# Light Ion Physics in EIC era: From nuclear structure to high-energy processes

Summer School, Florida International University, 19-27 June 2025

Wim Cosyn, Christian Weiss, Dien Nguyen, Organizer

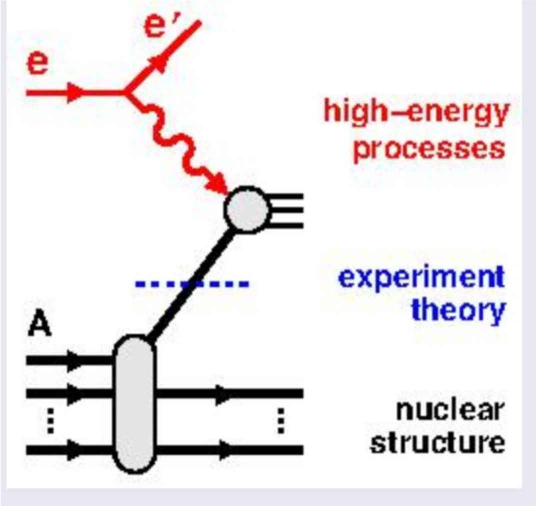

U.S. National Science Foundation

FIU FLORIDA INTERNATIONAL UNIVERSITY

# Nuclear Structure and Short-Range Correlations Experimental approach using Electron Probe

Dien Nguyen
University of Tennessee

THE UNIVERSITY OF TENNESSEE KNOXVILLE



# Lectures format

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

Many slides are adapted from my collaborators.
Special Thanks to Prof. L. Weinstein, Dr. Holly Szumila-Vance, Prof. O. Hen, Prof. D. Day, Prof. A. Schmidt, Dr. F. Hauenstein, Dr. Arun  and More

# Lectures Outlines:

**Lecture 1**:
Dien Nguyen

- ❑ Overview of an electron scattering probe
  - ❑ Elastic scattering
  - ❑ Quasi-elastic scattering
  - ❑ Deep inelastic scattering
  - ❑ Introduction to short range correlations

**Lecture 2:**
Jackson Pybus

- ❑ Short Range correlations (SRCs) status
  - ❑ Experimental results
  - ❑ Short range correlation properties

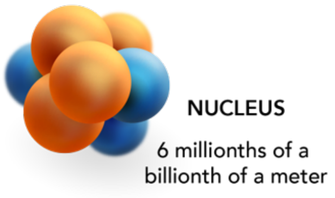
**Lecture 3:**
Jackson Pybus

- ❑ SRC factorization
  - ❑ GCF: contact formalism
  - ❑ Nuclear ground state

**Lecture 4:**
Jackson Pybus

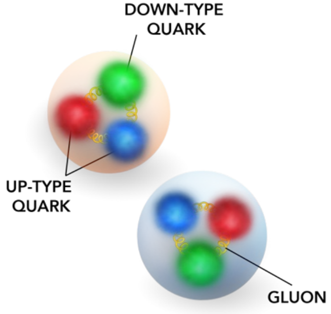
- ❑ SRC beyond electron probe
  - ❑ Hadron probe
  - ❑ Photon probe
  - ❑ Future direction

