Electron Scattering: Nuclear Microscope

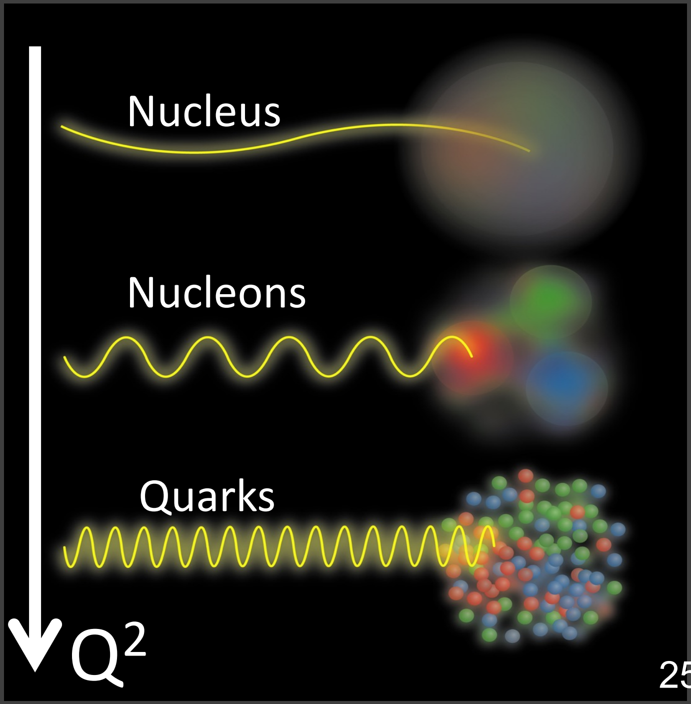
Goal: Study the internal structure (and dynamics) of complex objects

Means: using high energy lepton scattering

100s eV – 100s keV:
Material structure



100s MeV – 10s GeV:
Nuclear structure



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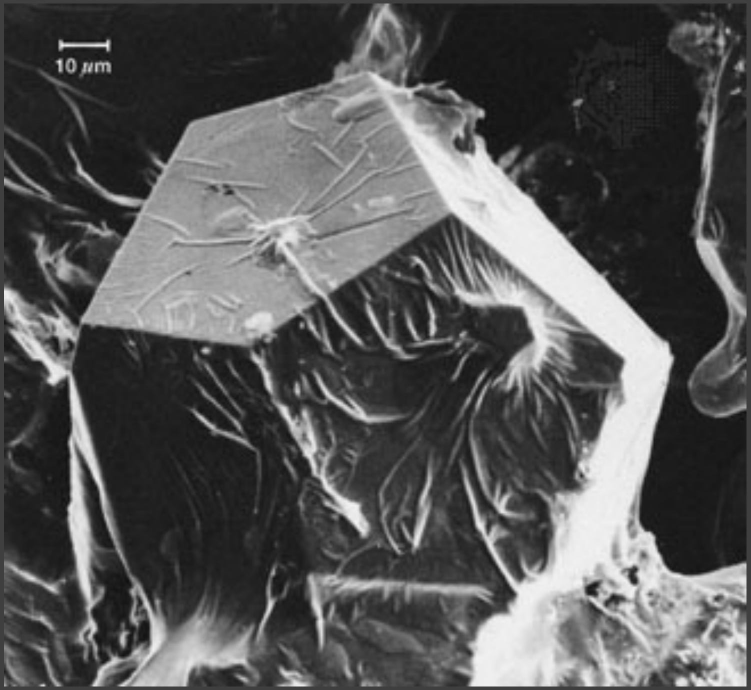

Energy
=
Resolution !

100s MeV – 10s GeV:
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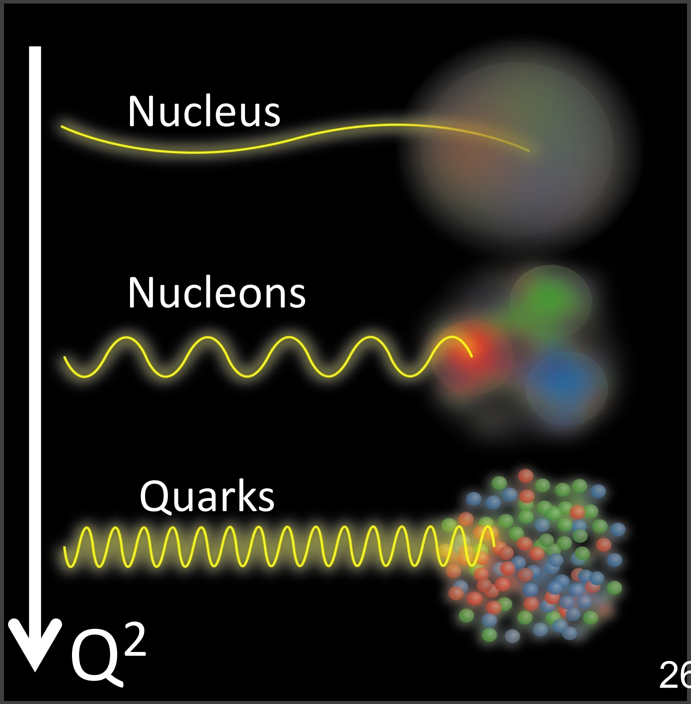
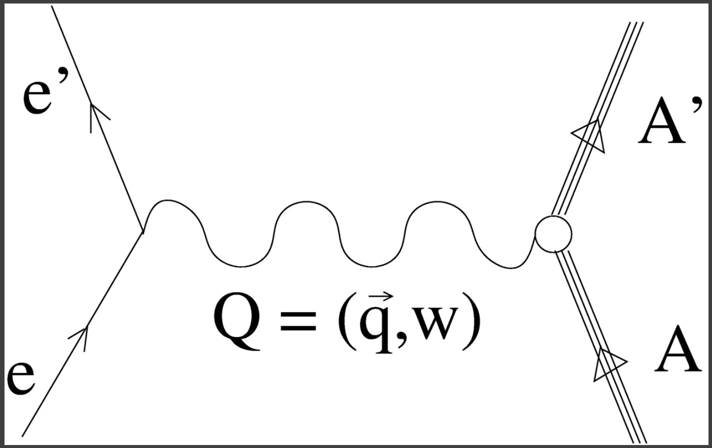


Why use electrons?

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

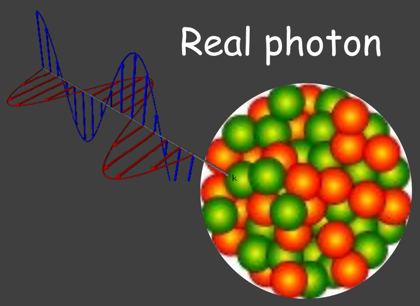
BUT:

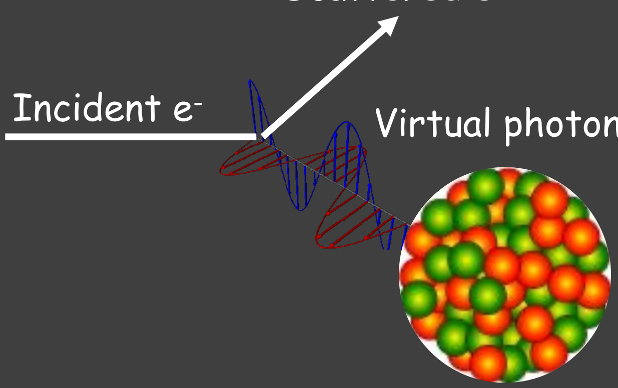
- Cross sections are small
- Electrons radiate



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"!

It's all photons!

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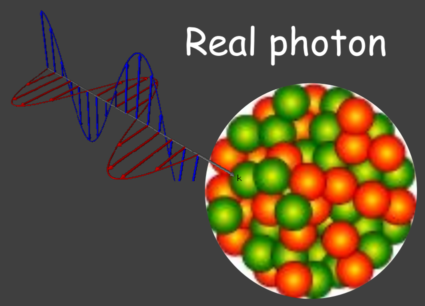

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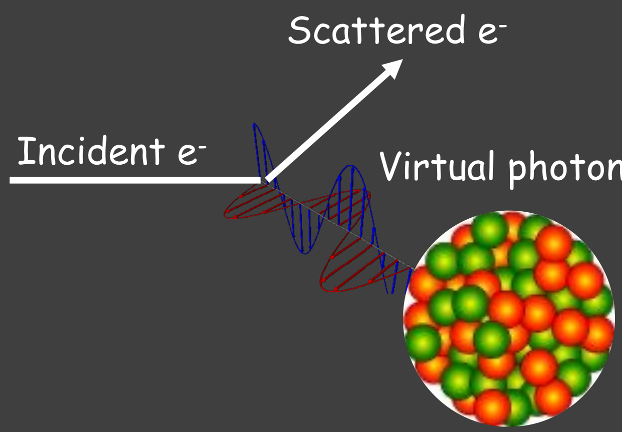


Virtual photon:
Momentum $q > \nu$ energy ν
$Q^2 = - q_\mu q^\mu = |\boldsymbol{q}|^2 - \nu^2 > 0$
Virtual photon "has mass"!

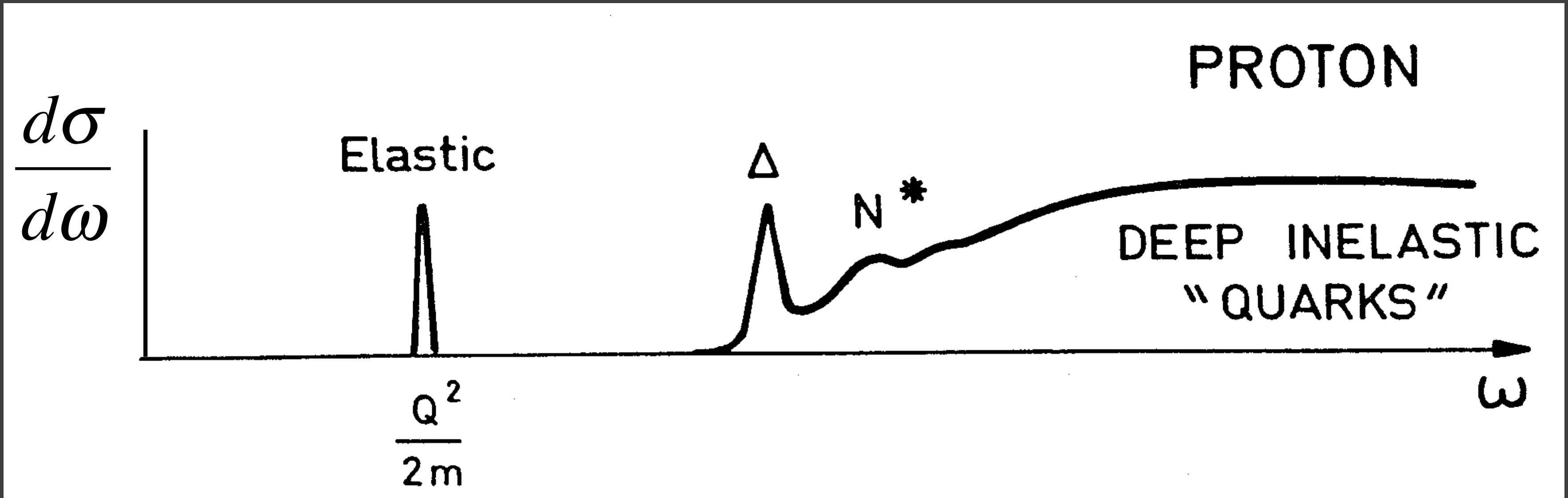
(ν and ω are both used for energy transfer)

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)

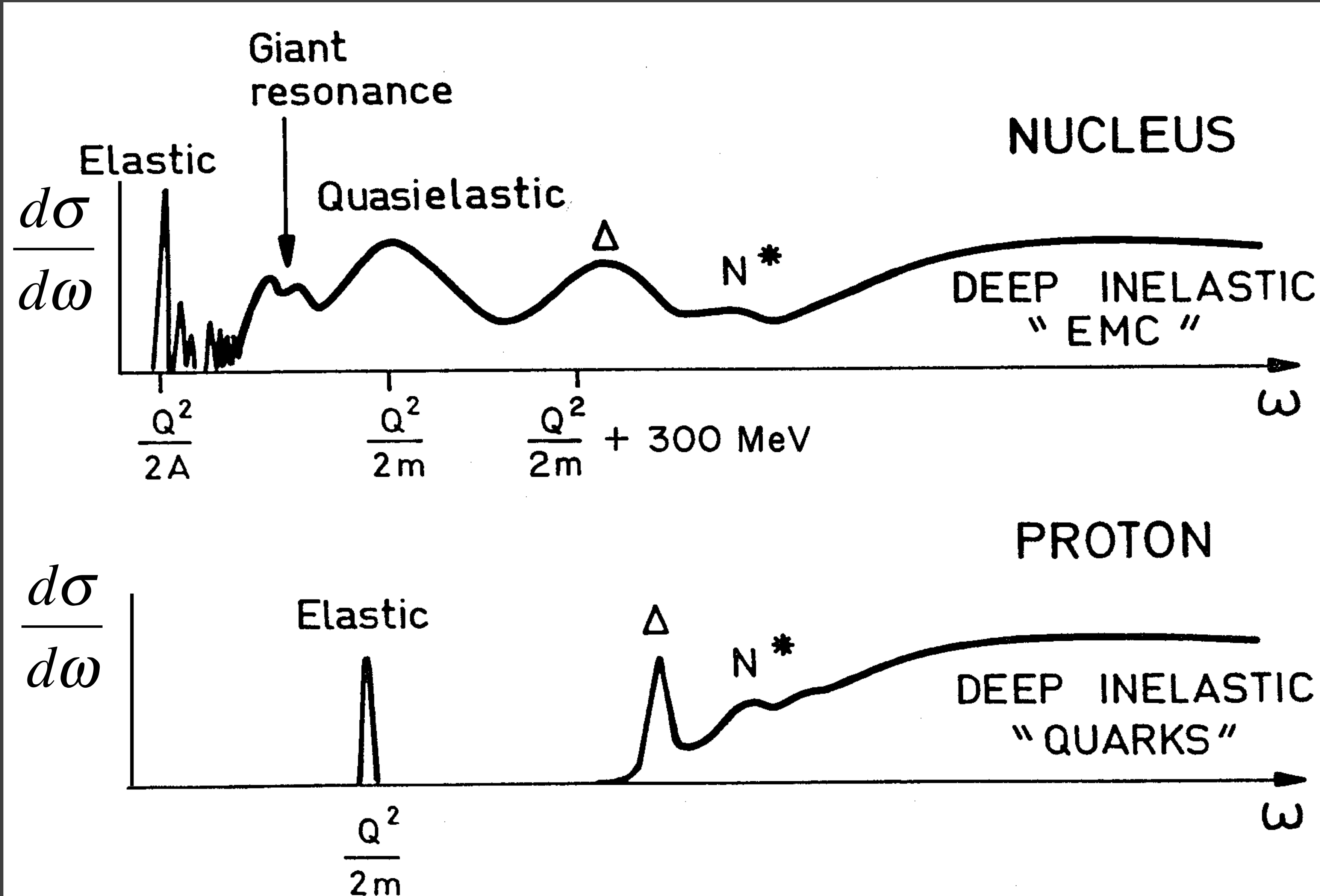
(e,e') Kinematics

(e,e’): Energy transfer defines physics

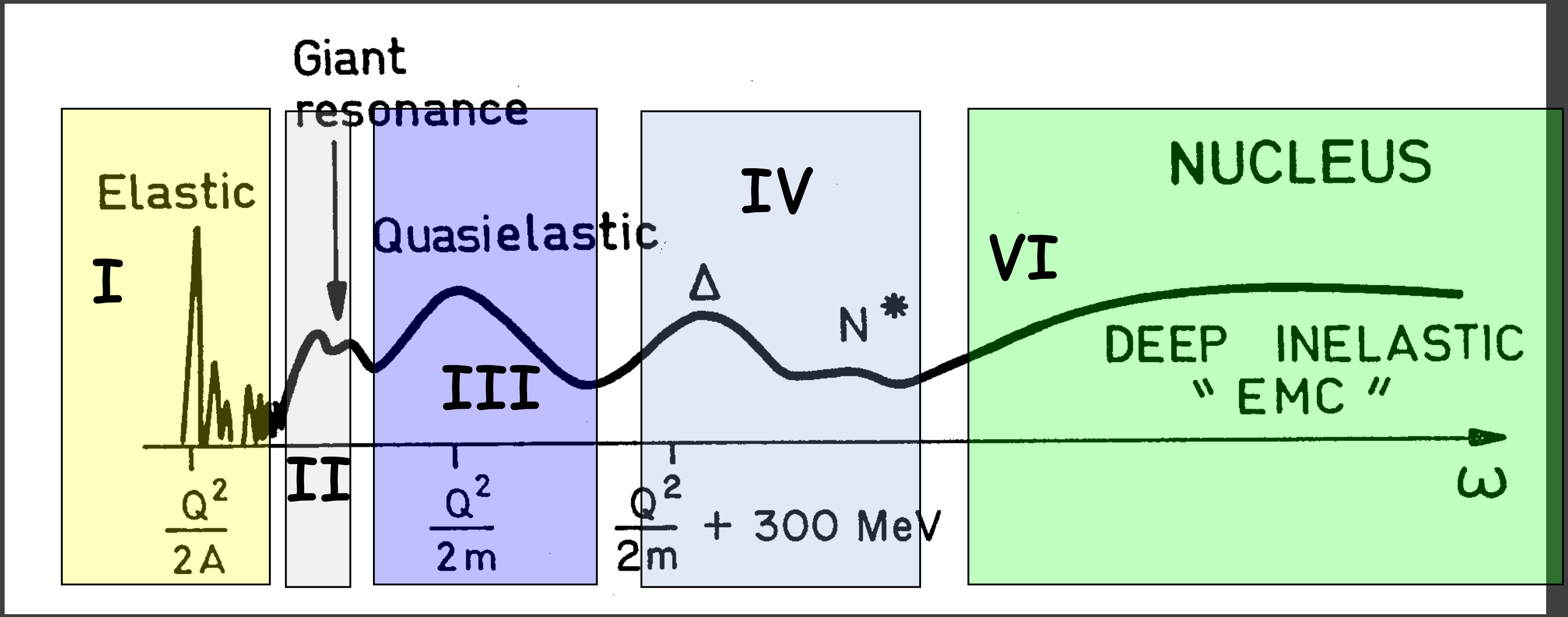


Generic Electron Scattering
at fixed momentum transfer

(e,e'): Energy transfer defines physics



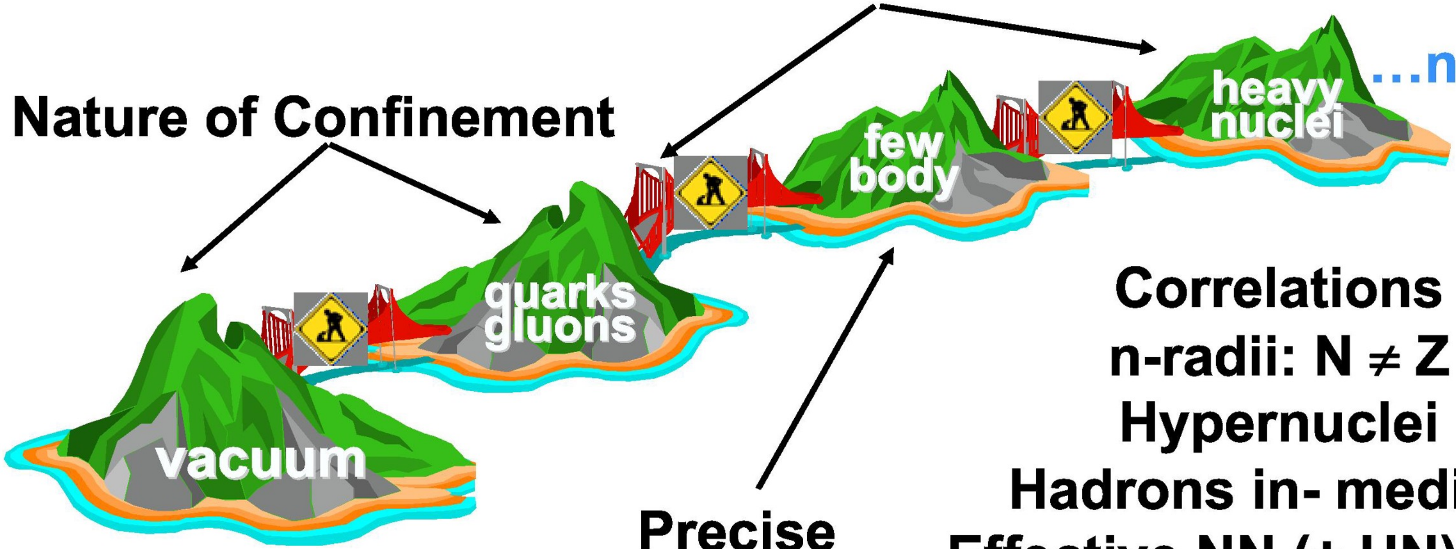
Everything is interesting…



Program central to all of nuclear science

Quark-Gluon Structure
Of Nucleons and Nuclei

Nature of Confinement

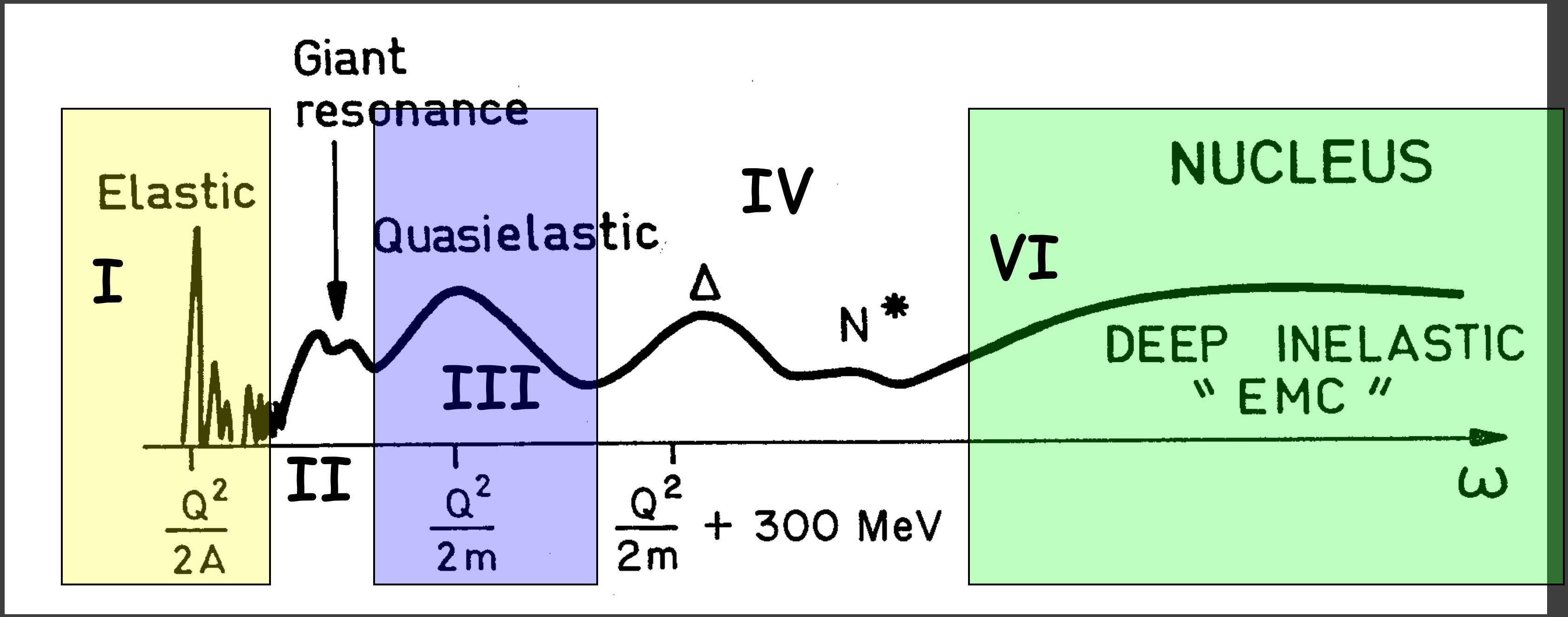


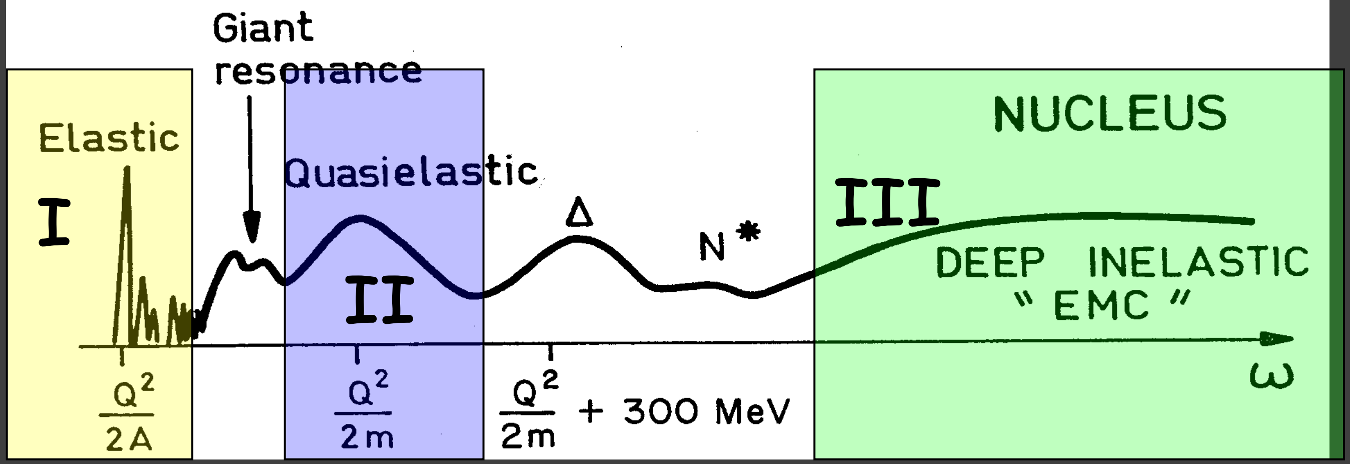
Correlations
n-radii: N ≠ Z
Hypernuclei
Hadrons in- medium
Effective NN (+ HN) force

Precise
few-nucleon
calculations

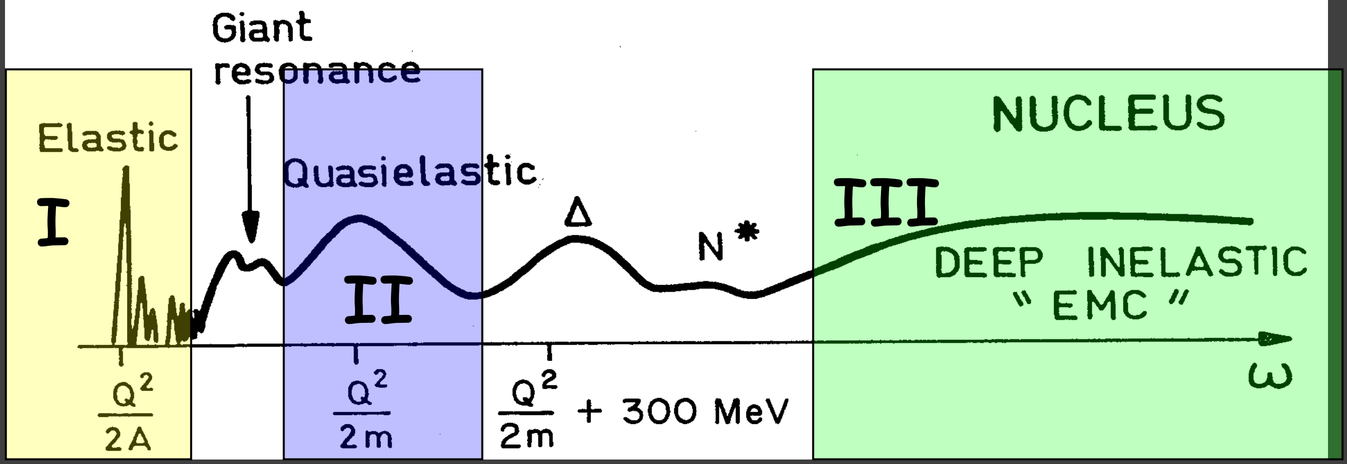
Exotic mesons
and baryons

...But we will focus on 3 regions





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



1. Elastic
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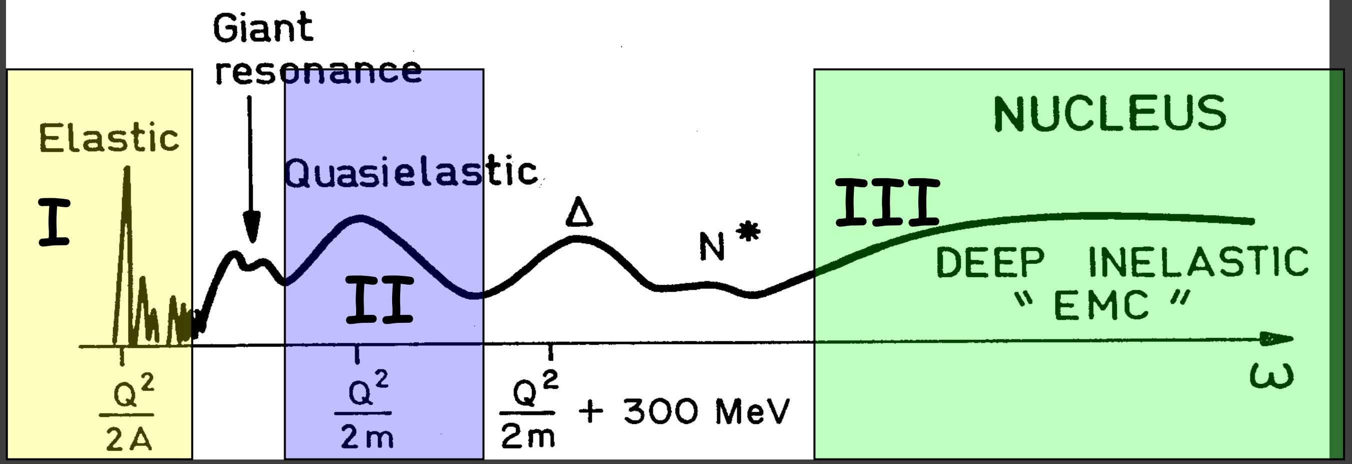
2. Quasielastic (QE)
    - Shell structure
        - Momentum distributions
        - Occupancies
    - Short Range Correlated nucleon pairs
    - Nuclear transparency and color transparency