# Systems




**Nucleus** as a system

- Collection of bound protons and neutrons




**Nucleons** as a system

- Collection of bound quarks

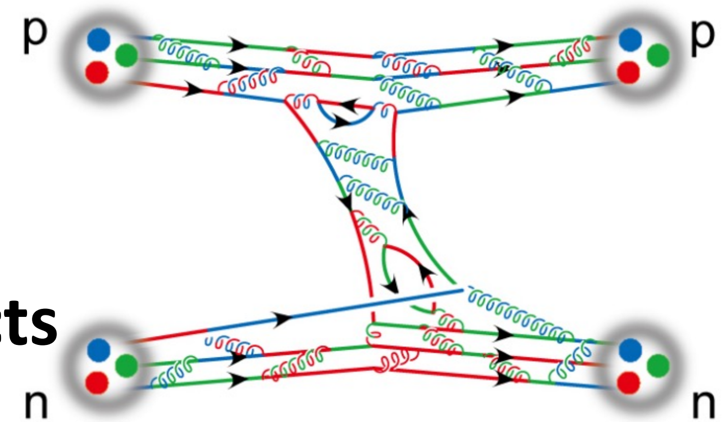
# Interactions

**Nucleon-nucleon interaction**

Arises from quark interactions

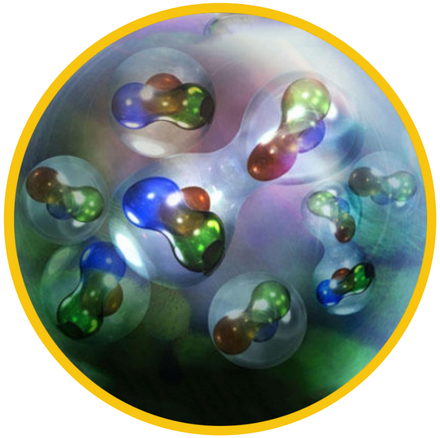
**Nucleon in-nuclear medium effects**

Affecting quark distributions



# Electron Scattering: Nuclear Microscope

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

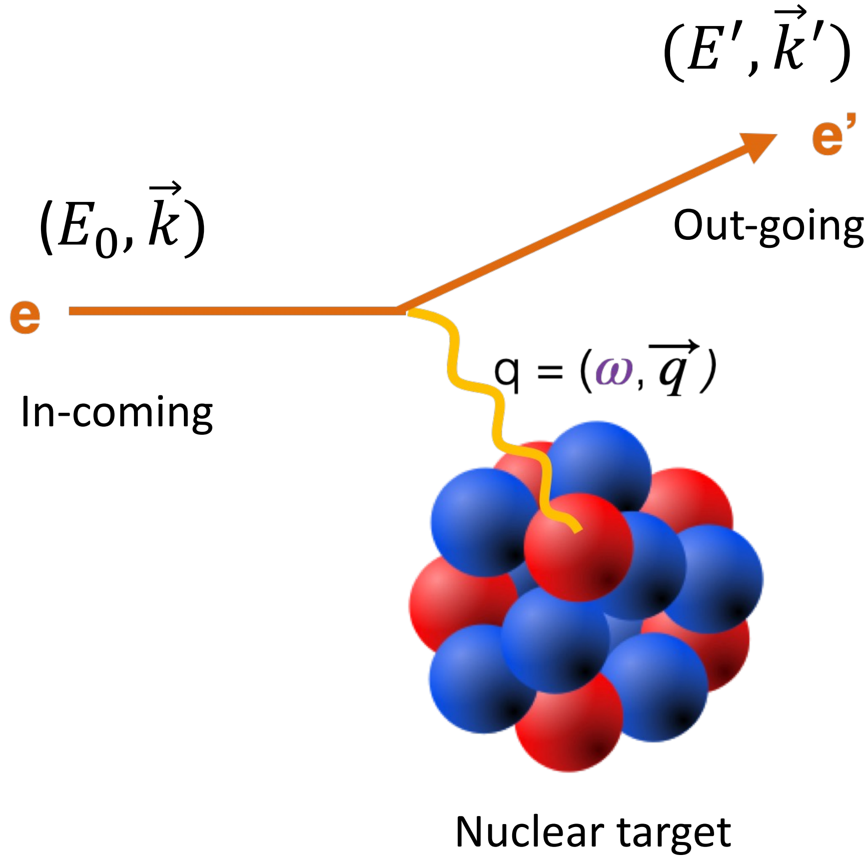


# Electron Scattering: Nuclear Microscope

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

**Means:**

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



# Scientific Method

Theory/hypothesis  about nuclear structure

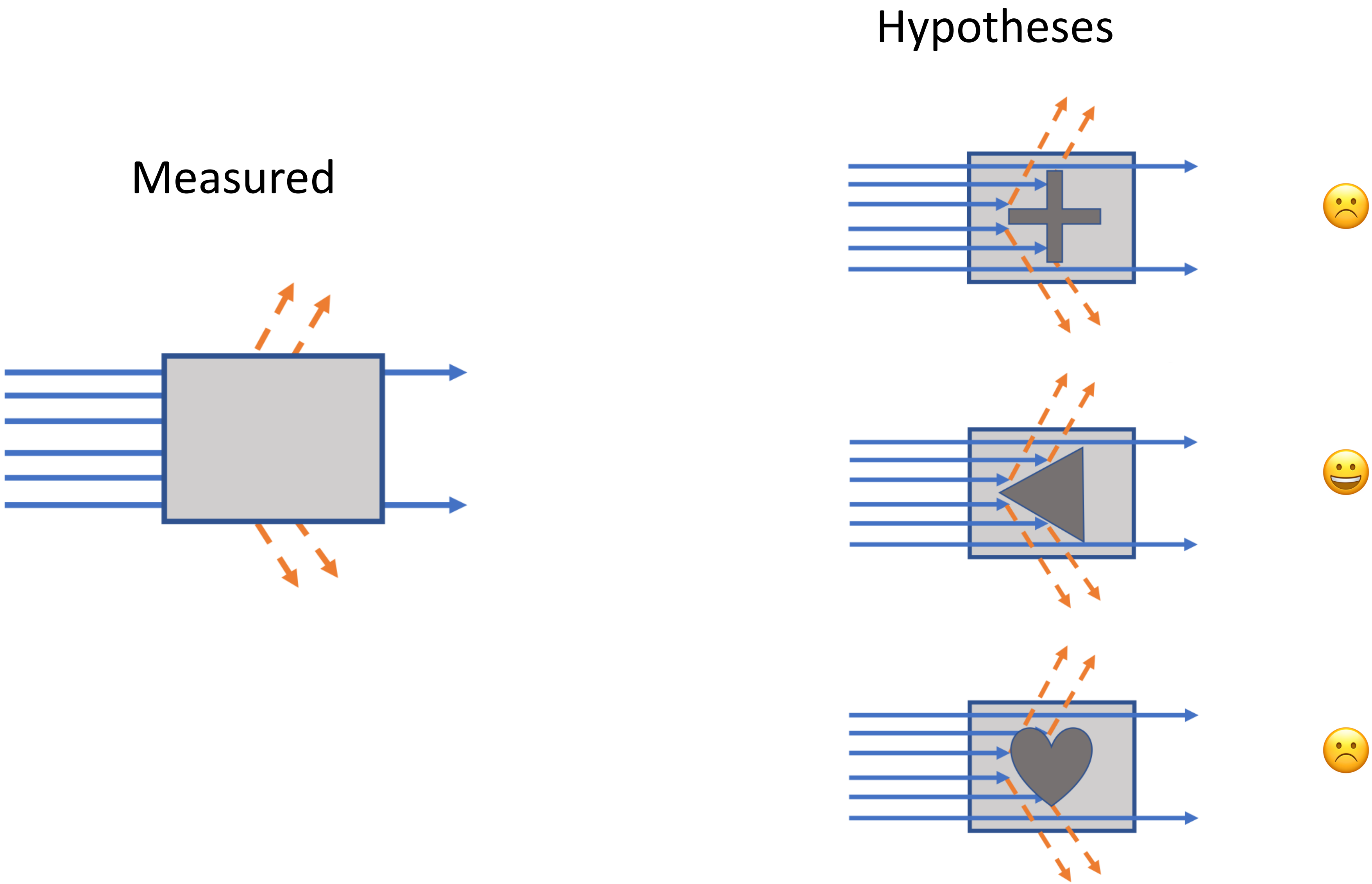
↓

Collect data to test theory

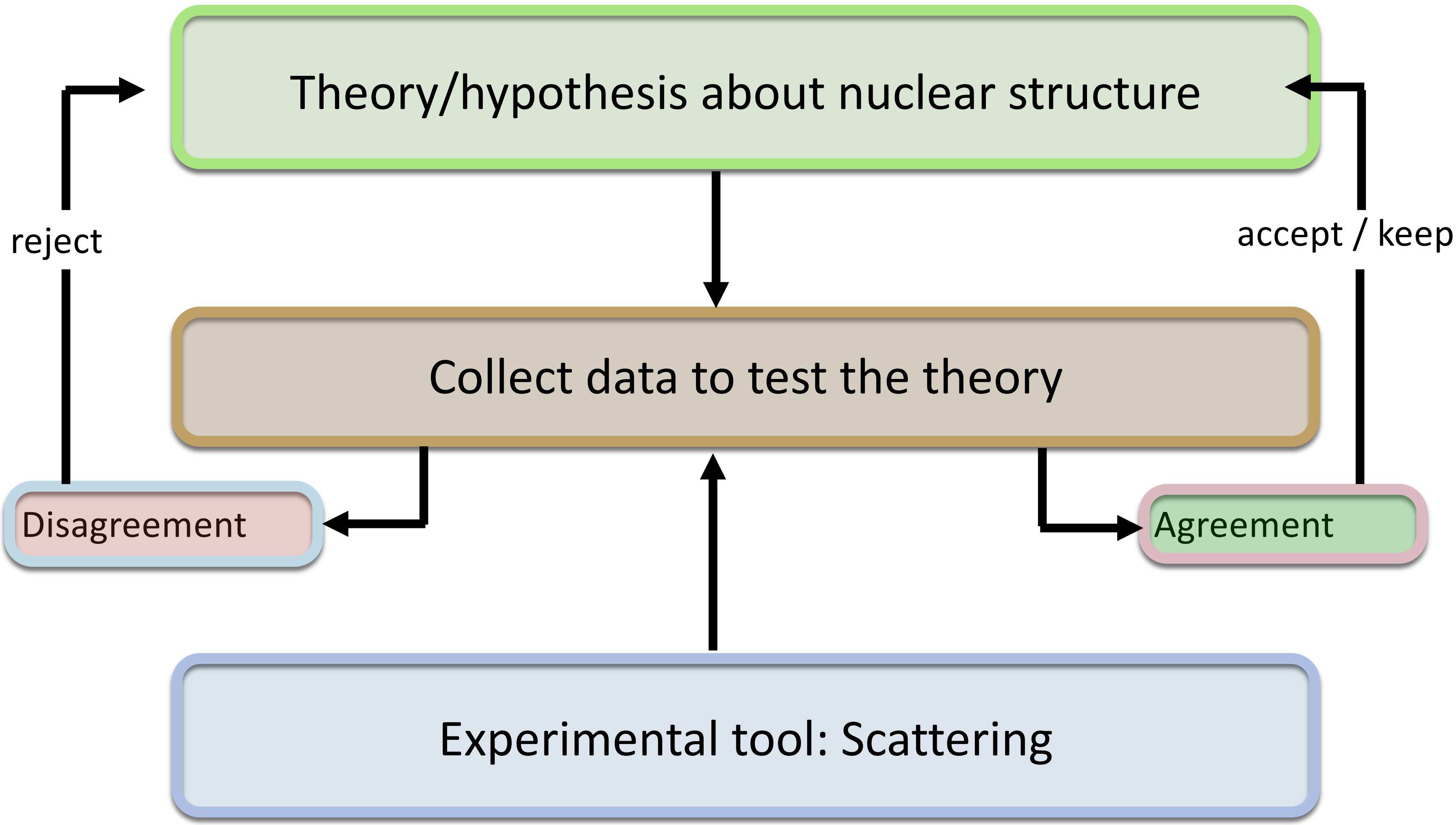
↑

Experimental tool: Scattering

# Determine Internal Structure with Scattering



# Scientific Method



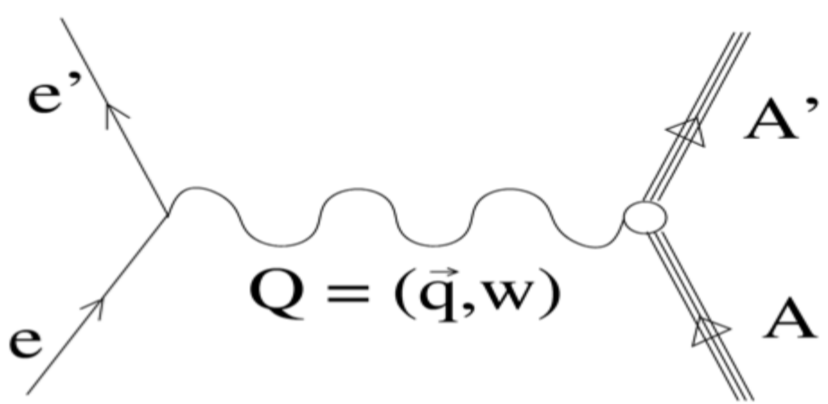
# Electron Scattering: Nuclear Microscope

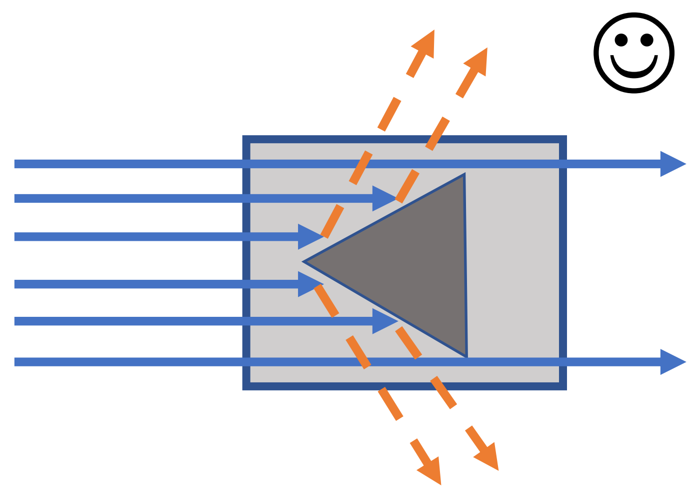
**Goal:** Study the internal structure (and dynamics) of complex objects

**Means:** Using high energy electron scattering

Reaction determined by kinematic variables:

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



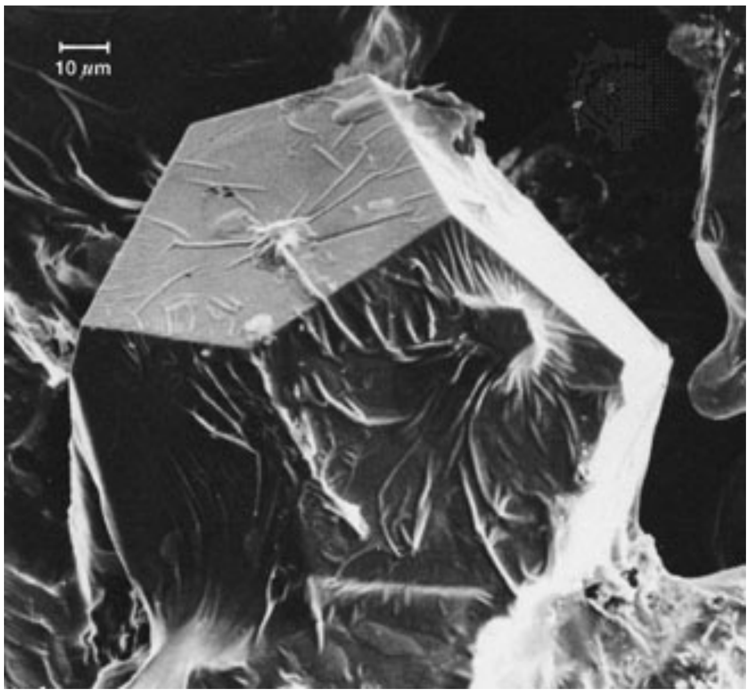



# Electron Scattering: Nuclear Microscope

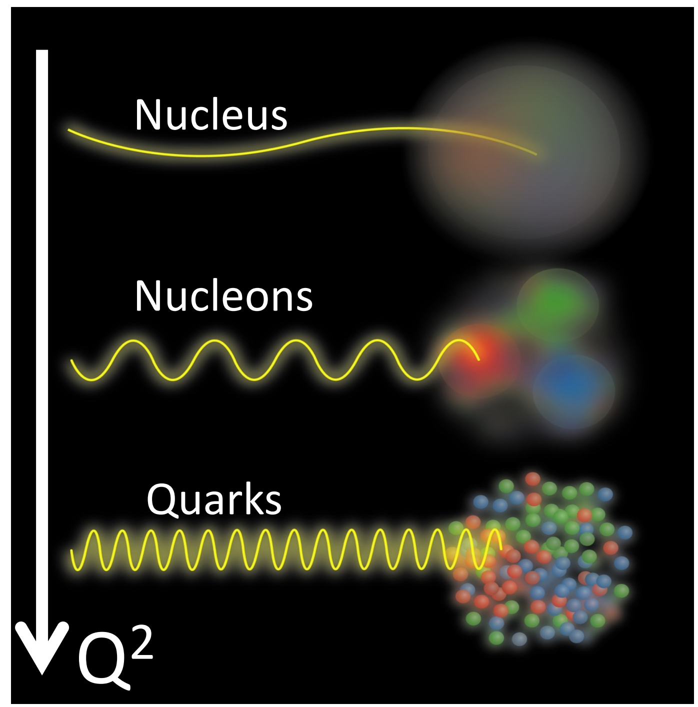
**Goal:** Study the internal structure (and dynamics) of complex objects

**Means:** Using high energy electron scattering

100s eV – 100s keV: Material structure




100s MeV – 10s GeV: Nuclear structure

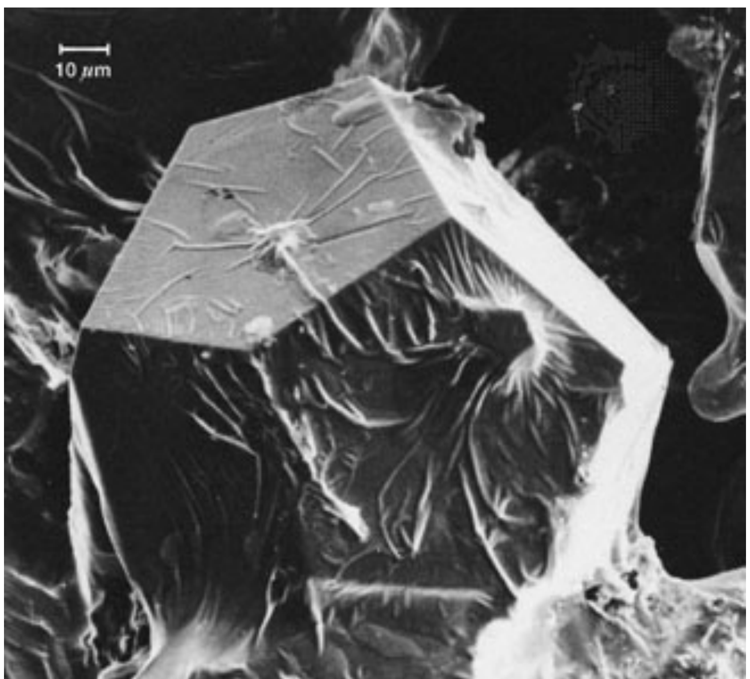


# Electron Scattering: Nuclear Microscope

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

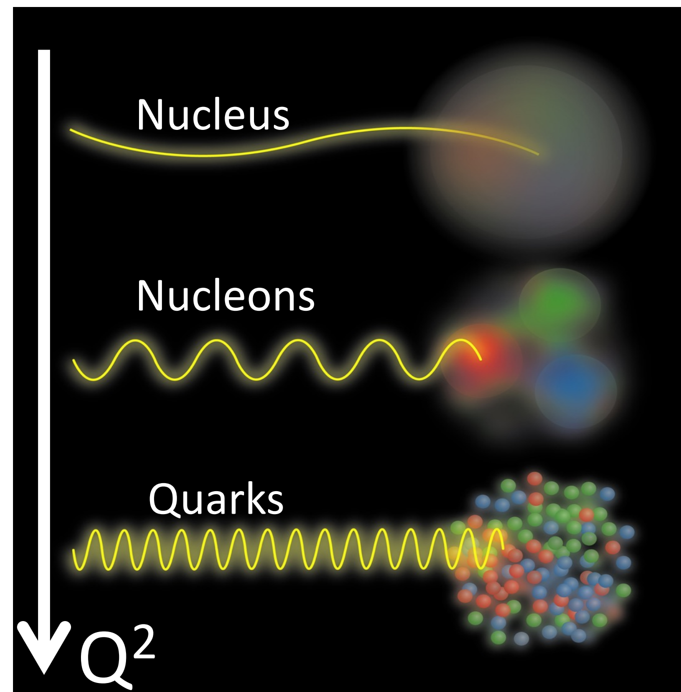
**Means:** Using high energy electron scattering

100s eV – 100s keV:
Material structure



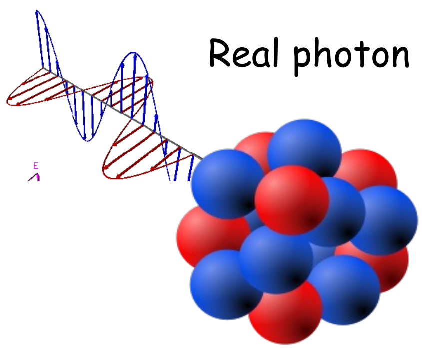

Energy
=
Resolution !

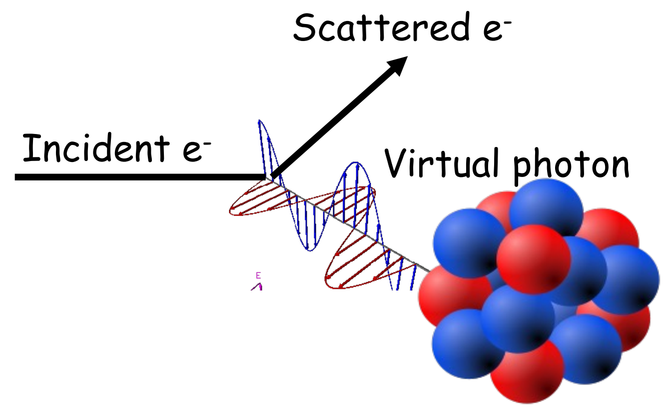
100s MeV – 10s GeV:
Nuclear structure



# It's all photons!

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




Real photon:

Momentum $q$ = energy $\nu$

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

Virtual photon:

Momentum $q$ > energy $\nu$

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

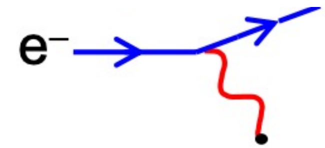
Virtual photon "has mass"!