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

Energy vs length

Select spatial resolution and excitation energy independently

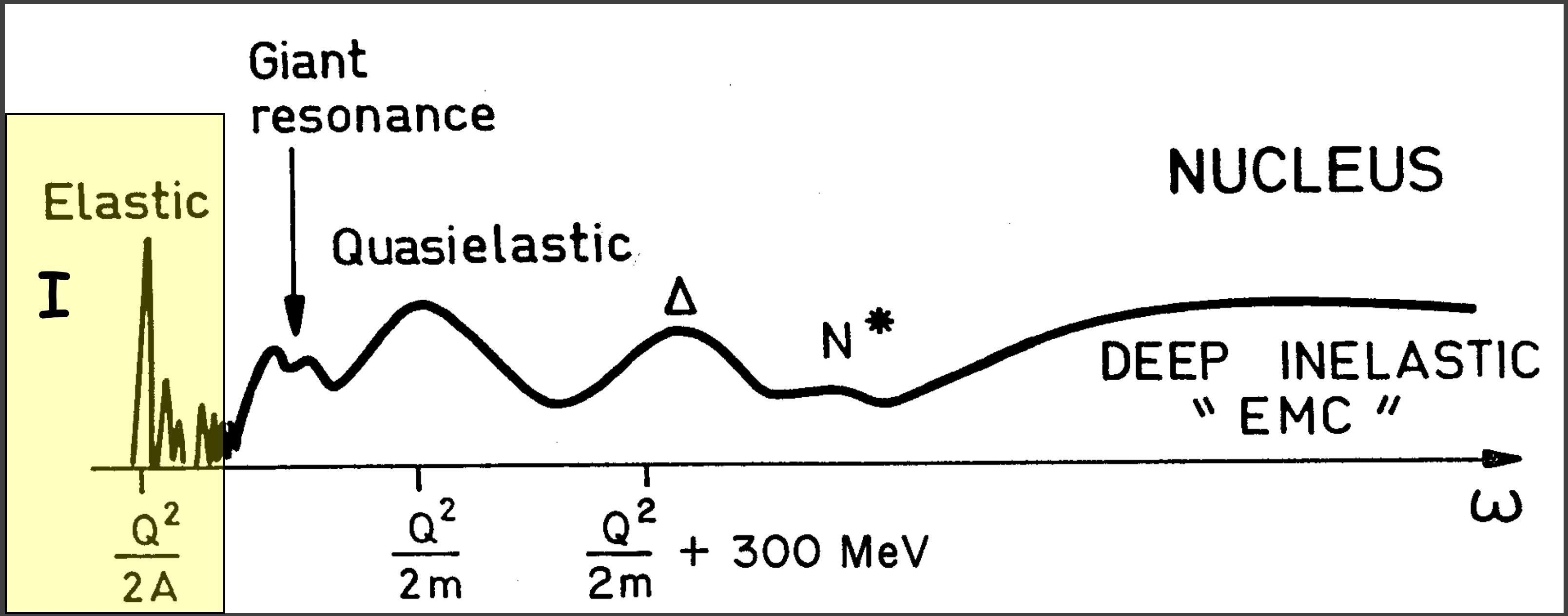
- Photon energy ν determines excitation energy
- Photon momentum q determines spatial resolution:

$$\lambda \approx \frac{\hbar}{q}$$

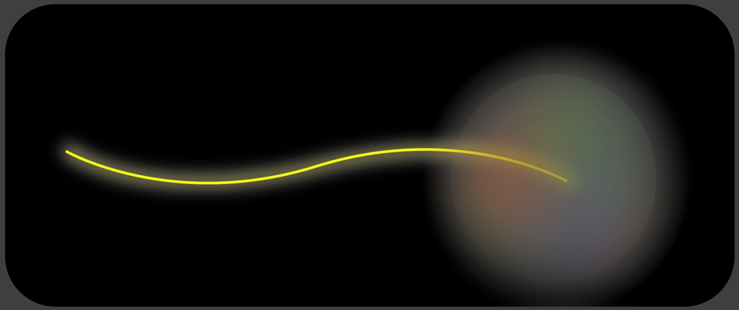
Three cases:

- 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

Quick Overview: Elastic



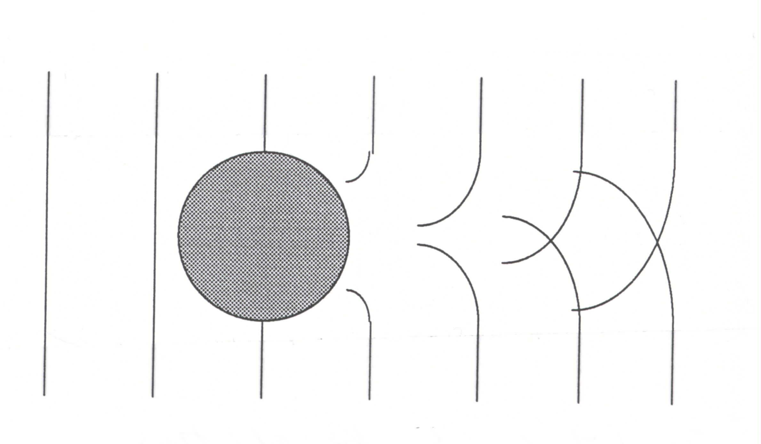
- Nuclear charge (proton) radius
- Nuclear Neutron radius
- Nucleon Form-Factors and charge densities



Electrons as Waves

Scattering process is quantum mechanical

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



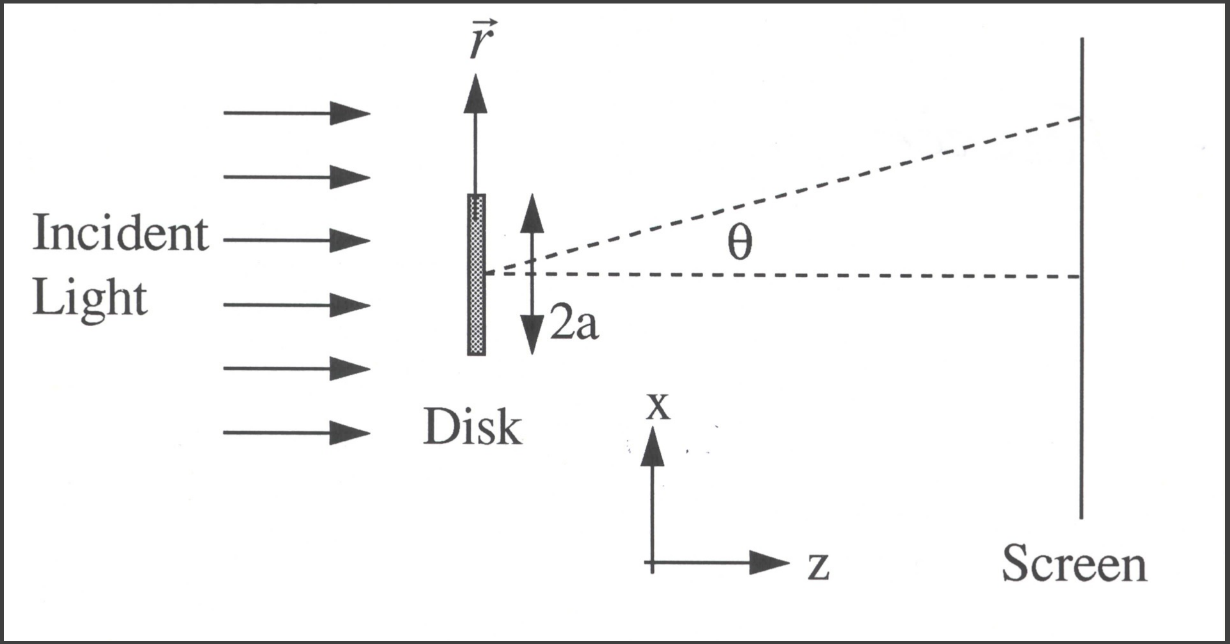
Electron energy: $E_e \approx pc$

$\hbar c = 197$ MeV-fm

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

Simple analogy for elastic electron scattering….

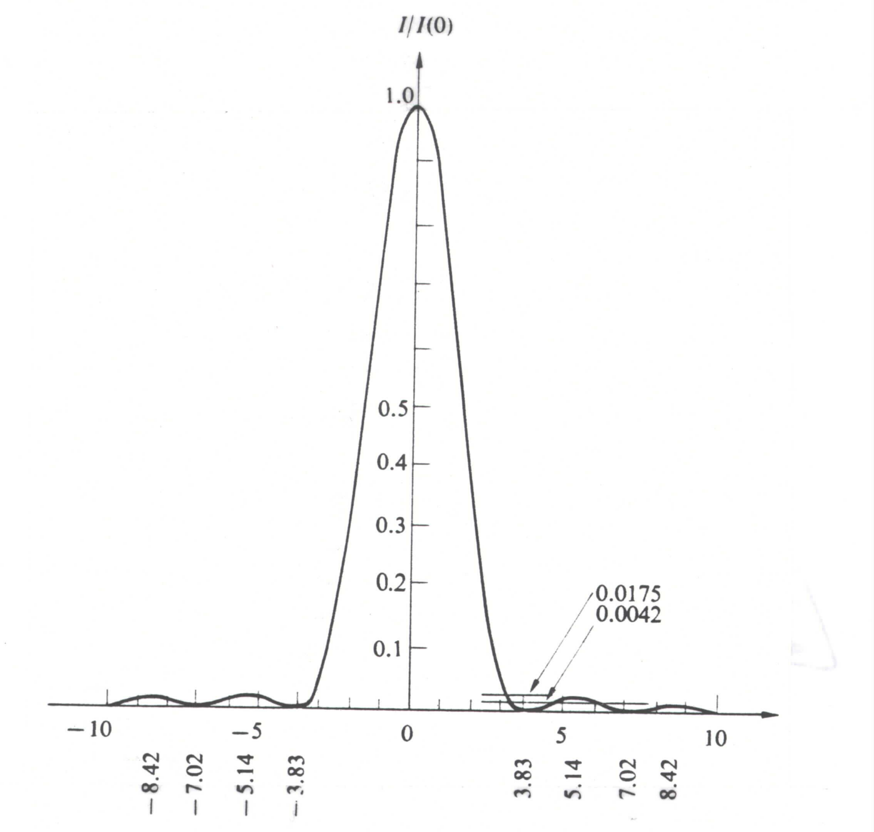
Classical Fraunhofer Diffraction



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:

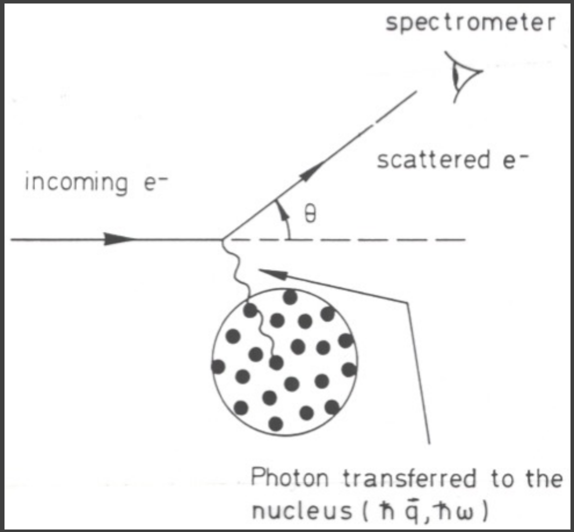
$$\Phi^2 \propto \left(\frac{J_1((2\pi a/\lambda)\sin\theta)}{\sin\theta} \right)^2$$