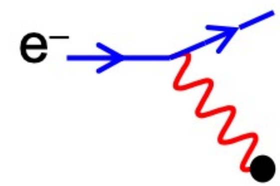
# Energy vs length

## Select spatial resolution and excitation energy independently

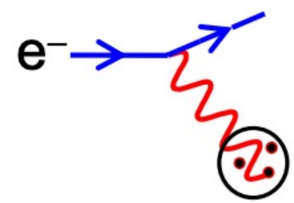
- Photon energy ν determines excitation energy
- Photon momentum $q$ determines spatial resolution: $\lambda \approx \dfrac{\hbar}{q}$

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

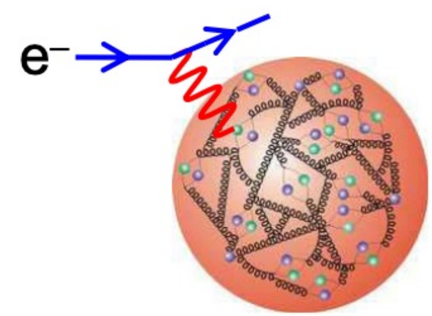



$\lambda \sim r_p$ Low electron energies (0.2-1 GeV/c), scattering is equivalent to that from extended charged object




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



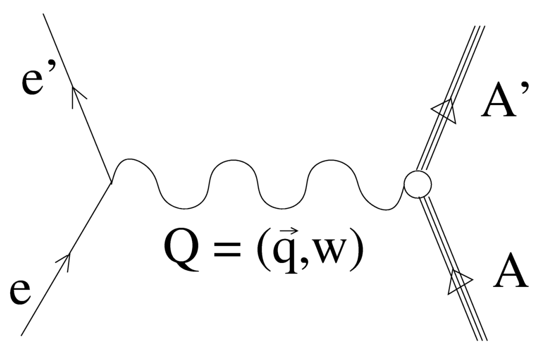

$\lambda \ll r_p$ Very high electron energies, proton appears to be a sea of quarks and gluons

# Why use electrons?

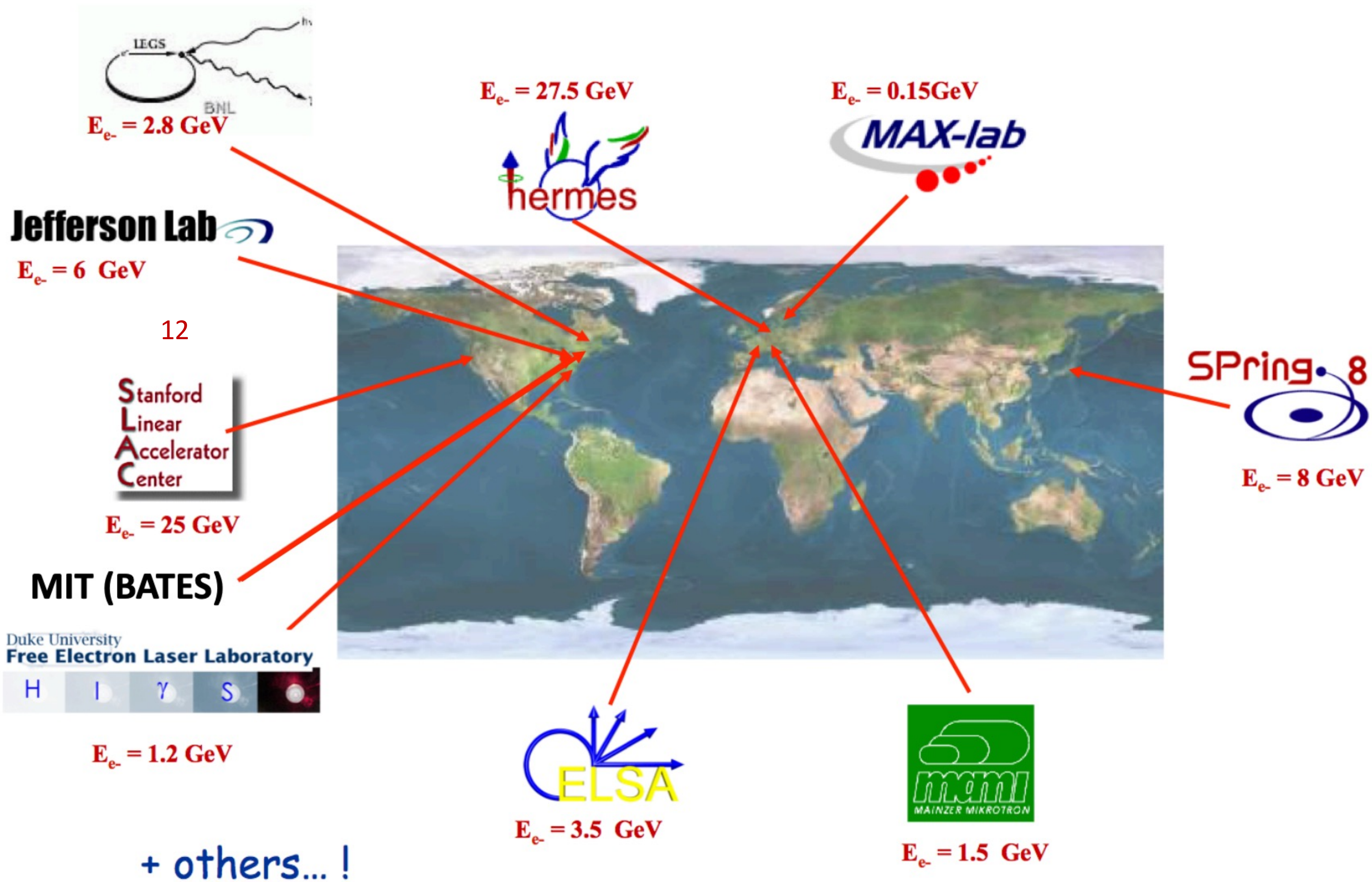
- ❑Probe structure understood (point particles)
- ❑Electromagnetic interaction understood (QED)
- ❑Interaction is weak ($\alpha = 1/137$)
  - Theory works: First Born approx / one photon exchange
  - Probe interacts only once
  - Study the entire nuclear volume

Drawback:

- ❑Cross sections are small
- ❑Electrons radiate

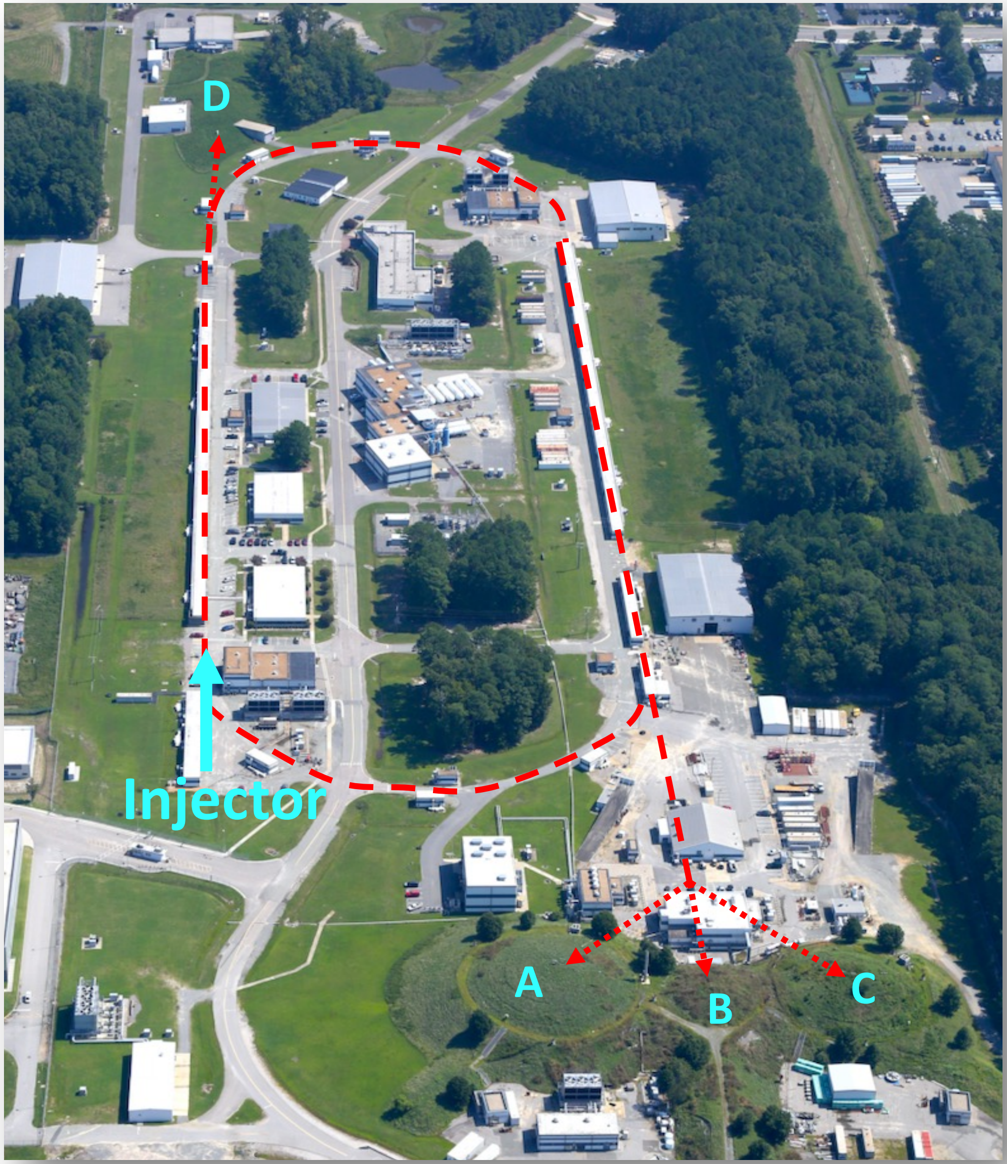


# Worldwide effort



# Jefferson Lab

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

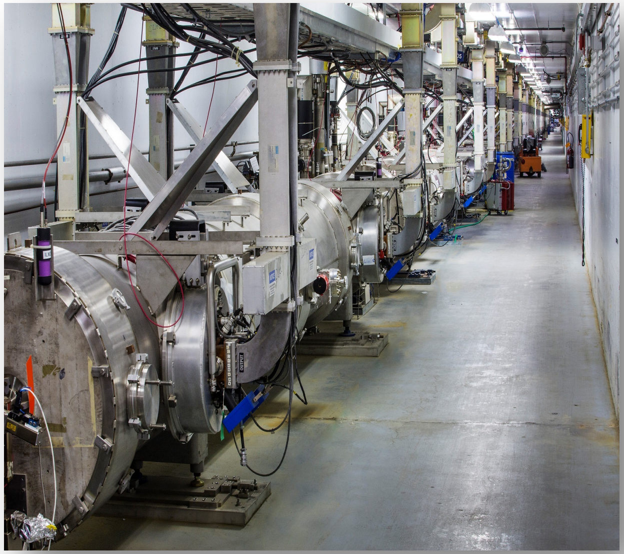


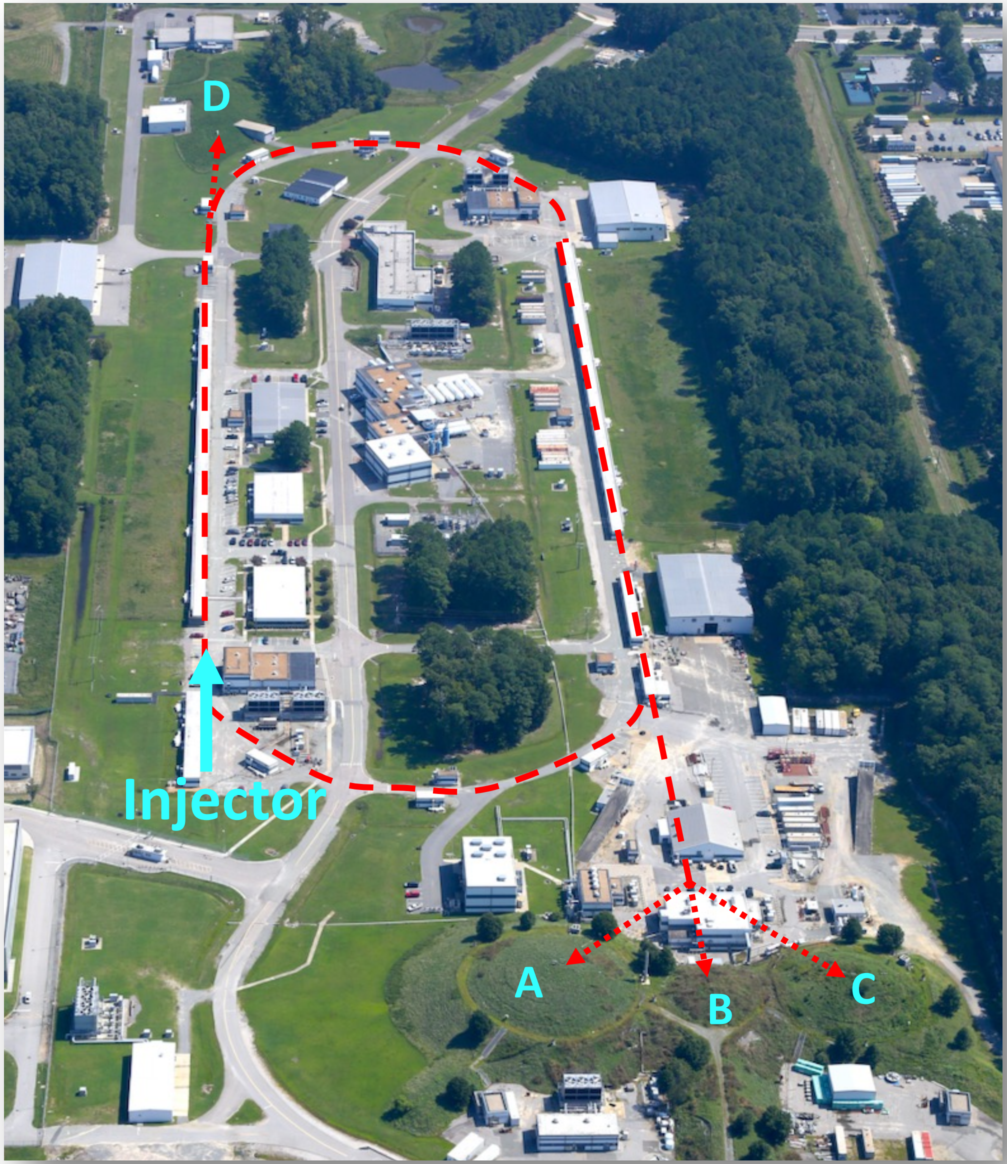
# Jefferson Lab

From Hesienburg's Uncertainty Principle:

$$\Delta x \, \Delta p \geq \hbar/2 \sim 0.2 \text{ GeV fm}$$

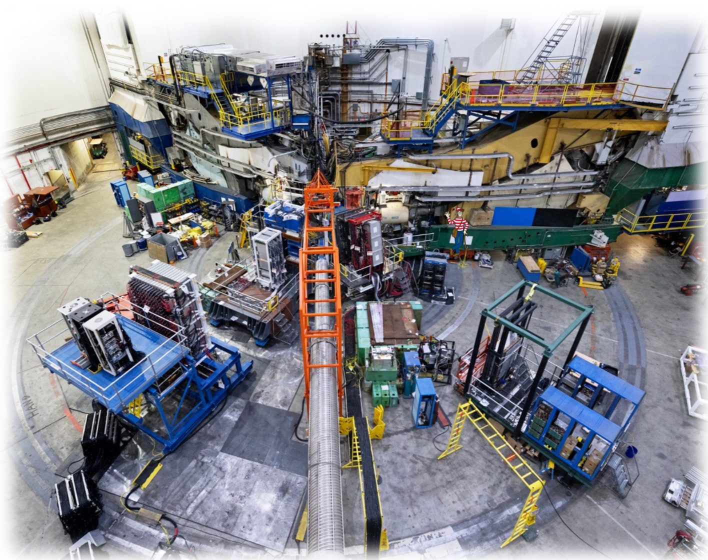
Proton is ~1 fm in size ($10^{-15}$m)
=> To "see" 0.02 fm one needs approx. 10 GeV momentum



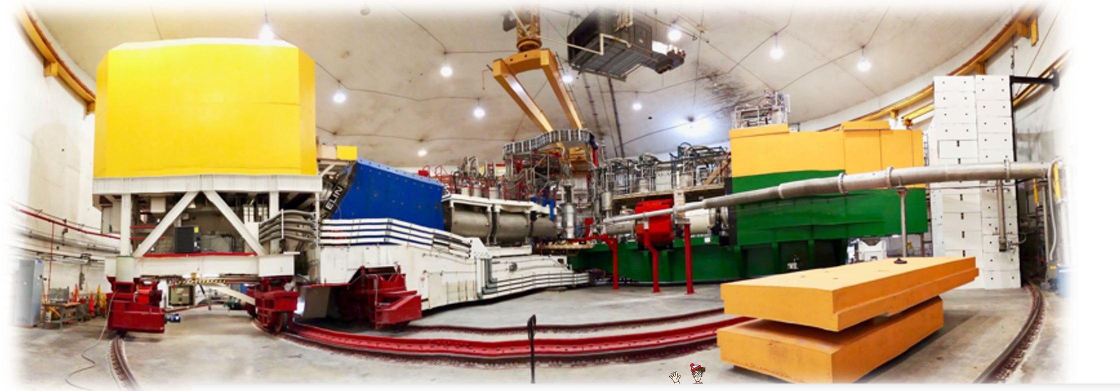


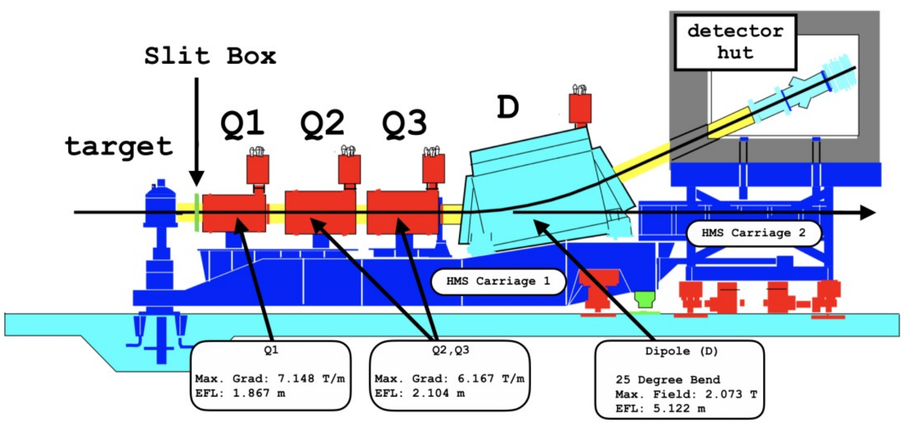
# 4 experimental Halls

Hall A



Hall C





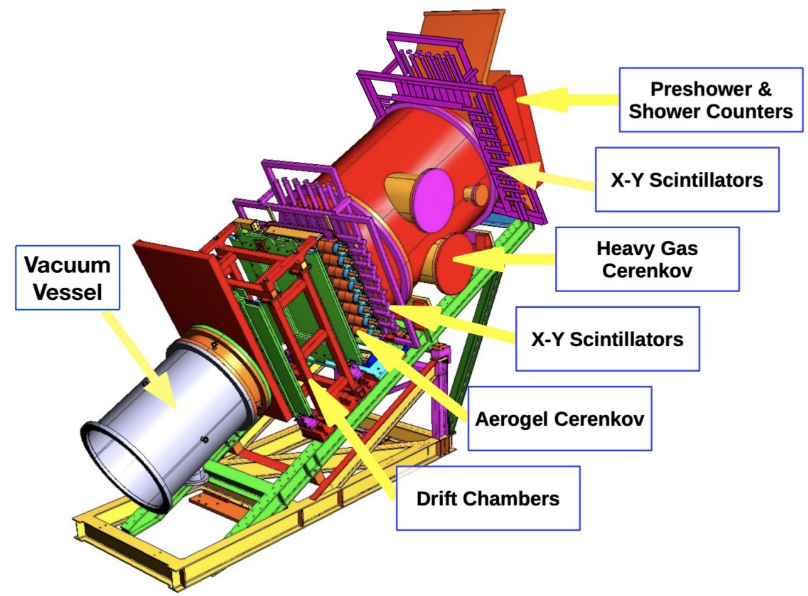
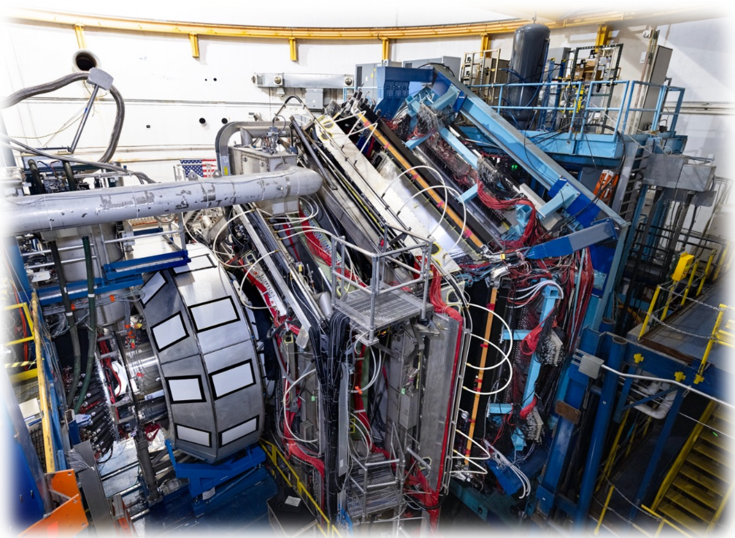



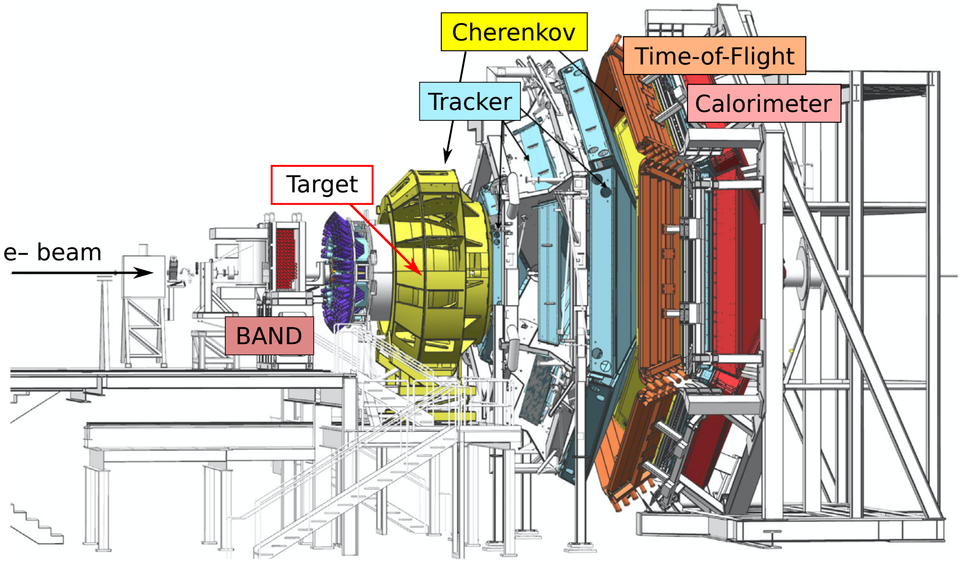

Figure 3.22: High Momentum Spectrometer (HMS) detector stack.