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

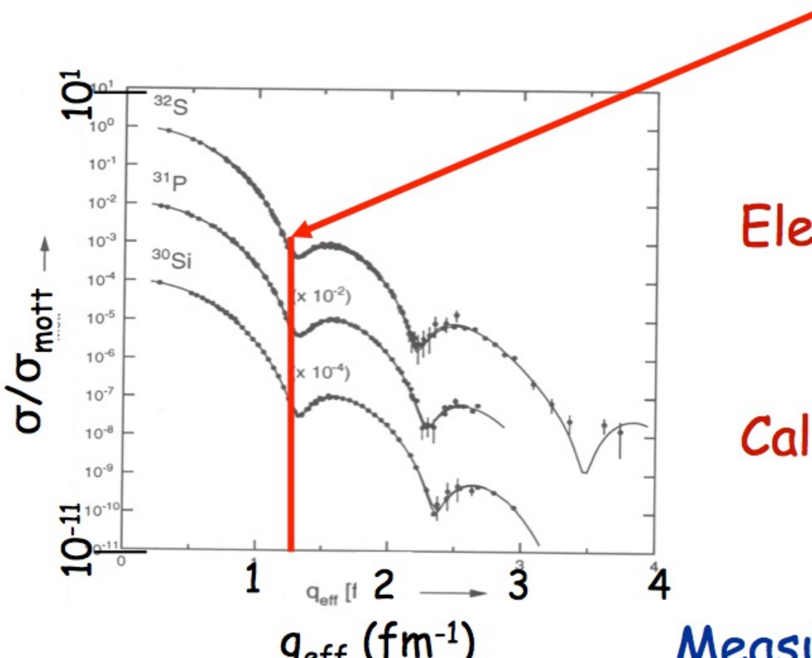
…some algebra…

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

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



Cross Section ⇔ Charge Form Factor



1st minimum = 1.3 fm^{-1}

➔ $\theta = 32.8^o$

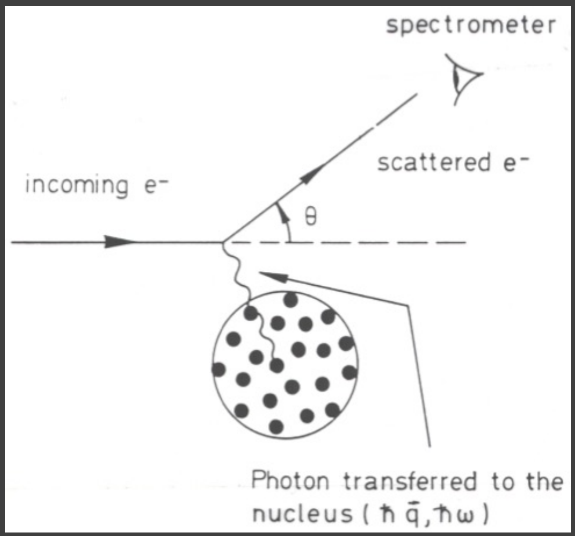
Electron energy = 454.3 MeV

➔ $\lambda = 2.73$ fm

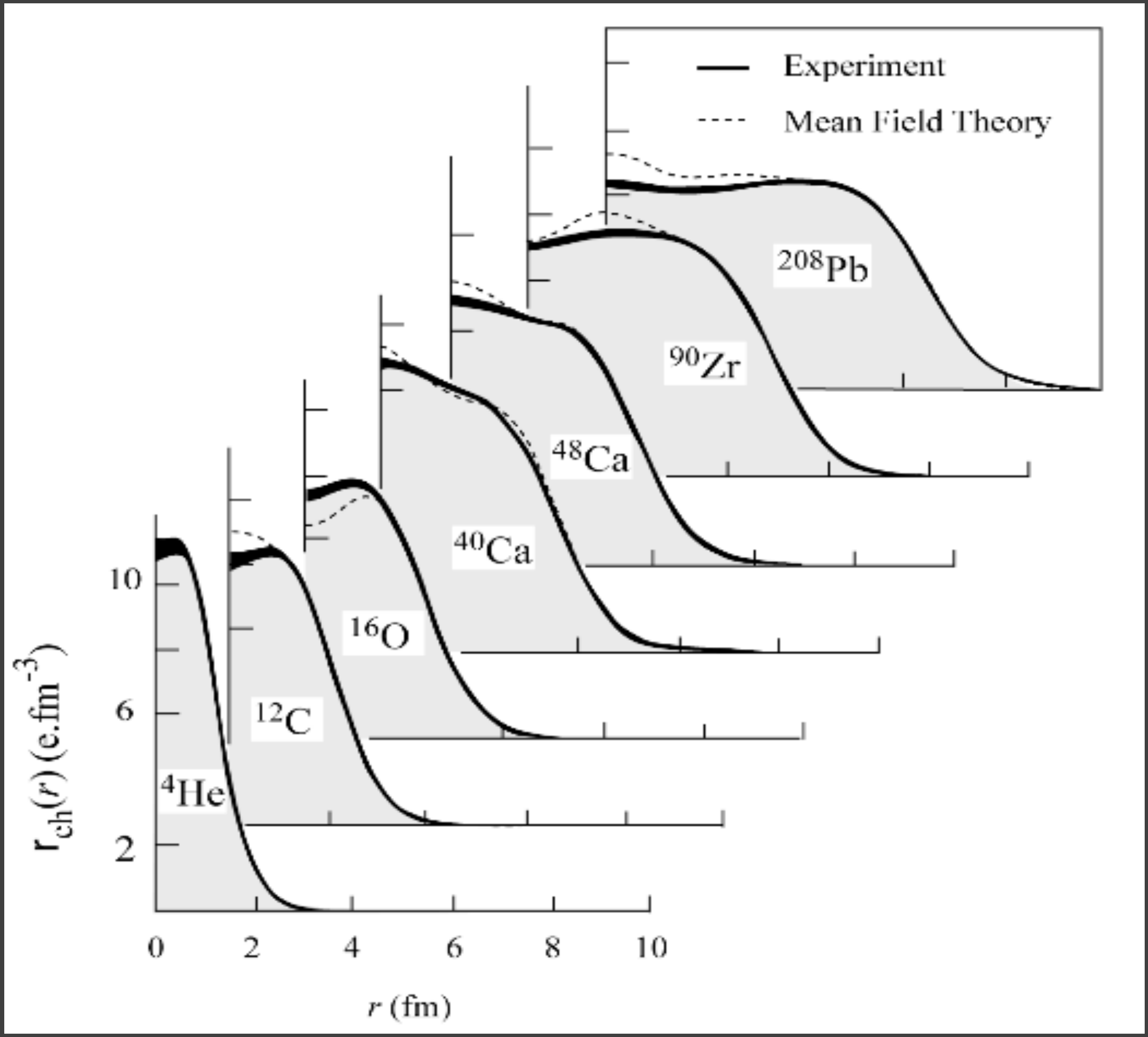
Calculated radius = 3.07 fm

Measured rms radius = 3.19 fm

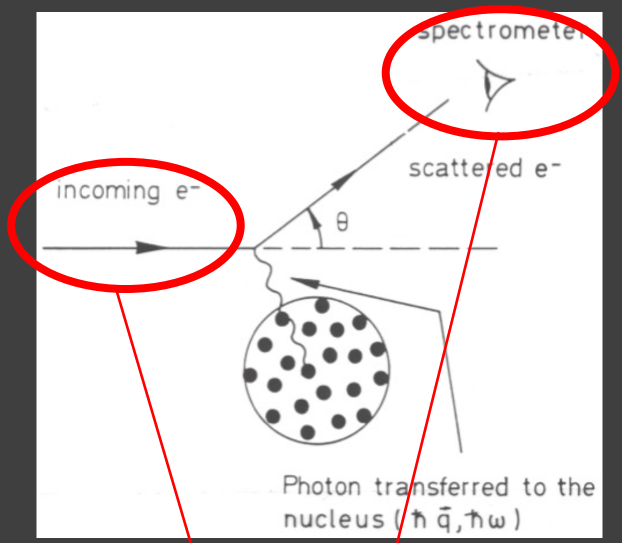
Diffraction Measurements of Small Radii



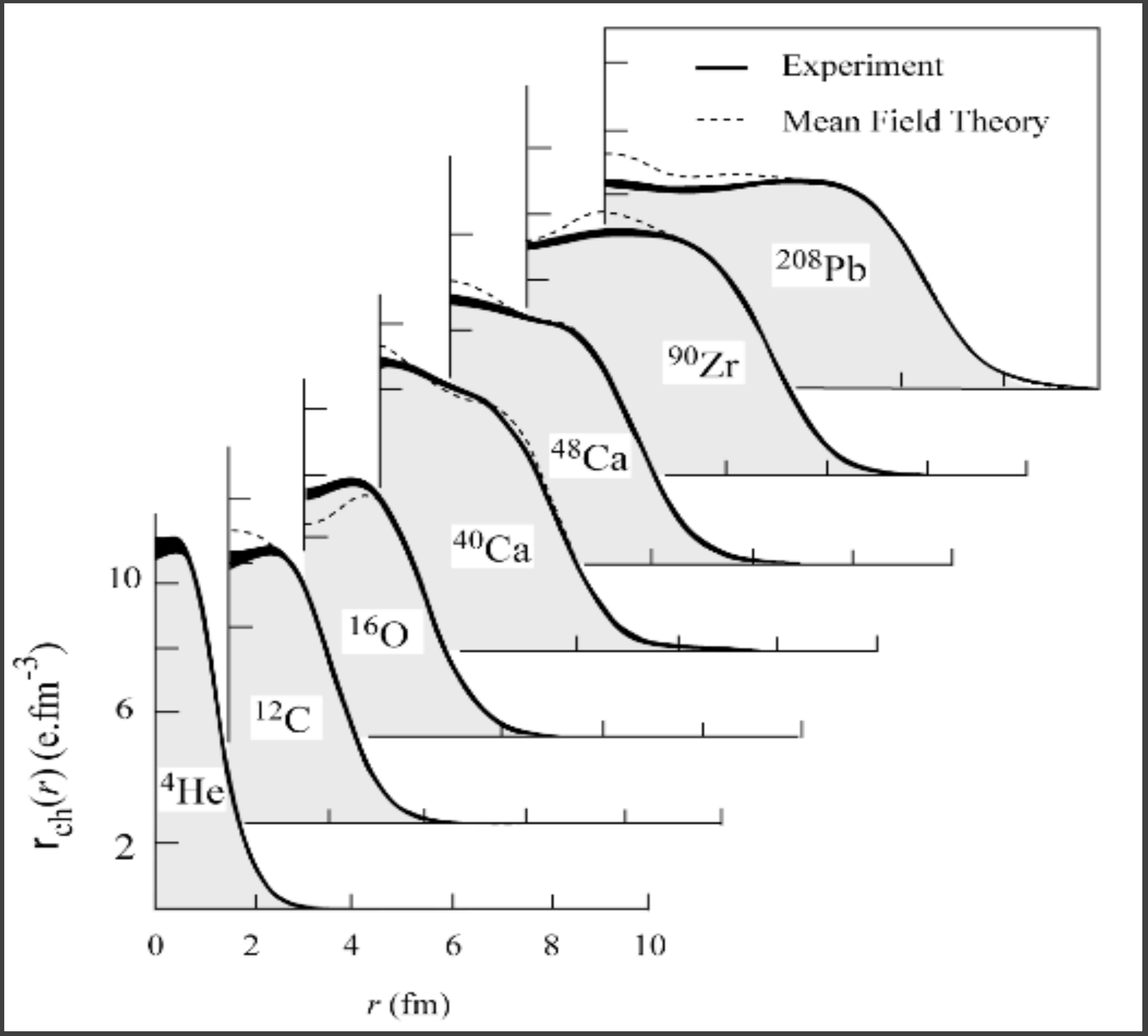
Charge Distribution, $\rho_{CH}(r)$, is a Fourier Transform of the Charge Form Factor, F(q)



Diffraction Measurements of Small Radii



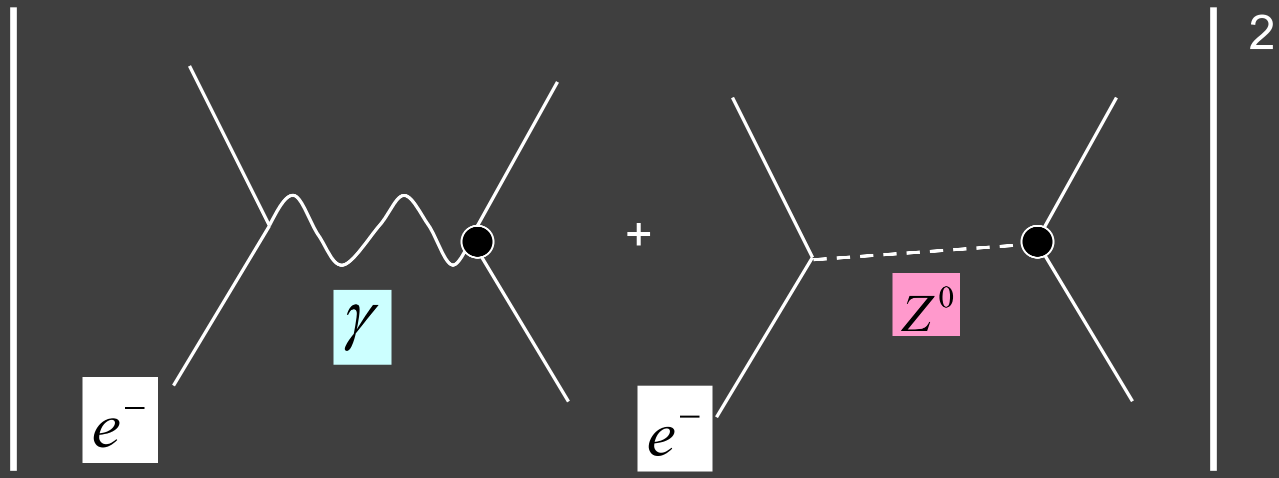
10s – 100s Million Dollar Machines



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

Weak Interaction: Neutron Distribution

Z^0 of Weak Interaction:
Clean Probe Couples Mainly to Neutrons

$F_W(Q^2)$: ^{208}Pb
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Clean Probe Couples Mainly to Neutrons

	proton	neutron
Electric charge	1	0
Weak charge	0.08	1

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

$$Q_w = 2\,T_3 - 4\,Q_\epsilon\ \sin^2\theta_w = 2\cdot\left(-\tfrac{1}{2}\right) = -1 \approx\ -0.99$$

$$Q_w = 2\,T_3 - 4\,Q_\epsilon\ \sin^2\theta_w\ =\ 2\ \tfrac{1}{2} - 4\ \sin^2 29^\circ\ \approx\ 1 - 0.94016\ =\ 0.0598$$

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

High Accuracy:

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

R_n = neutron matter radius

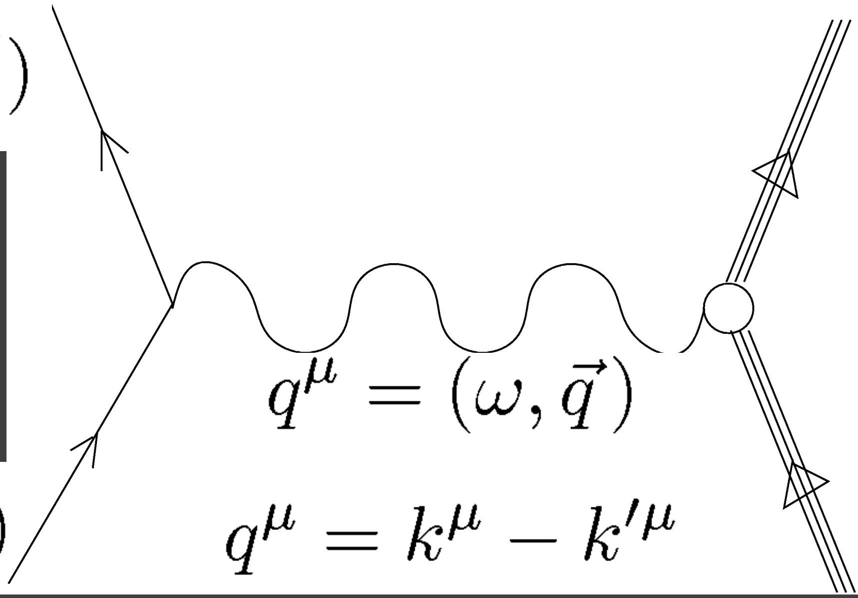
From Intuition to Formalism

Lab frame kinematics

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

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

(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:

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

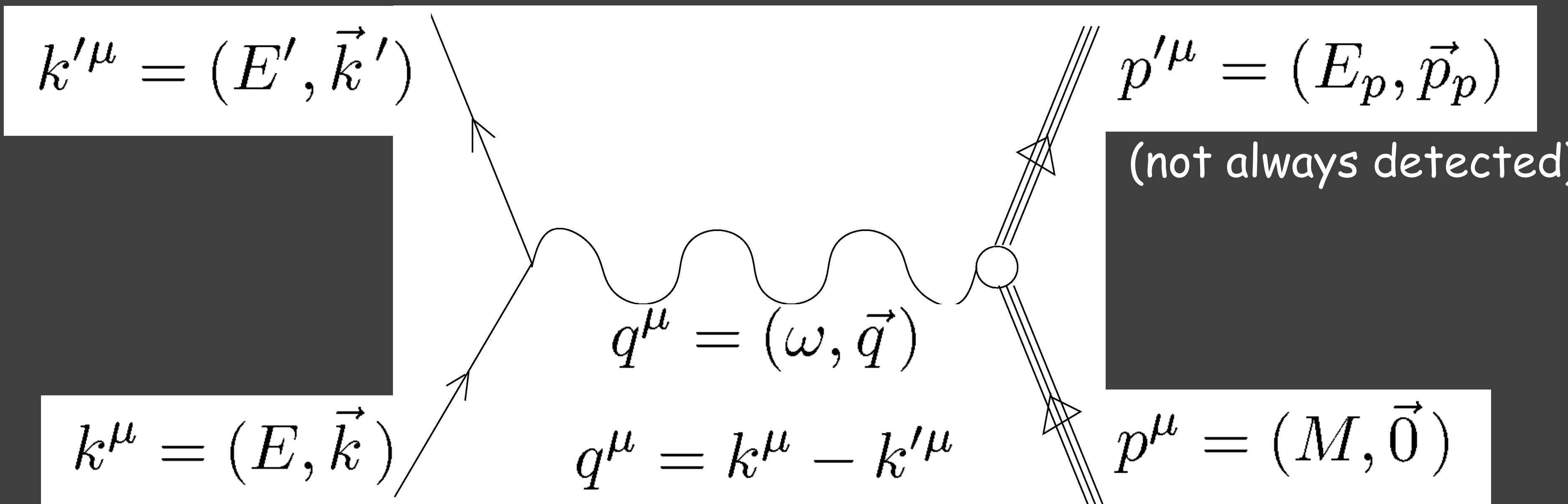
$$Q^2 = -q^{\mu} q_{\mu} = |\vec{q}\,|^2 - \omega^2$$

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

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

From Intuition to Formalism

Lab frame kinematics



Invariants:

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

From Intuition to Formalism (Elastic)

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

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

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

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

From Intuition to Formalism (Elastic)

Recoil factor Form factors

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

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

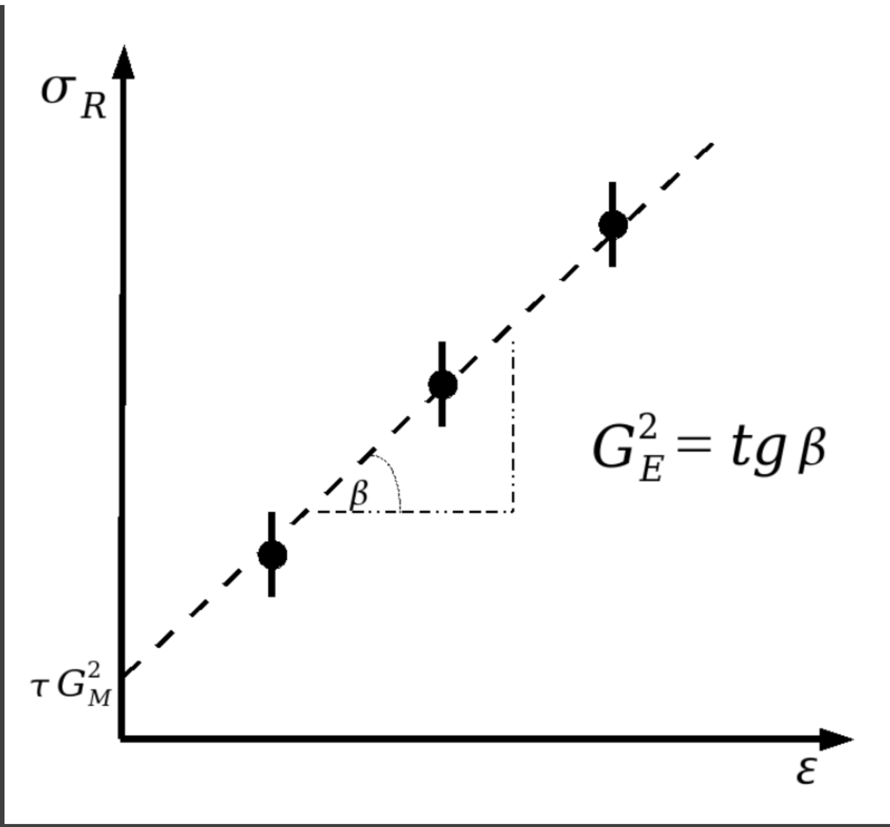
$$= \sigma_M \frac{E'}{E}\left[\frac{Q^4}{\vec{q}^4} R_L(Q^2) + \left(\frac{Q^2}{2\vec{q}^2} + \tan^2\frac{\theta}{2}\right) R_T(Q^2)\right]$$

nucleons

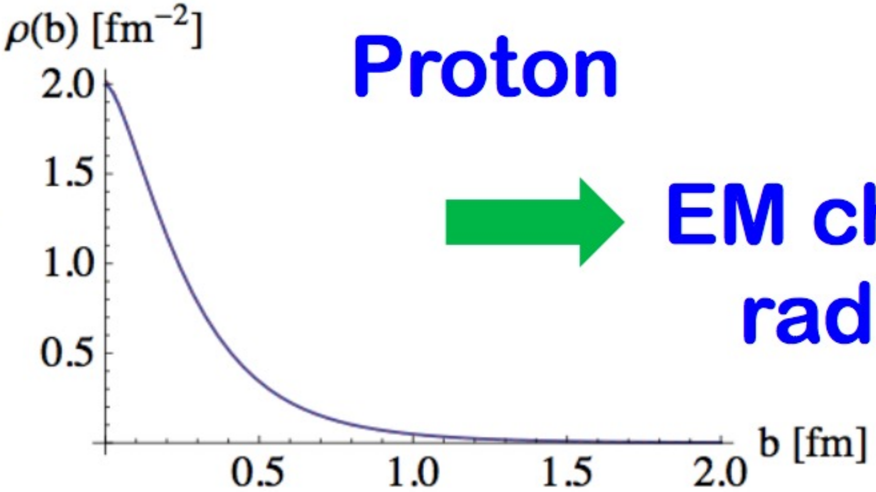
- F_1, F_2: Dirac and Pauli form factors
- G_E, G_M: Sachs form factors (electric and magnetic)
  - $G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2)$ $\tau = Q^2/4M^2$
  - $G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$ (more standard definition of F_1 and F_2)
- R_L, R_T: Longitudinal and transverse response functions

Form Factors: Cross-Sections

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

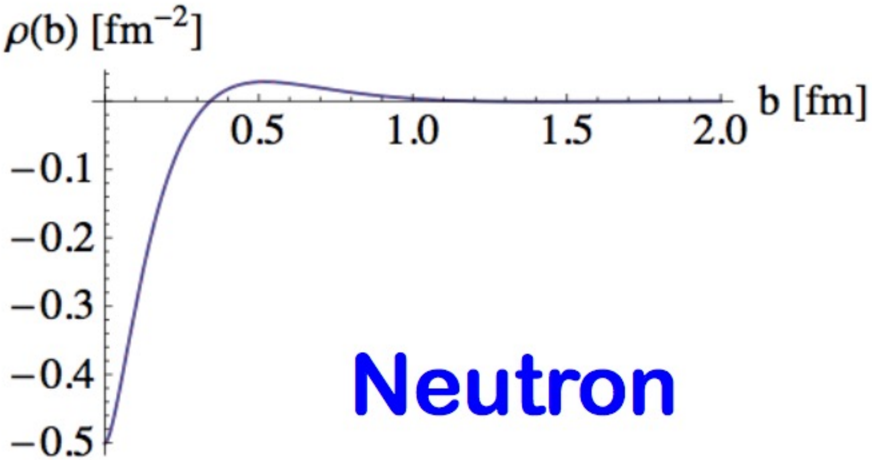


Electric charge distribution



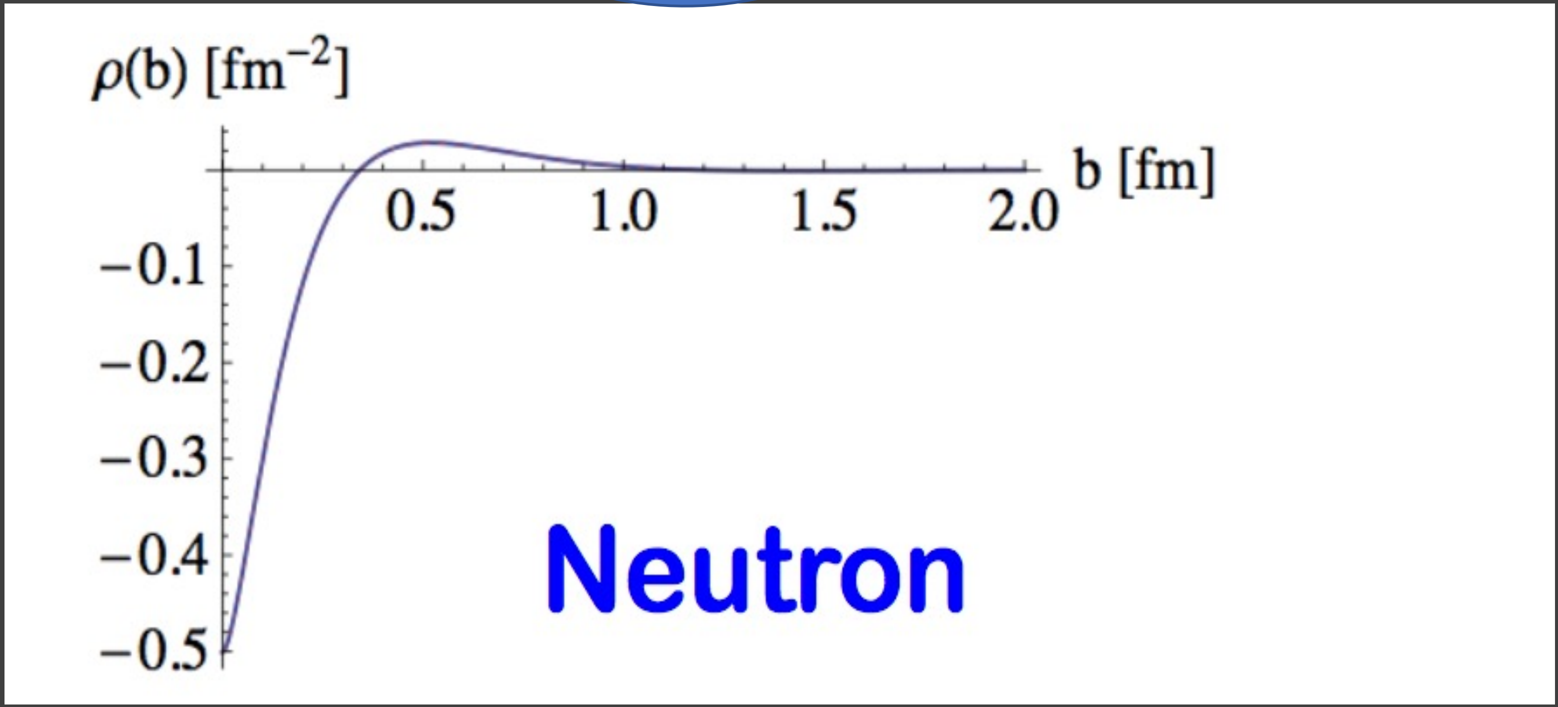
Proton

EM charge radius!