# 4 experimental Halls

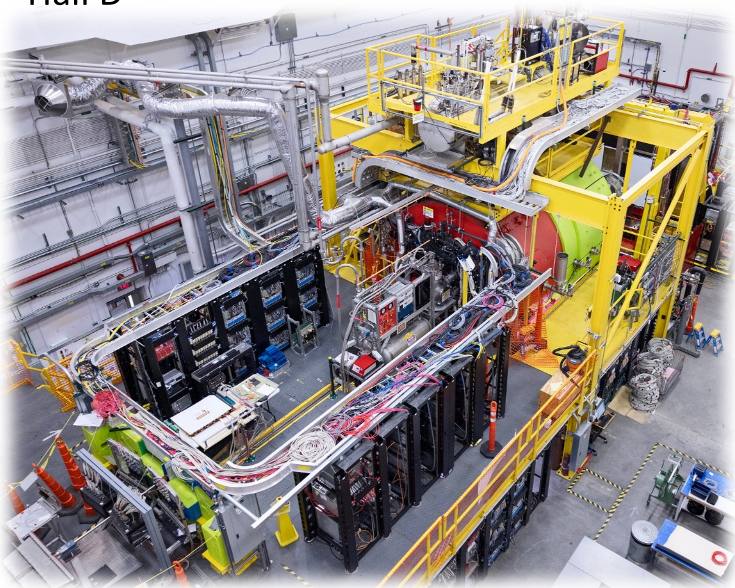
Hall B



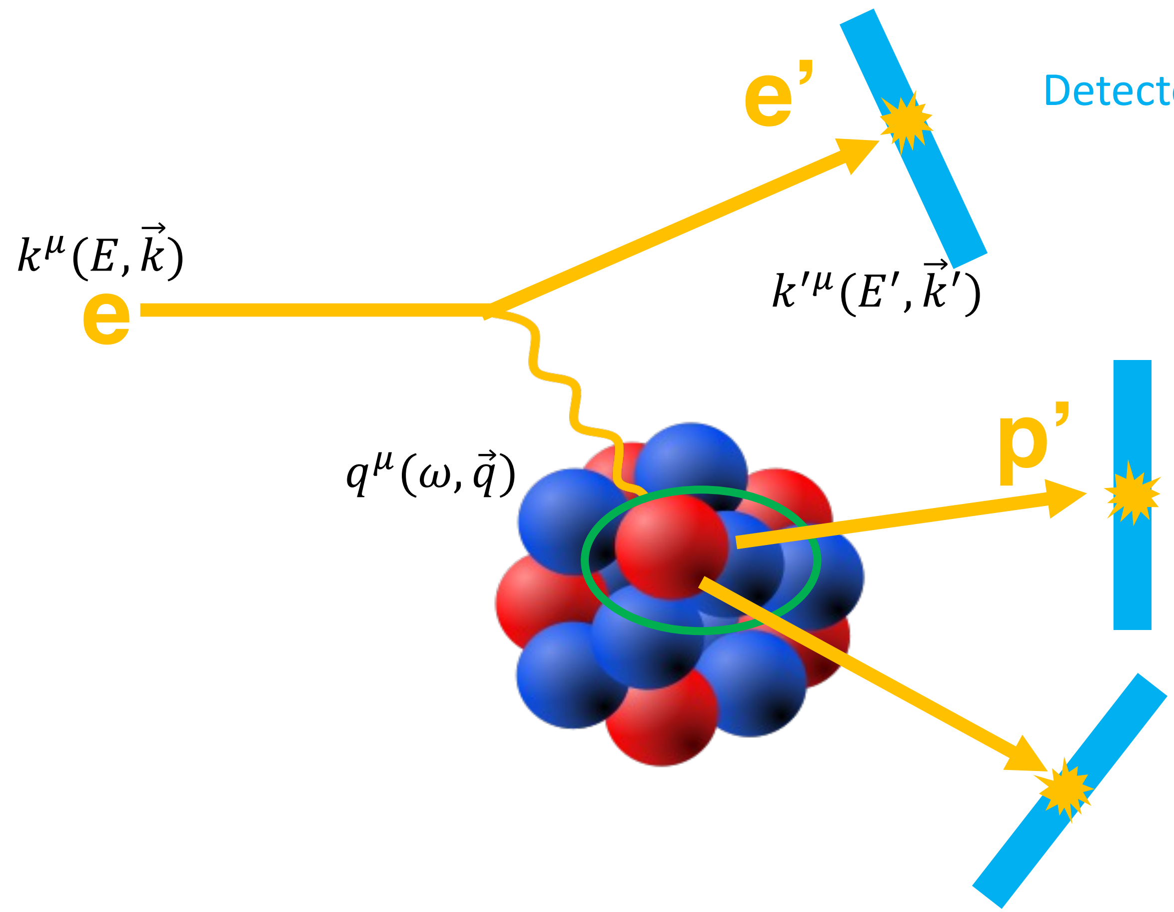
Large acceptance detector




Hall D

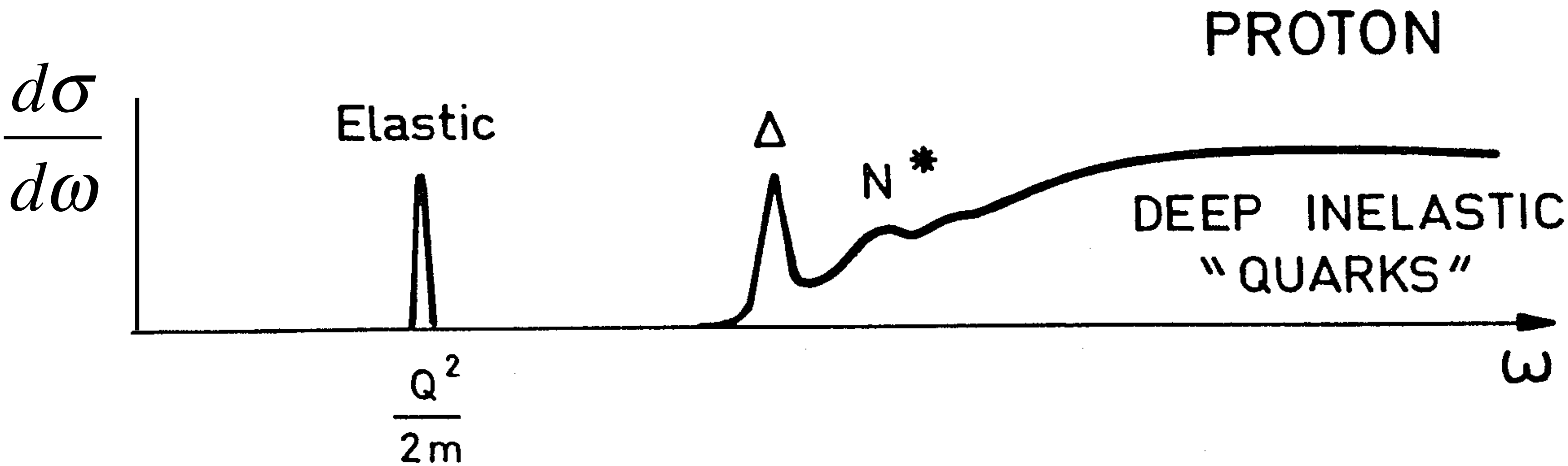


# How experimentalist study the reactions

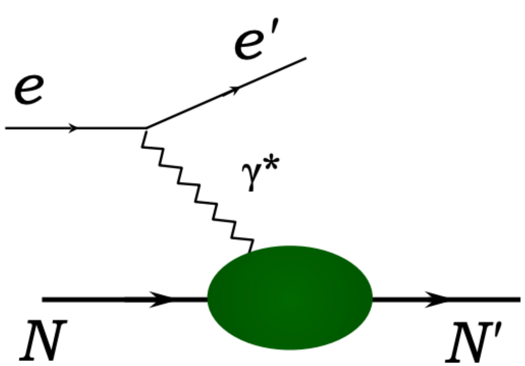



- (e, e'): inclusive: Detect only scattering electron (e')
- (e, e'P): Single knock out proton: Detect e' and knock-out proton
- (e, e'NN): Two knockout nucleons: Detect e' and two knock-out nucleon

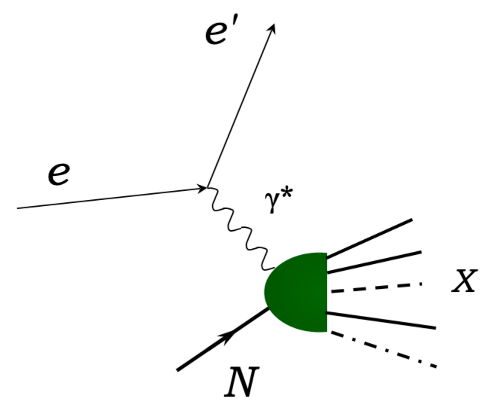
# Generic (e,e’) at fixed momentum transfer



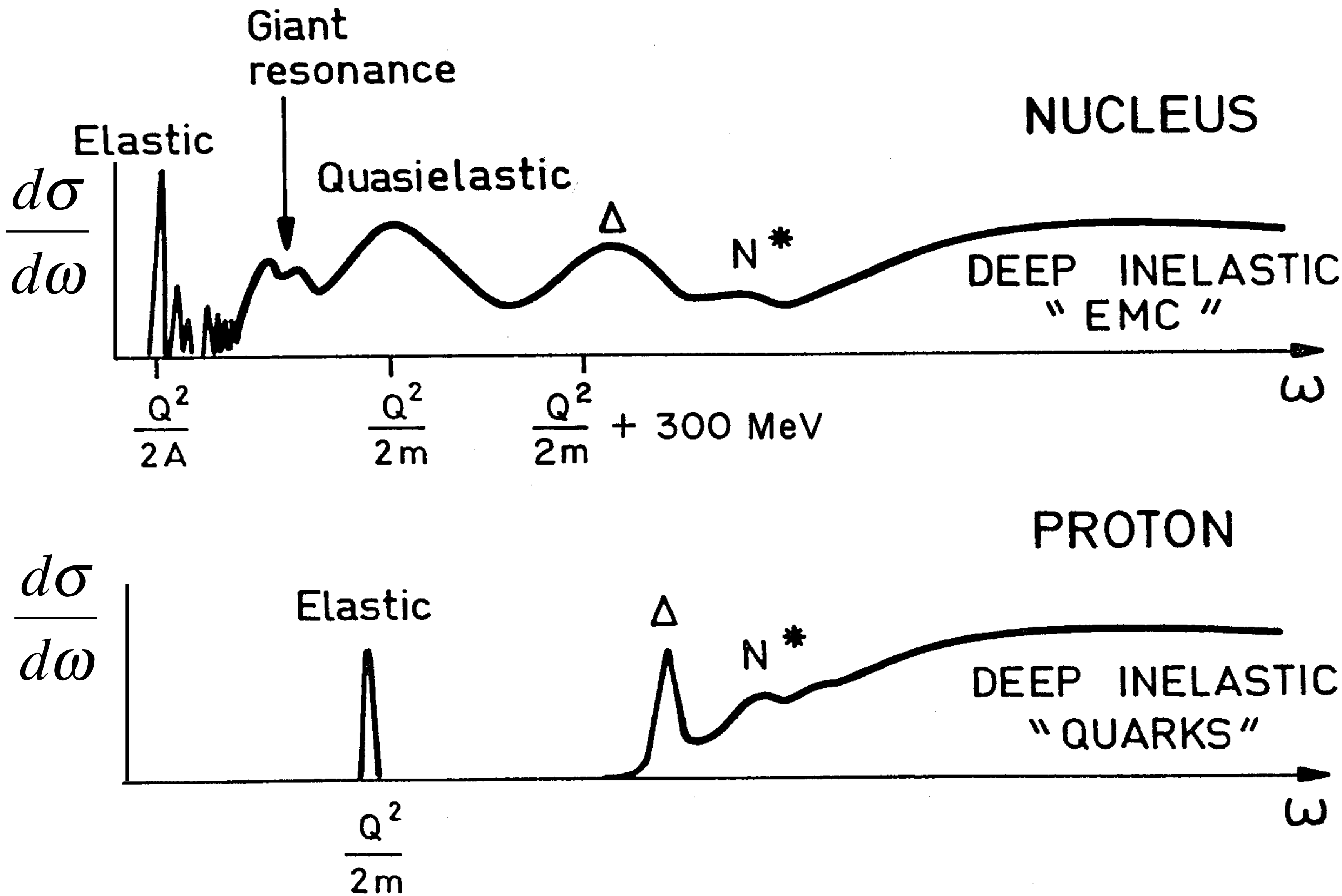

**Elastic scattering**:
nucleon initial and final state the same



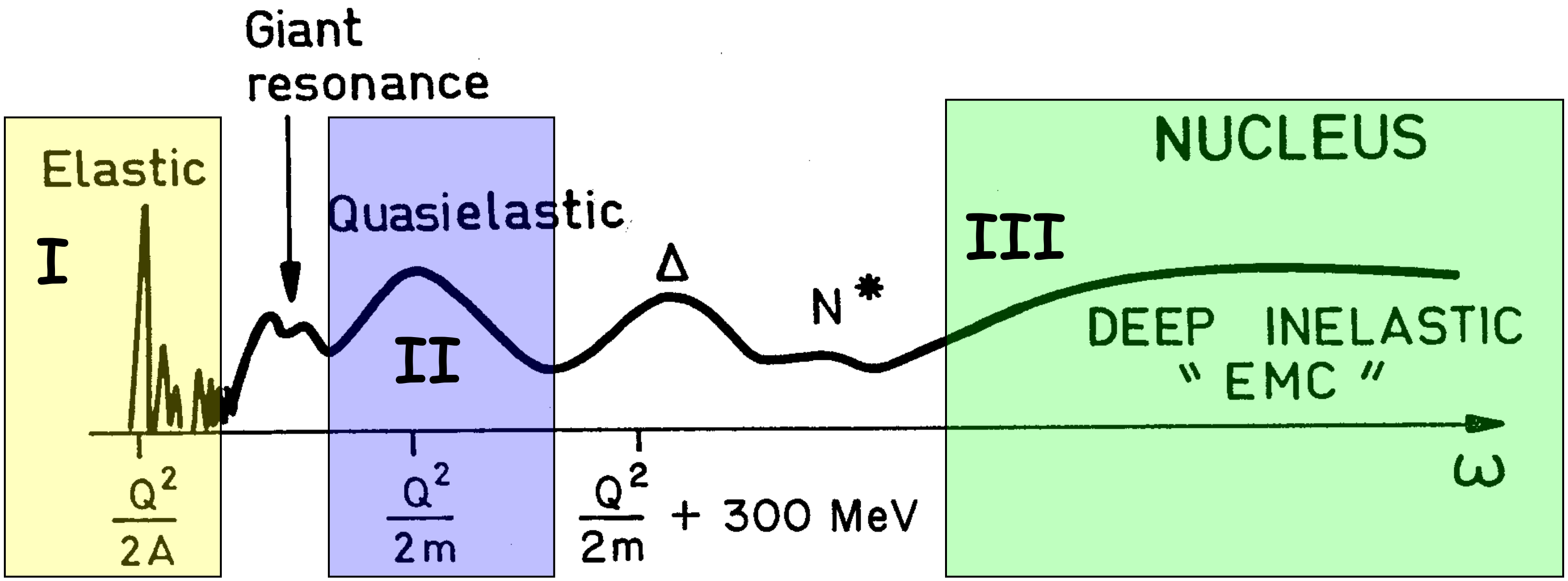

**Deep inelastic scattering**:
nucleon state has changed, creates new particles



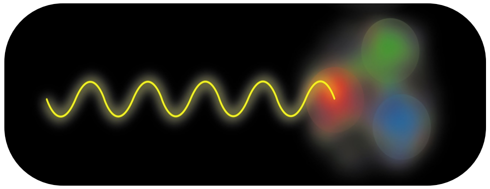
# Generic (e,e') at fixed momentum transfer



# Different reactions teach us different things

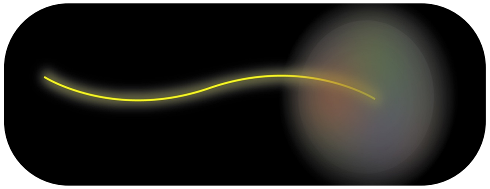



Quasi-elastic: electron scatters elastically off an almost free nucleon.