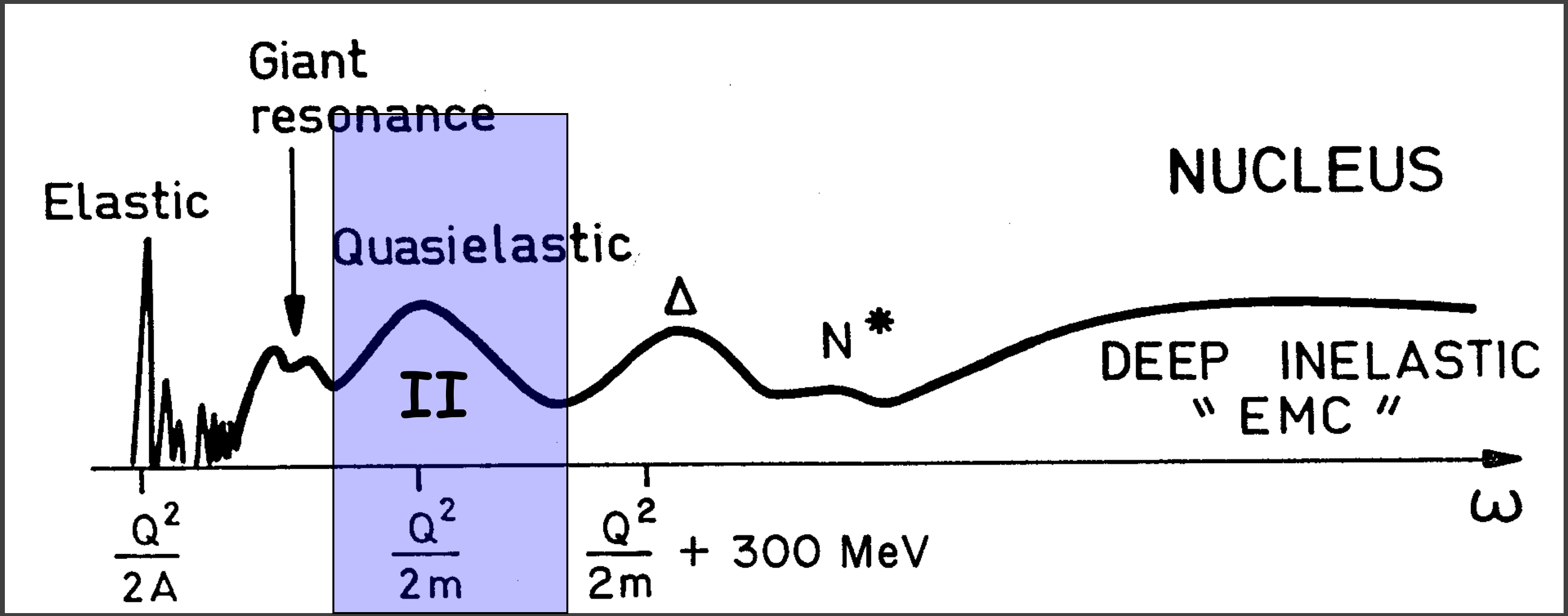


Neutron

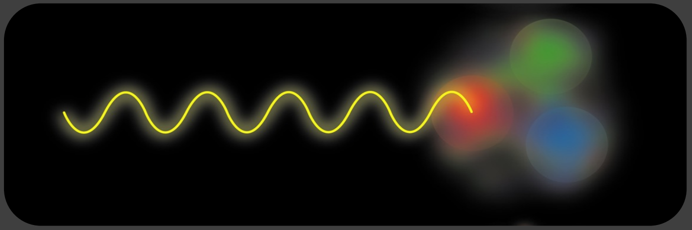
Neutron is negative in its center and positive in the edge!



Quick Overview: Quasi-Elastic

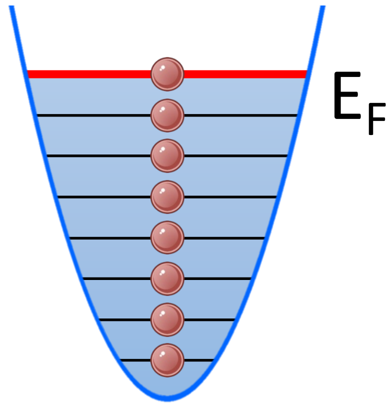


- Momentum Densities: Fermi Gas
- Y-Scaling
- Shell Structure and spectroscopic factors



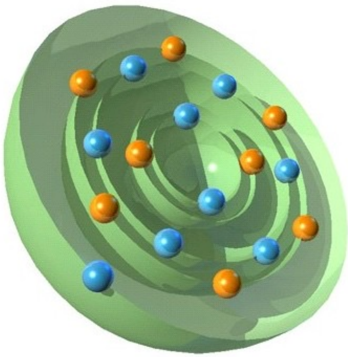
What is a Nucleus ?

Fermi Gas Model

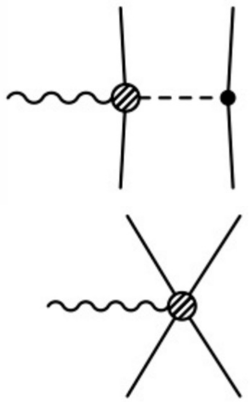


Liquid Drop Model

Shell Model



Chiral Perturbation Theory*

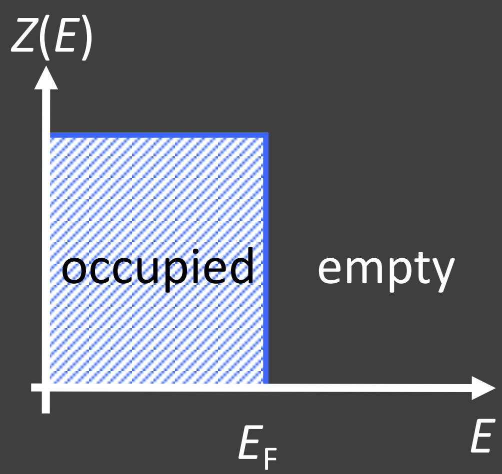


Independent Particle Shell model (IPSM)

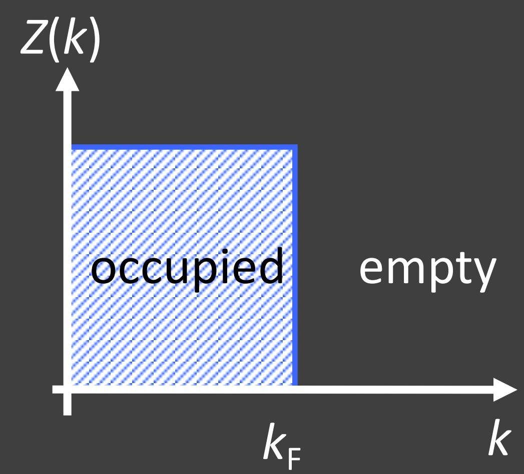
- single particle approximation:
  nucleons move independently from each other
  in an average potential created by the other nucleons (mean field)

  spectral function $S(E,k)$:
  probability of finding a proton with initial momentum k and
  energy E in the nucleus
- factorizes into energy & momentum part

nuclear matter:



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

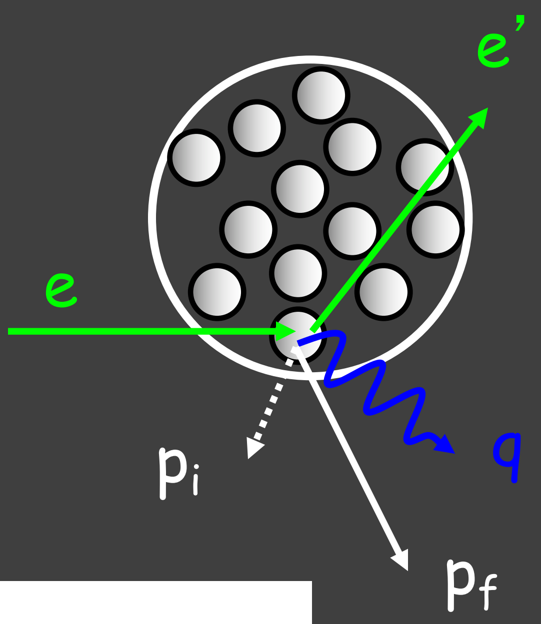


nuclei: $$S(\vec{p},E) = \sum_i |\Phi_a(p)|^2 \delta(E+\epsilon_a)$$

Not 100% accurate, but a good starting point

Fermi gas model:

how simple a model can you make ?



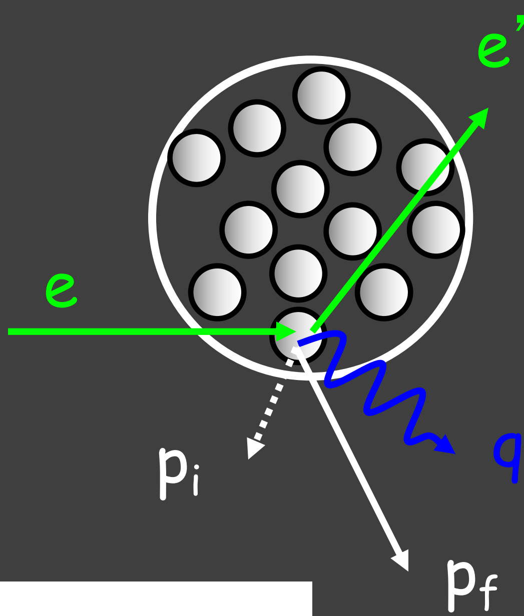
Initial nucleon energy: $KE_i = p_i^2 / 2m_p$

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

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

Fermi gas model:

how simple a model can you make ?



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

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

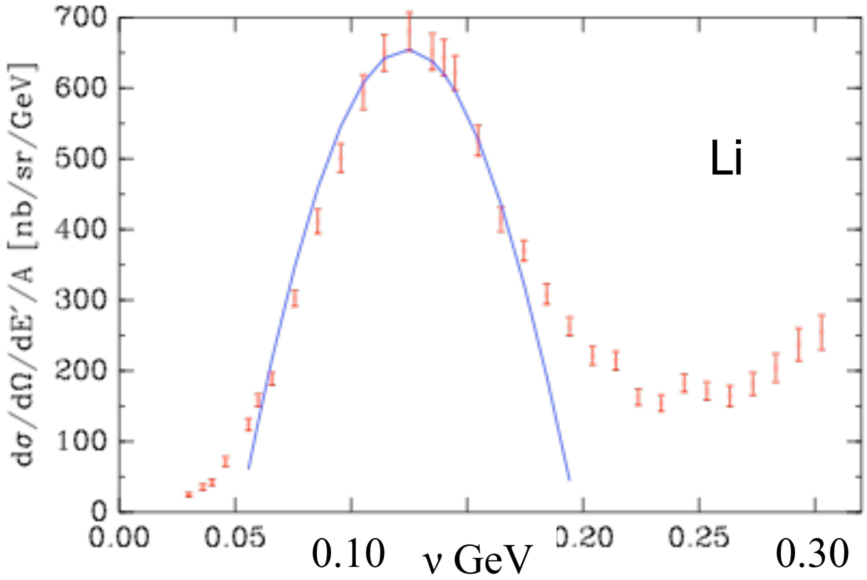
Early 1970's Quasielastic Data

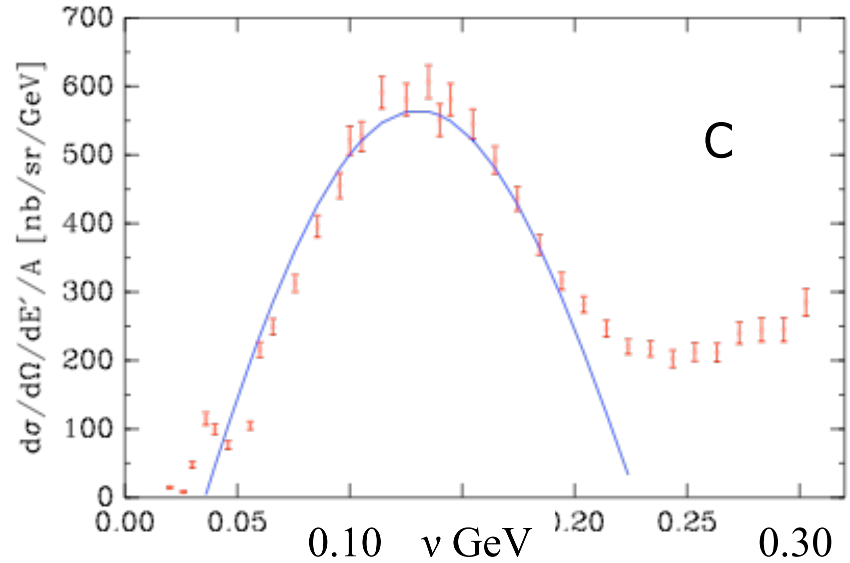
-> getting the bulk features

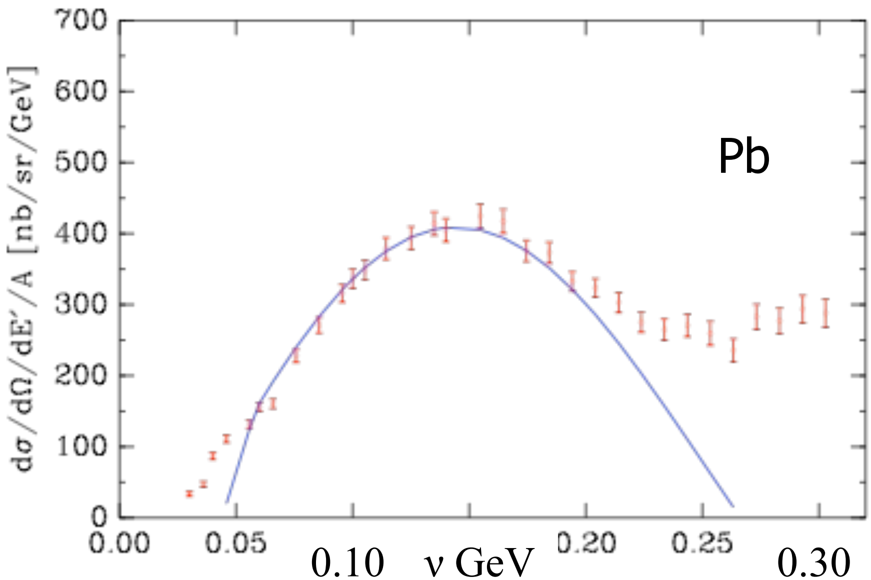
500 MeV, 60 degrees

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

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







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

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)

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)

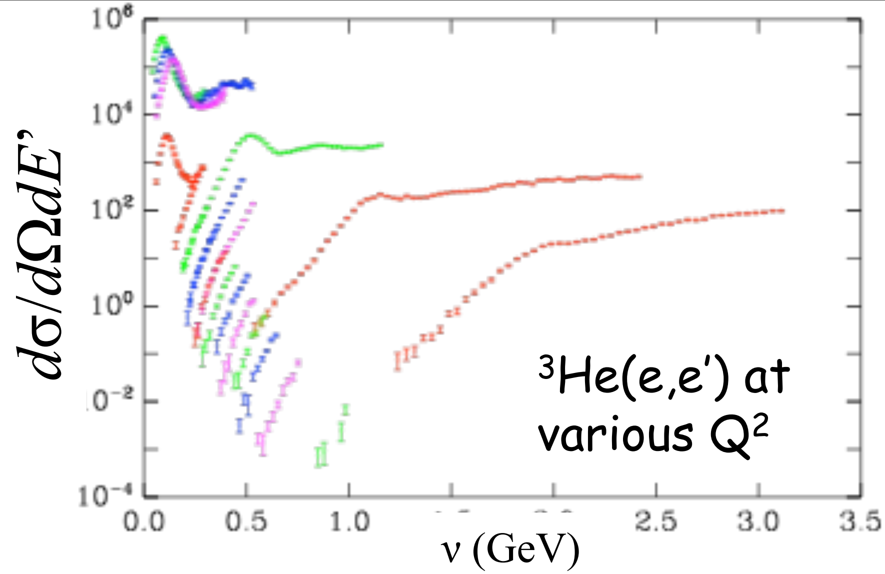
IF the scattering is quasifree, then $F(y)$ is the integral over all perpendicular nucleon momenta (nonrelativistically).