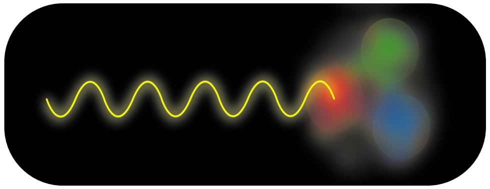


# What can we learn?

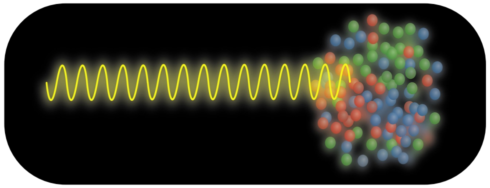
1. Elastic
   - structure of the nucleon/nucleus
     - Form factors, charge distributions



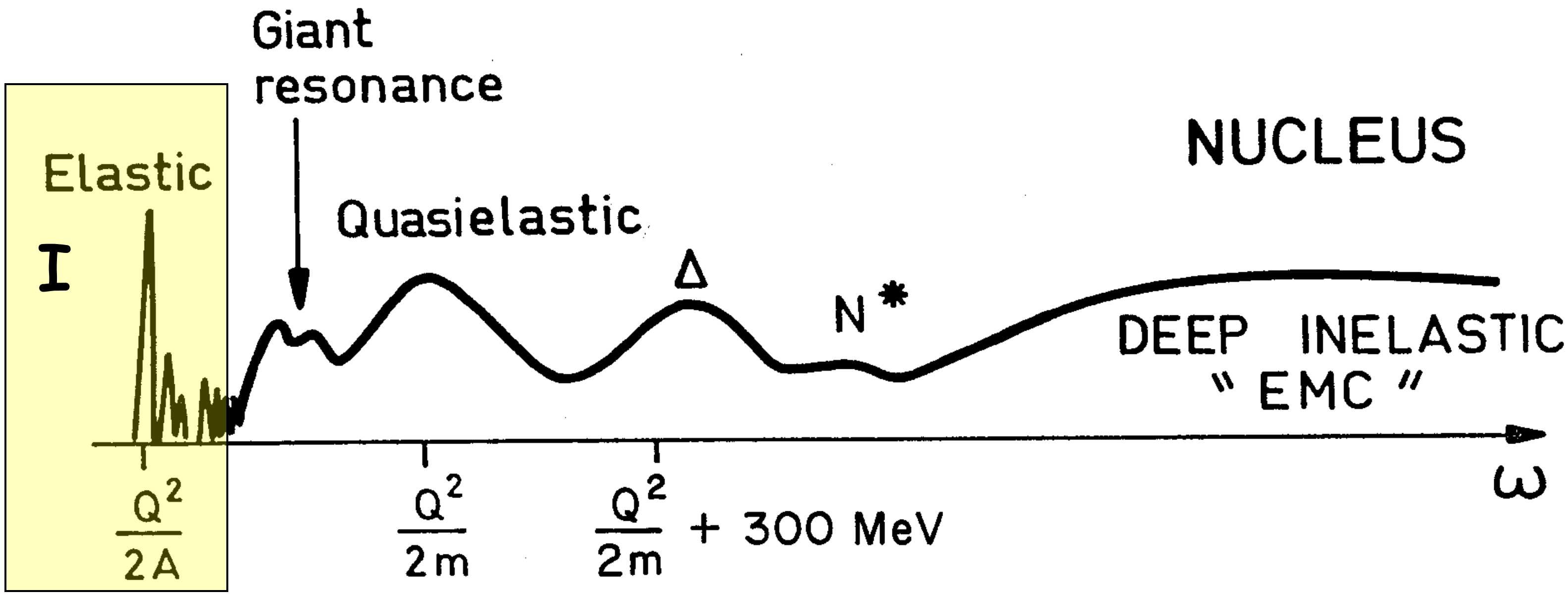
2. Quasi-elastic (QE)
   - Shell structure
     - Momentum distributions
     - Occupancies
   - Short Range Correlated nucleon pairs



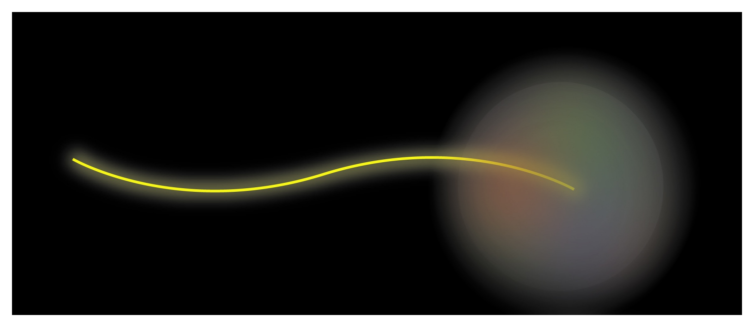
3. Deep Inelastic Scattering (DIS)
   - The EMC Effect and Nucleon modification
   - Quark Hadronization in nuclei



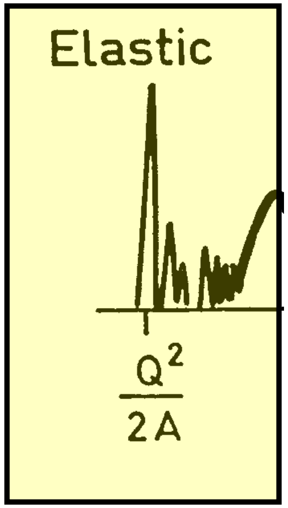
# Quick Overview: Elastic




- ❑ Elastic scattering
  - Charge distribution
  - Form Factors



# Elastic Electron Scattering: form factor

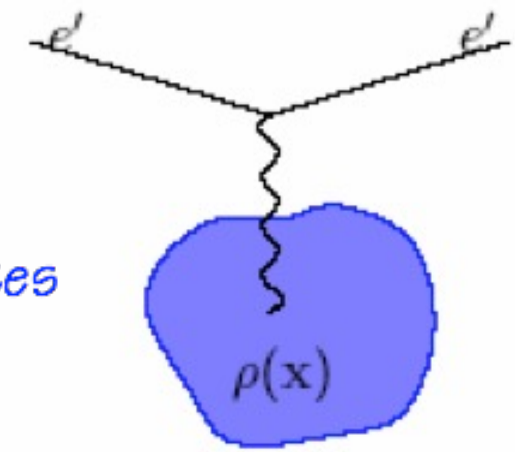



## Fermi's Golden Rule

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

$M_{fi}$: scattering amplitude

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

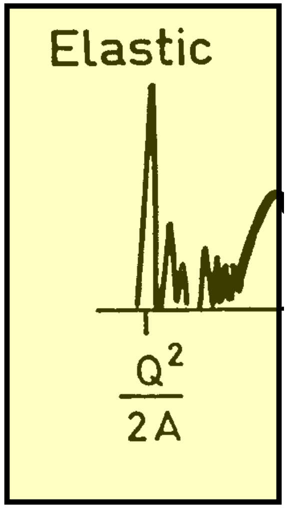



$$\begin{aligned} M_{fi} &= \int \Psi_f^* V(x) \Psi_i d^3x \\ &= \int e^{-k_f \cdot x} V(x) e^{-k_i \cdot x} d^3x \\ &= \int e^{iq \cdot x} V(x) d^3x \end{aligned}$$

Plane wave approximation for incoming and outgoing electrons

Born approximation (interact only once)

# Elastic Electron Scattering: form factor




## Form Factor and Charge Distribution

Using Coulomb potential from a charge distribution, ρ(x),

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

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

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

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

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

Charge form factor F(q) is the Fourier transform of the charge distribution ρ(x)

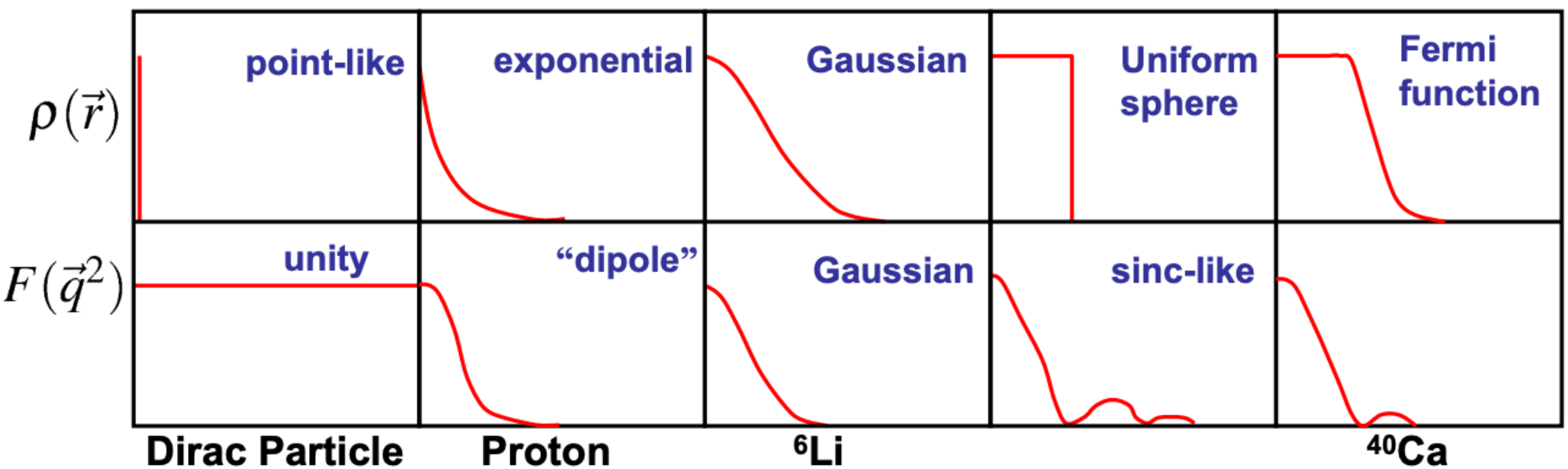
# Elastic scattering: Form factors

Mott cross section:

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

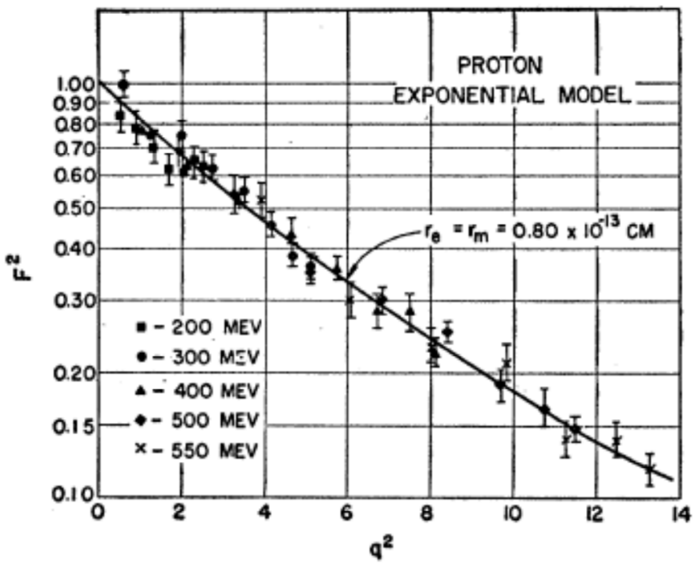
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \rightarrow \underbrace{\frac{\alpha^2}{4E^2\sin^4\theta/2}\cos^2\frac{\theta}{2}}_{\text{Mott XS}}\underbrace{|F(\vec{q}^2)|^2}_{\text{FF}}$$

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



# Elastic scattering: Form factors

Elastic e-p scattering




Robert Hofstadter, Nobel prize in physics 1961

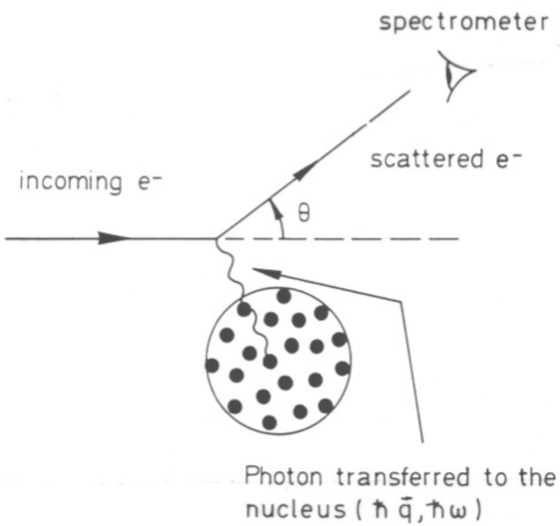
For his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discovery concerning the structure of nucleons

**Proton is not a point-like particle but has finite size!**

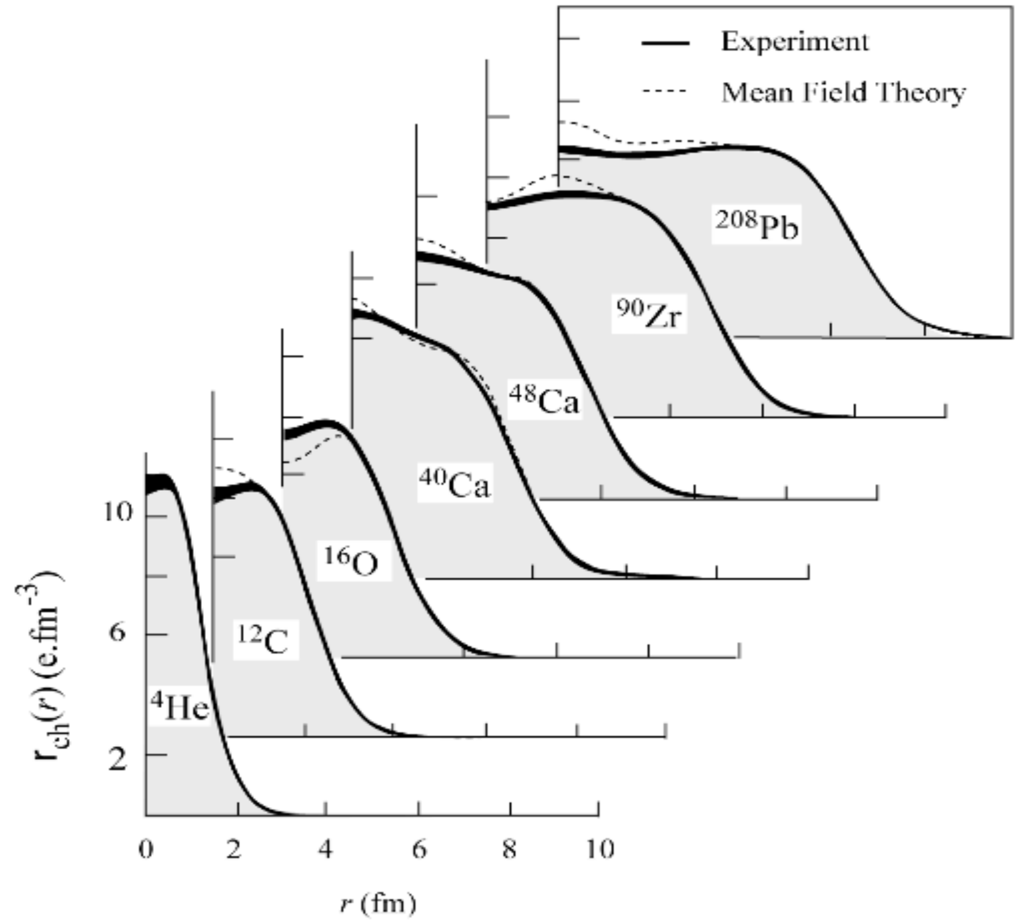
**Form factors → charge distributions**

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

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




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



# Proton recoiling and finite size

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

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

Rutherford | Proton recoil | Electric/ Magnetic scattering | Magnetic term due to spin

But the proton is not point-like!

The finite size of the proton accounted for by 2 form factors:

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

Recoil factor — Form factors

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

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

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

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

# Measuring the form factors

We can rewrite the cross section as:

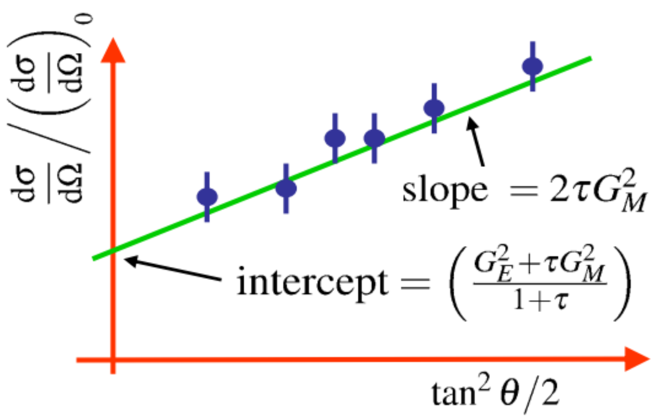
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_0 \left(\frac{G_E^2 + \tau G_M^2}{(1+\tau)} + 2\tau G_M^2 \tan^2\frac{\theta}{2}\right)$$

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

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

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

# Charge Radius of the Proton using e-p elastic scattering

- For the proton we make use of the fact that as $Q^2$ goes to zero the charge radius is proportional to the slope of $G_E$

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

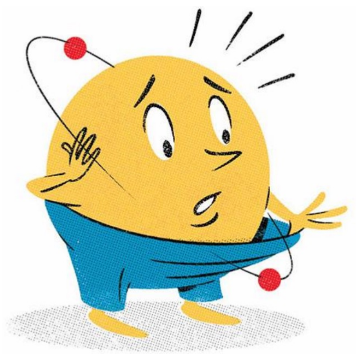
$$r_p \equiv \left( -6 \left. \frac{dG_E(Q^2)}{dQ^2} \right|_{Q^2=0} \right)^{1/2}$$

This definition of $r_P$ has been shown to be consistent with the radius extracted from the muonic hydrogen data.



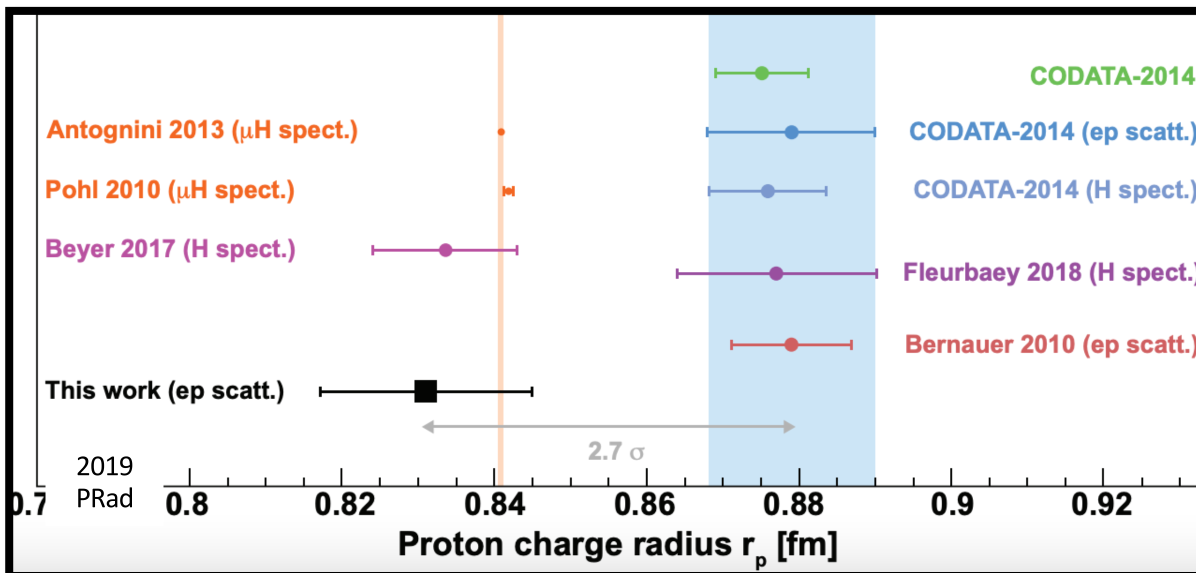
Gerald A. Miller, Phys. Rev. C **99** (2019) 035202.

# Determining the proton charge radius



- Atomic Hydrogen Lamb Shift ( ~ 0.88 fm )
- Muonic Hydrogen Lamb Shift ( ~ 0.84 fm)
- Elastic electron scattering!

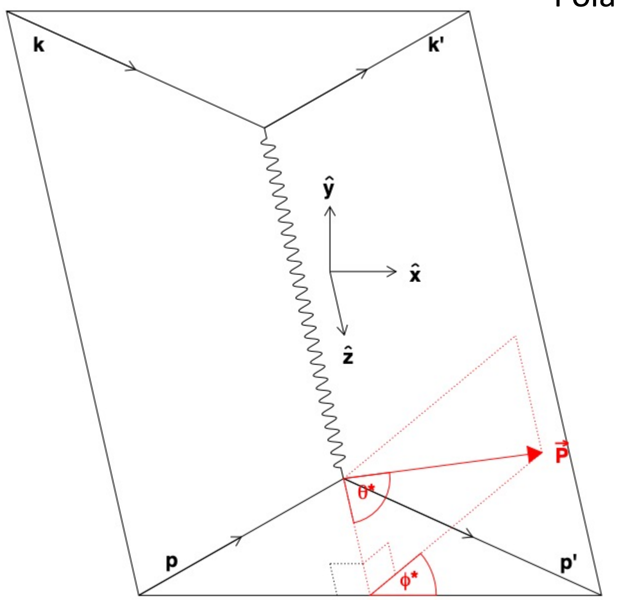
While the proton radius definition is the same whether done on muonic hydrogen or elastic electron-proton scattering, there is a historical division amongst the results.




*Nature* **volume 466**, pages213–216 (2010)

# Form factors: polarization measurement

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




Polarization transfer: $\vec{e}N \rightarrow e\vec{N}$ or spin-target asymmetry: $\vec{e}\vec{N} \rightarrow eN$,

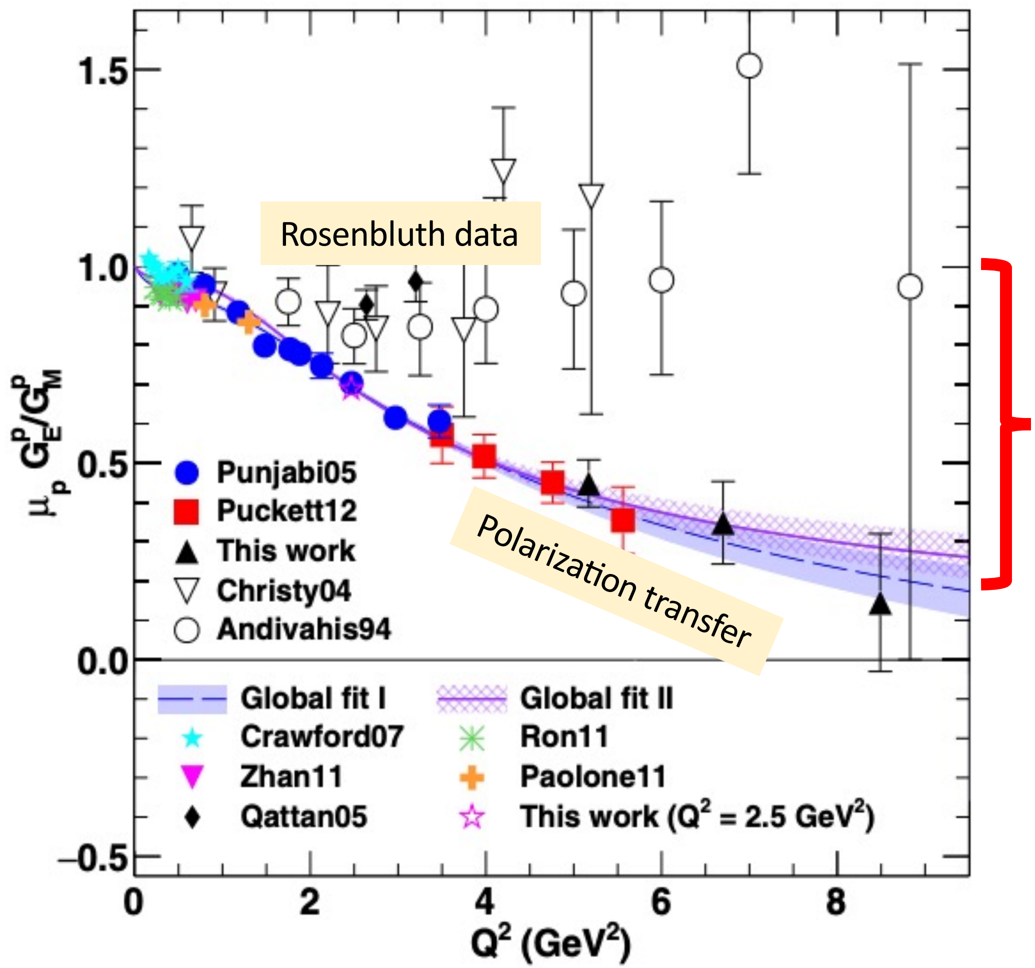
$$P_t = -hP_e\sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}}\frac{G_E G_M}{G_M^2 + \frac{\epsilon}{\tau}G_E^2},$$

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

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

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

# Form factor ratio




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

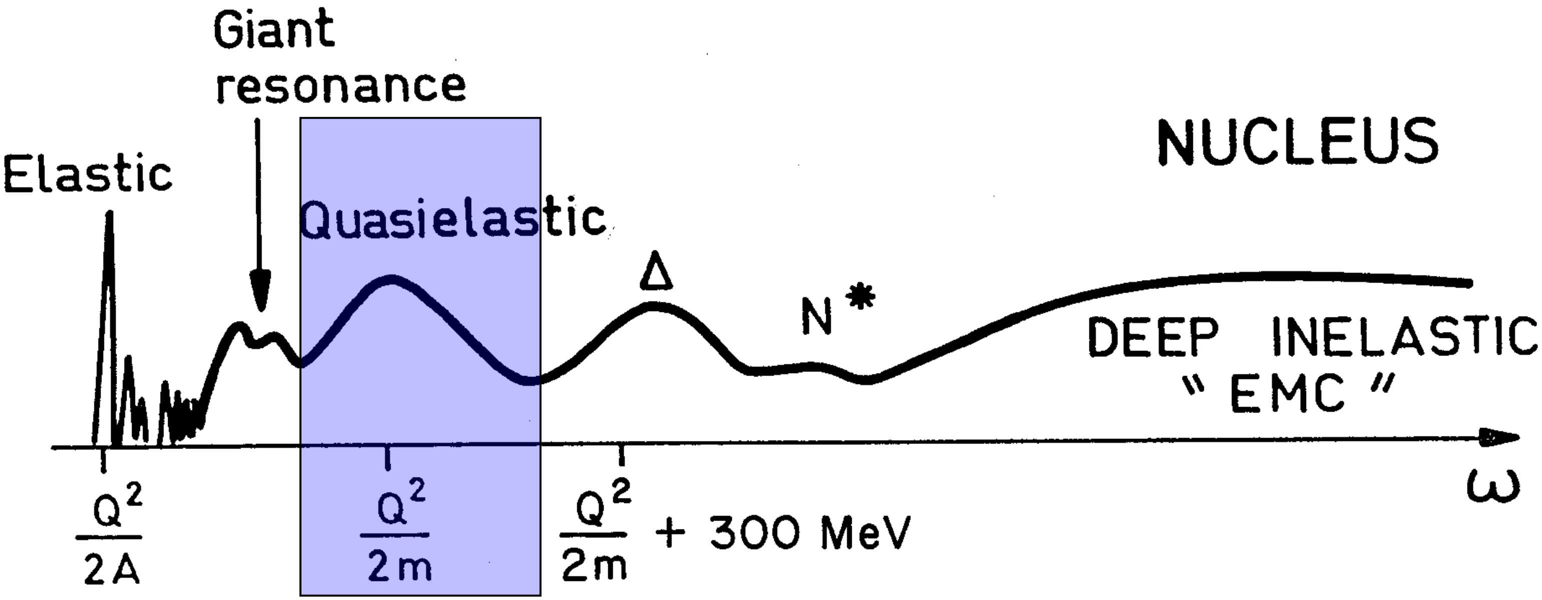
Large discrepancy between Rosenbluth-extracted data and polarization transfer measurements!

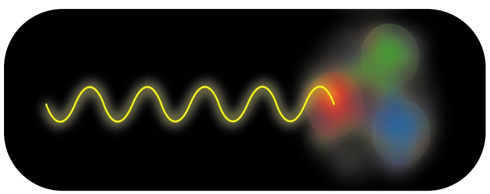
Two photon exchange correction neglected in Rosenbluth data is significant to the radiative corrections.