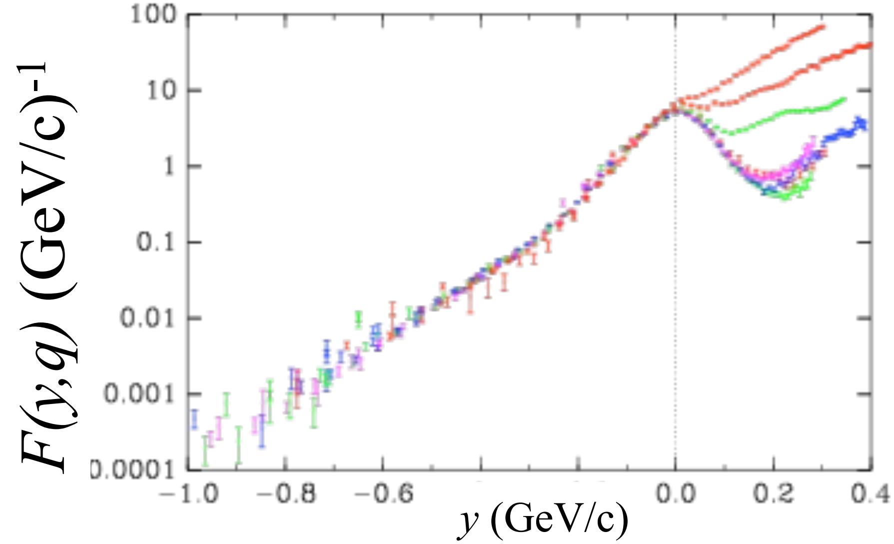
Goal: extract the momentum distribution $n(k)$ from $F(y)$.

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

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

y-scaling: inclusive scattering from ^3He





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

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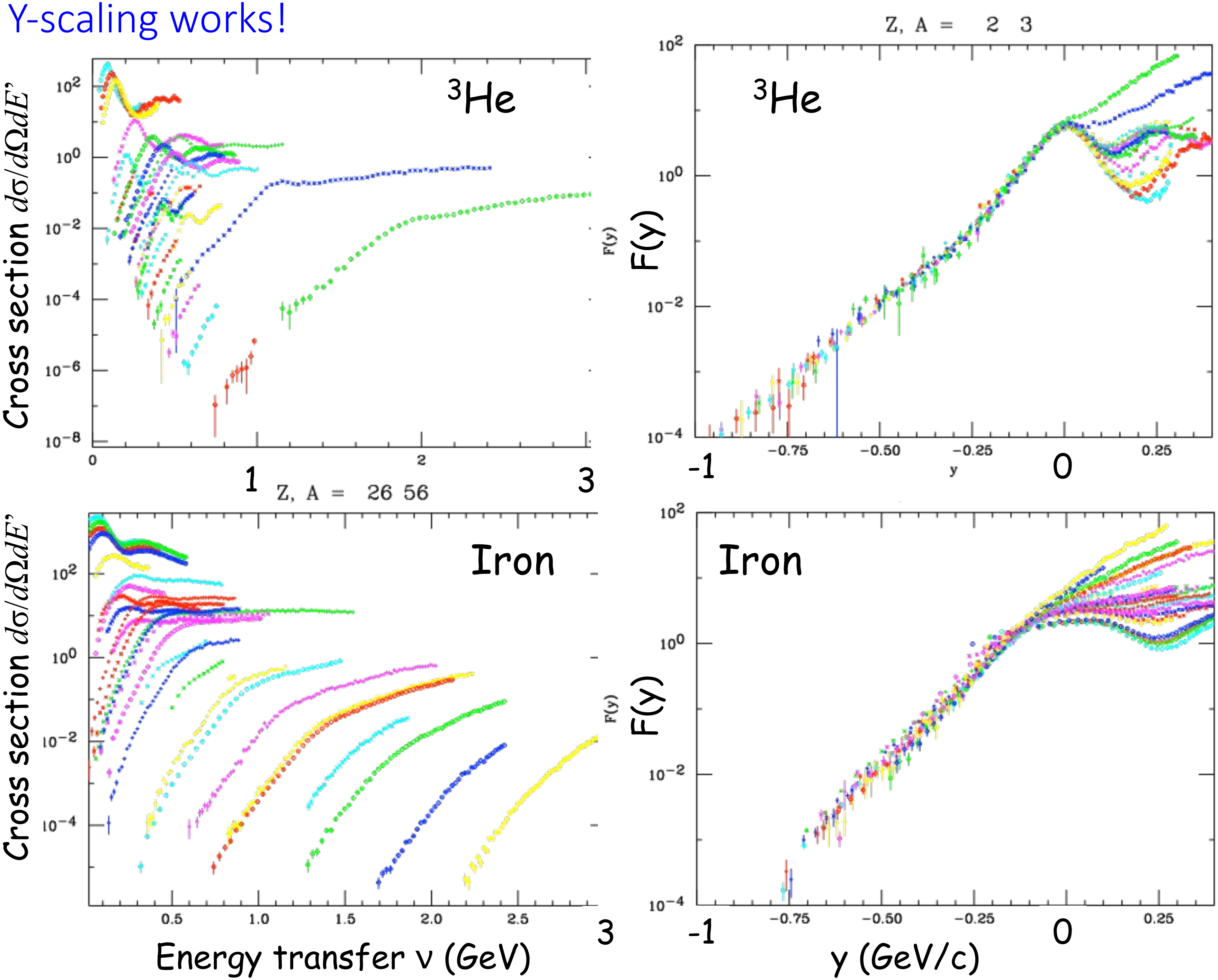
Goal: extract the momentum distribution $n(k)$ from $F(y)$.

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)

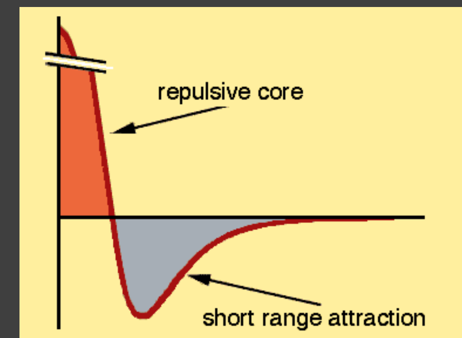
Y-scaling works!



But what about the Shell Model?

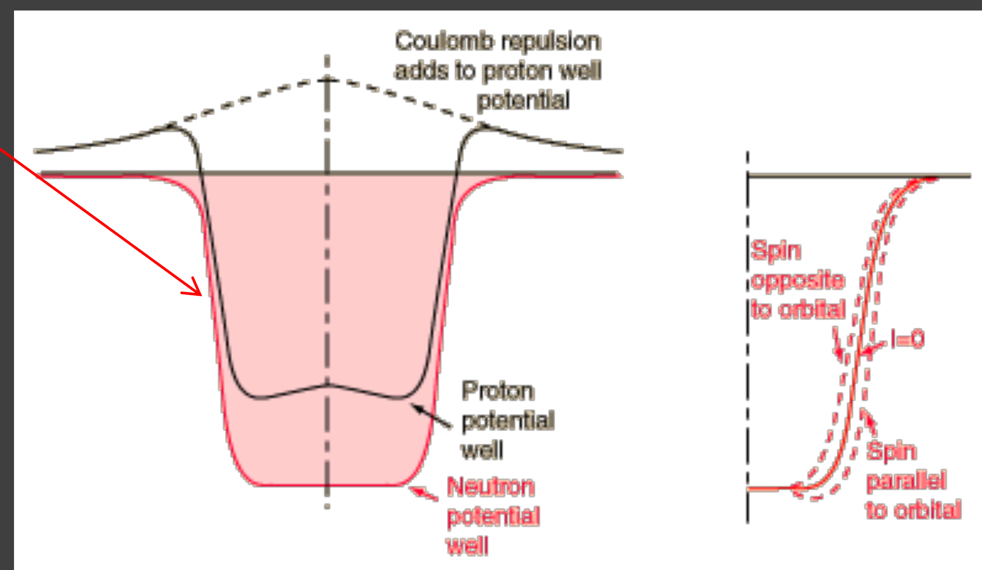
- Many-Body Hamiltonian:

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



- Mean-Field Approximation:

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

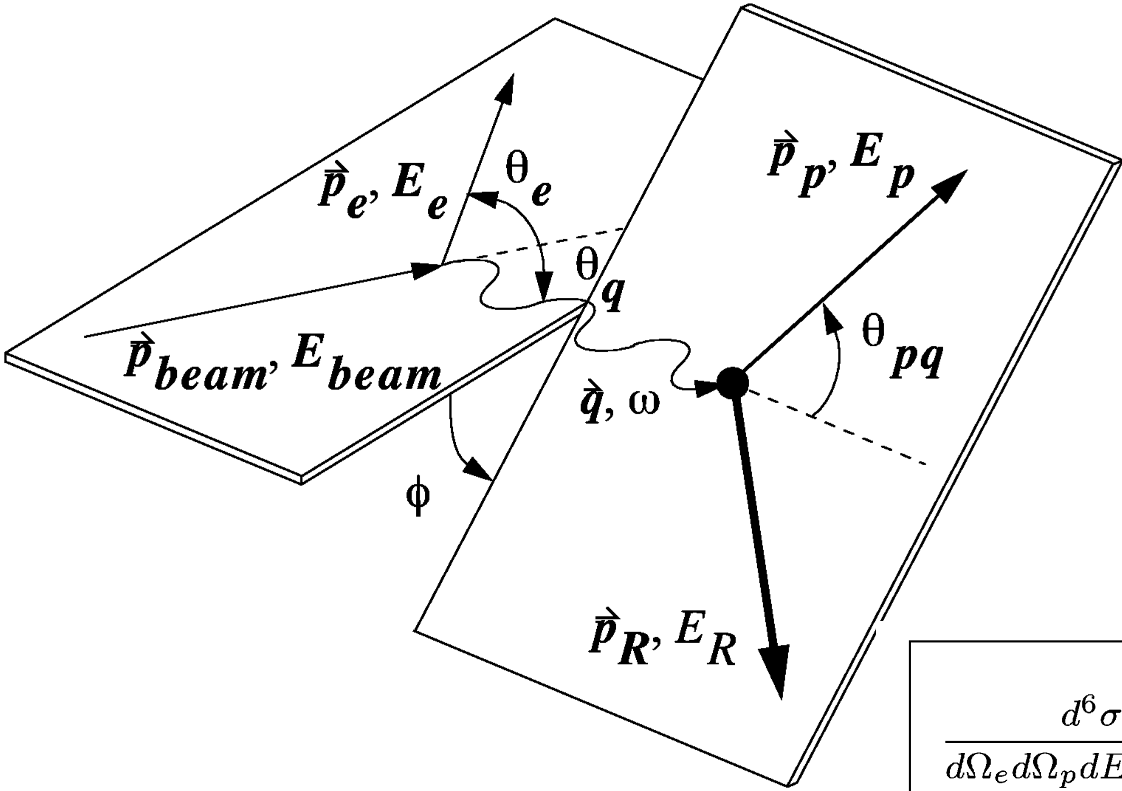


Results in an "atom-like"

shell model:

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

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



(e,e'p) Spectroscopy

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

where

K = (phase space)

σ_{Mott} = (relativistic Rutherford scattering)

$v = v\ (q, \omega)$ (electron kinematics)

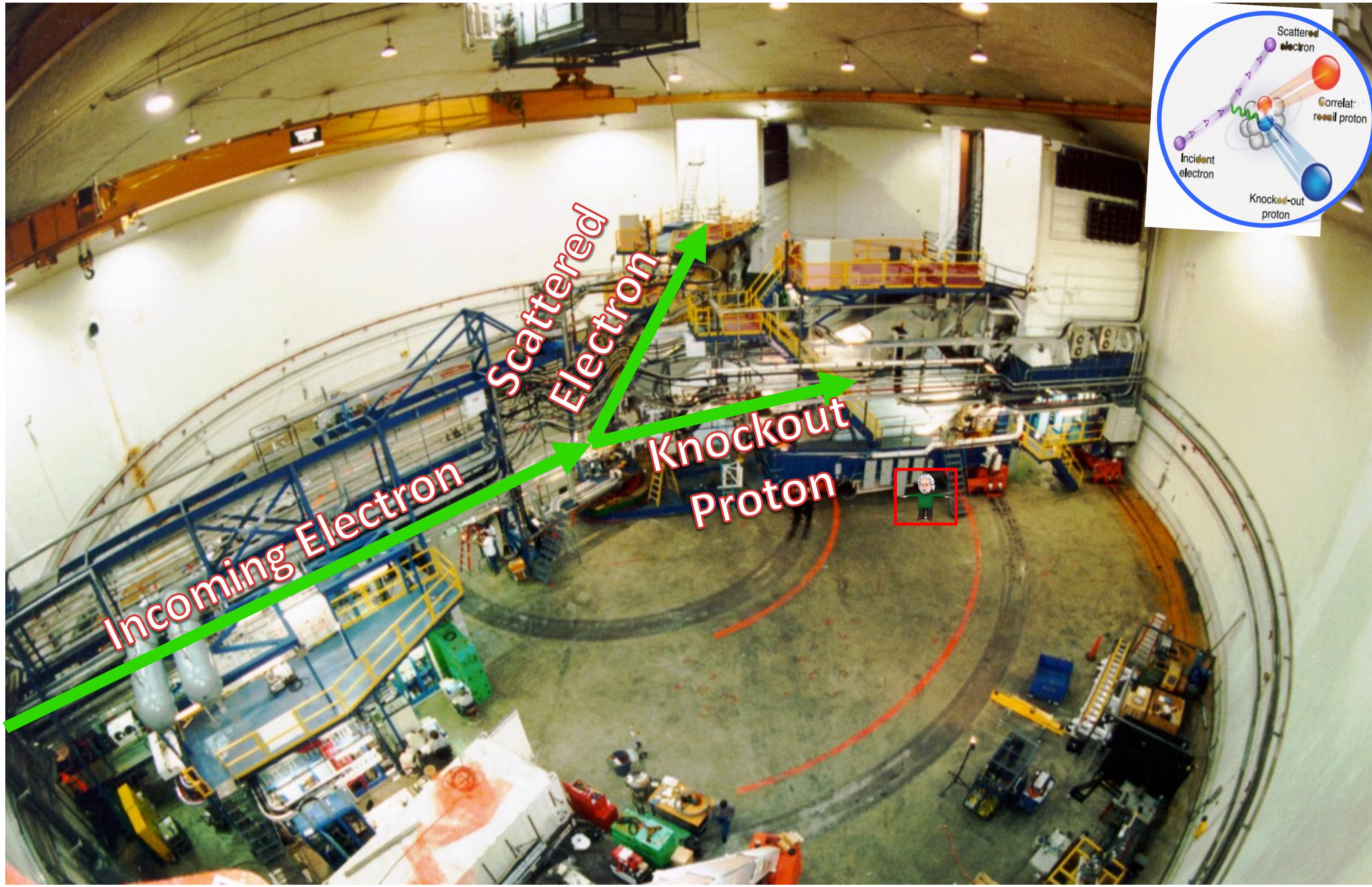
And then there were four (response functions, that is)

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

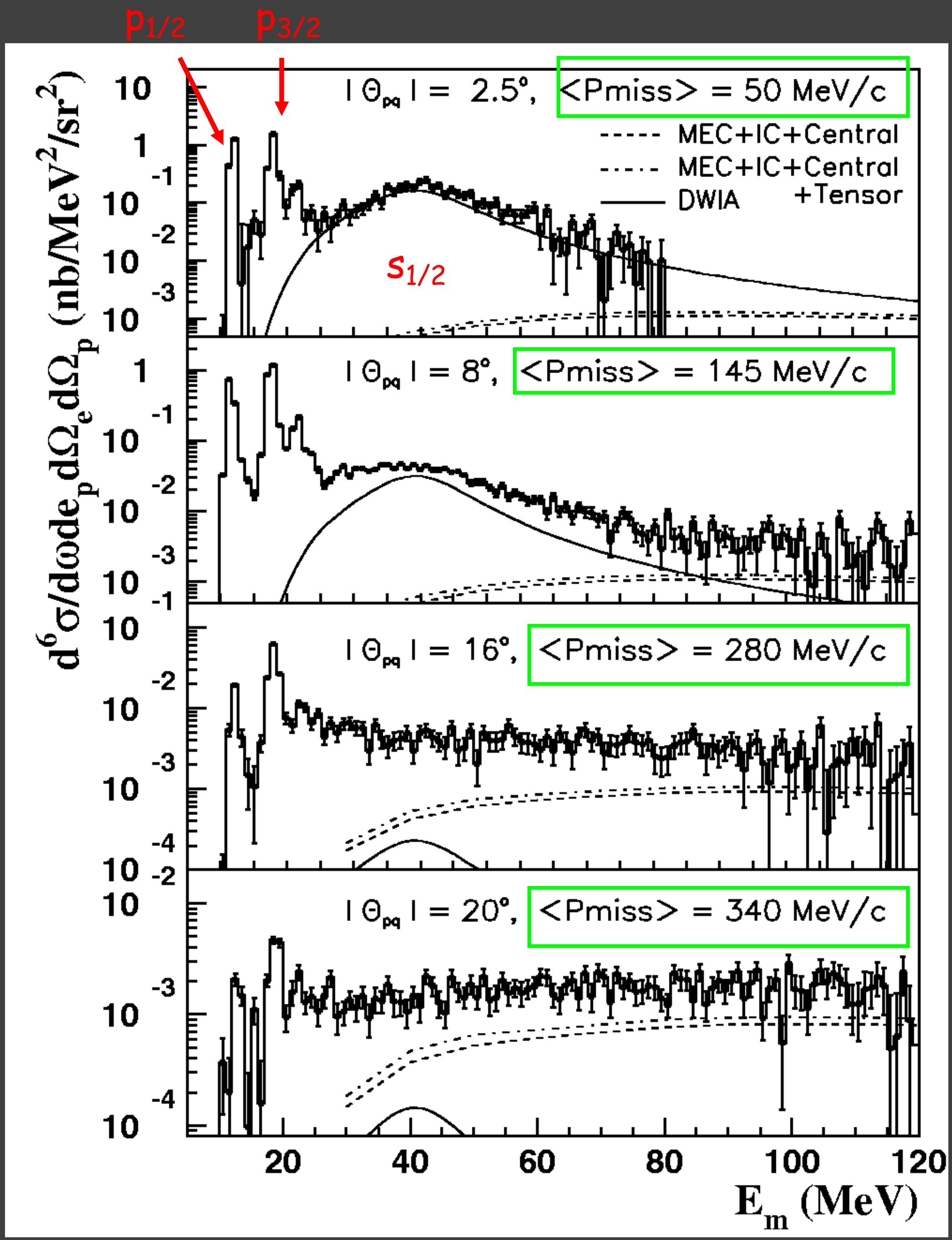
(When you include electron and proton spin, there are 18!)

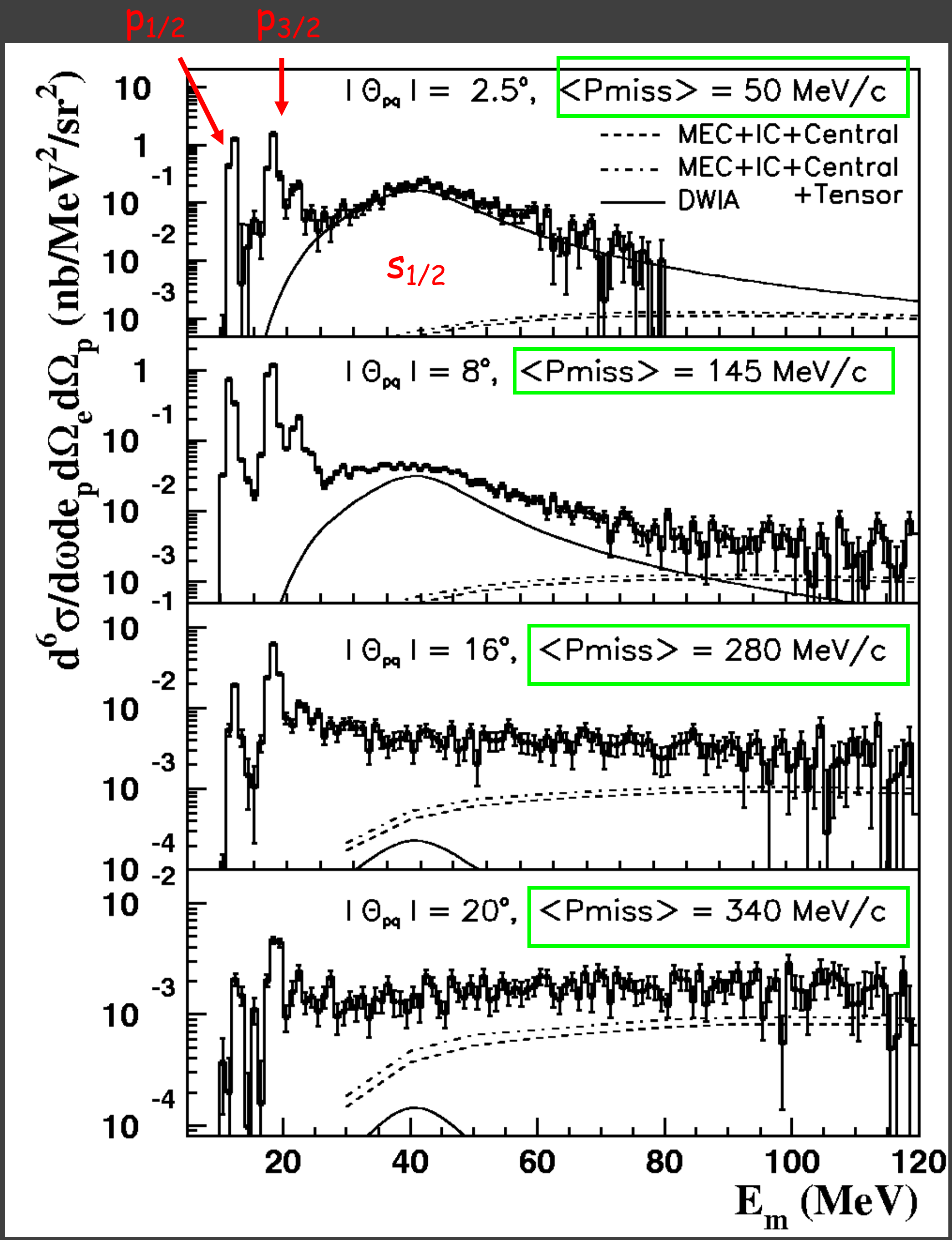
(And if you scatter from a polarized spin-1 target, there are 41. Double Yikes!!)

Hall-A: High-Resolution Spectrometers

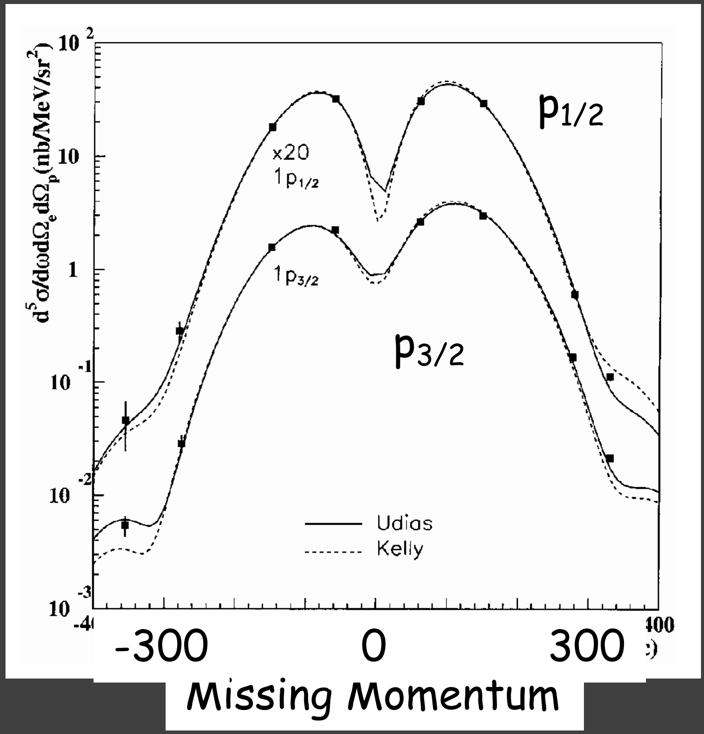


$^{16}O(e,e'p)$ and shell structure





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

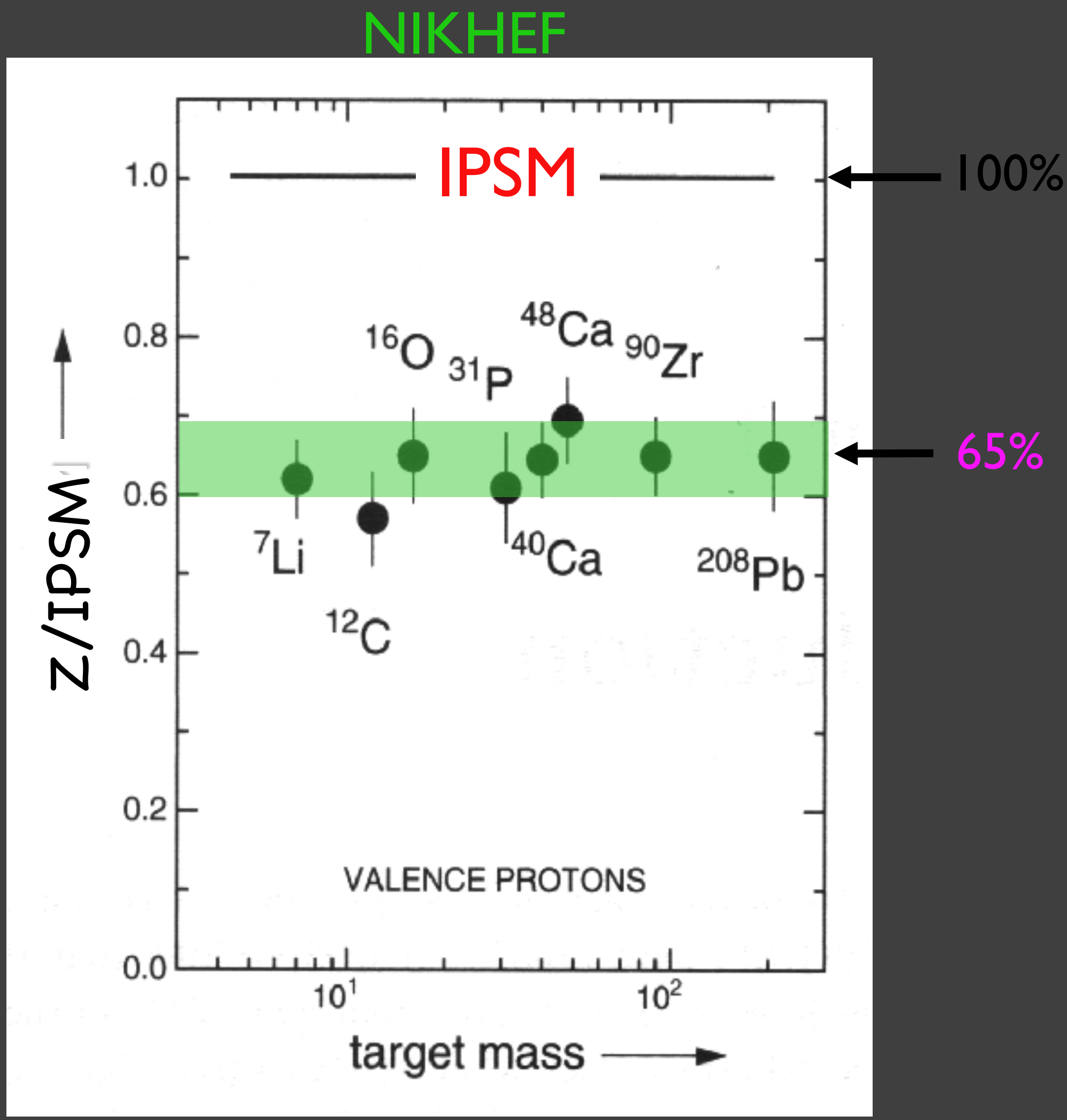


$1p_{1/2}$, $1p_{3/2}$ and $1s_{1/2}$ shells visible

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!