# 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!

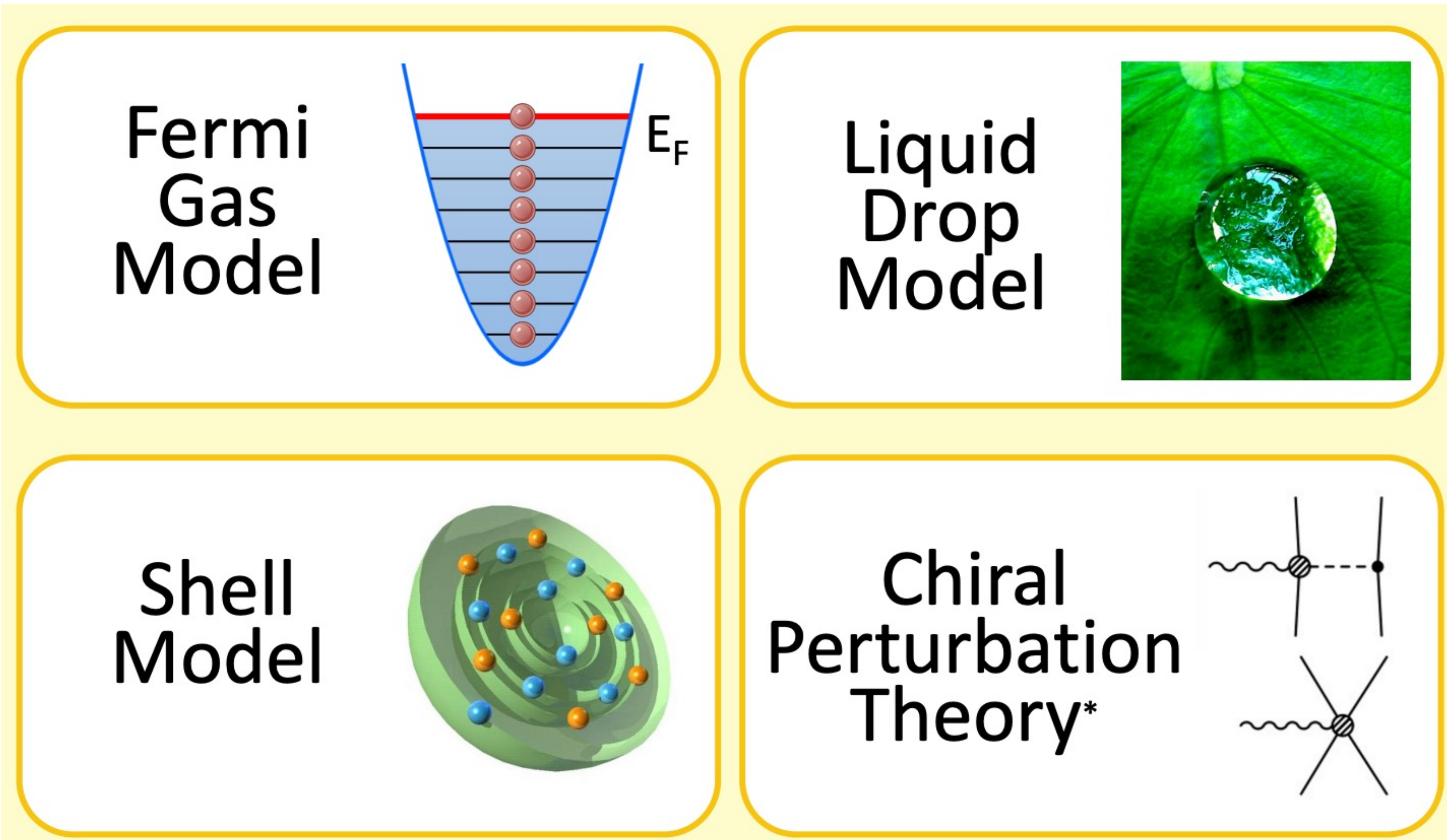
# Quick overview: Quasi-elastic scattering



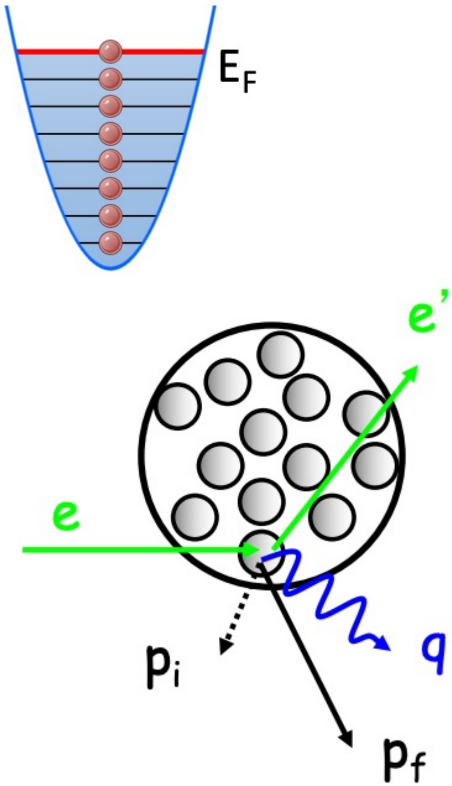



- ❑ Shell structure
  - Momentum distributions
  - Occupancies
- ❑ Short Range Correlated nucleon pairs

# Effective descriptions of the nucleus



# 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

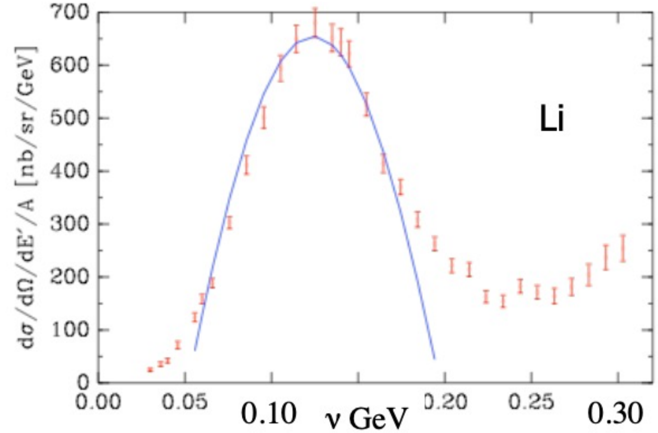
500 MeV, 60 deg
q≈ 500 MeV/c

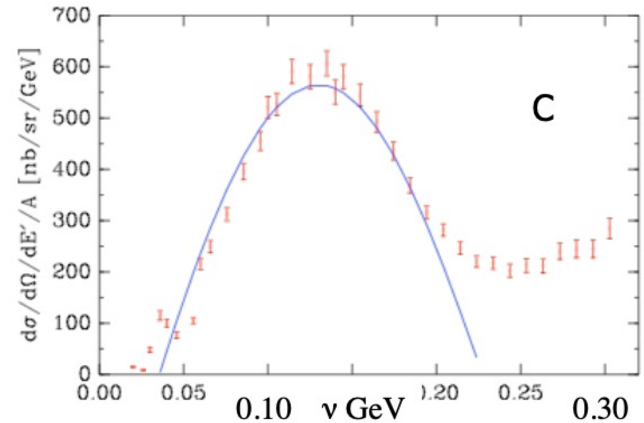
Width ~ $k_F$
(Fermi momentum)

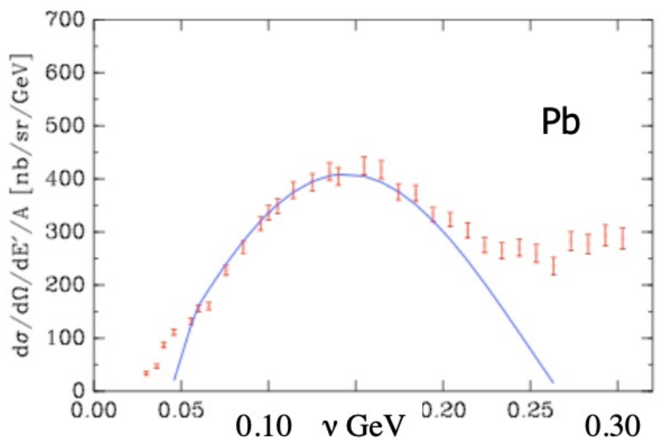
Mean ~ $\varepsilon$
(separation energy)

- Peak broadens with increasing A

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



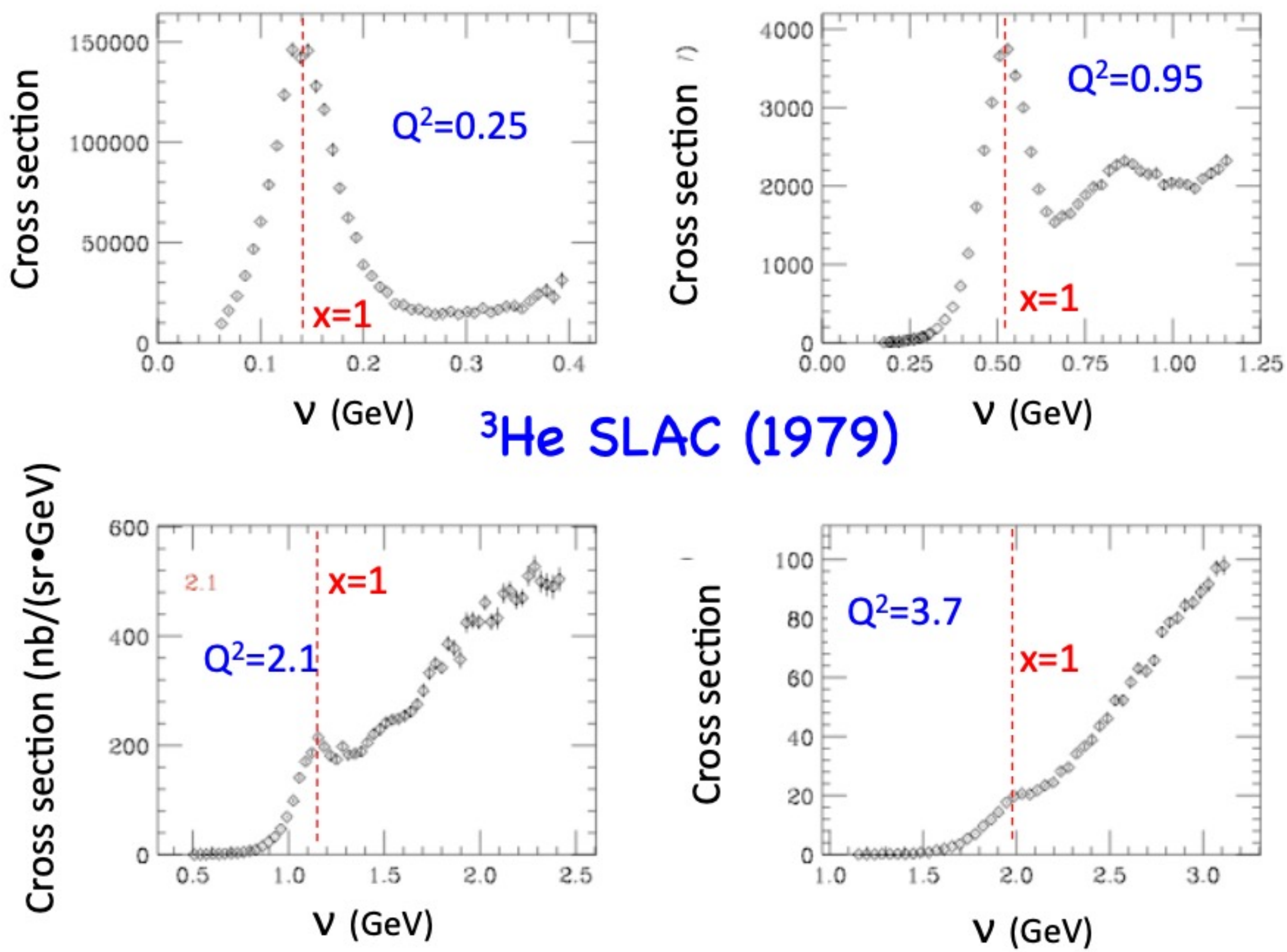




| Nucleus | $k_F$ MeV/c | $\bar{\varepsilon}$ MeV |
|---|---|---|
| $^{6}$Li | 169 | 17 |
| $^{12}$C | 221 | 25 |
| $^{24}$Mg | 235 | 32 |
| $^{40}$Ca | 251 | 28 |
| $^{nat}$Ni | 260 | 36 |
| $^{89}$Y | 254 | 39 |
| $^{nat}$Sn | 260 | 42 |
| $^{181}$Ta | 265 | 42 |
| $^{208}$Pb | 265 | 44 |

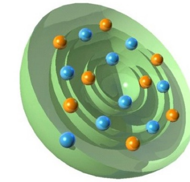
compared to Fermi model:fit parameter $k_F$ and ε

# Quasielastic peak




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

# Independent particle shell model

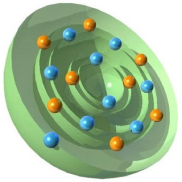


$$H = \underbrace{[T + V_M]}_{\text{IPSM}} + \underbrace{[V_{2-body} + V_{3-body} + ... - V_M]}_{\text{neglected in IPSM}} .$$

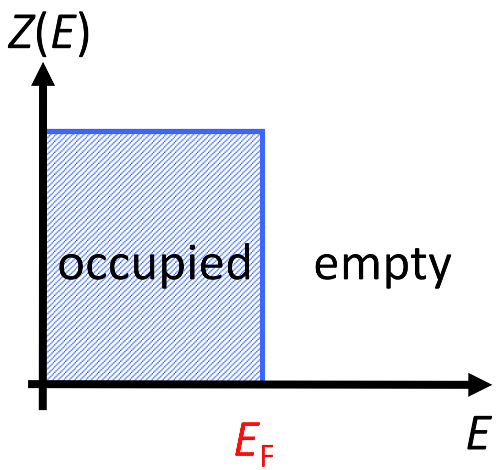
## Assumptions:

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

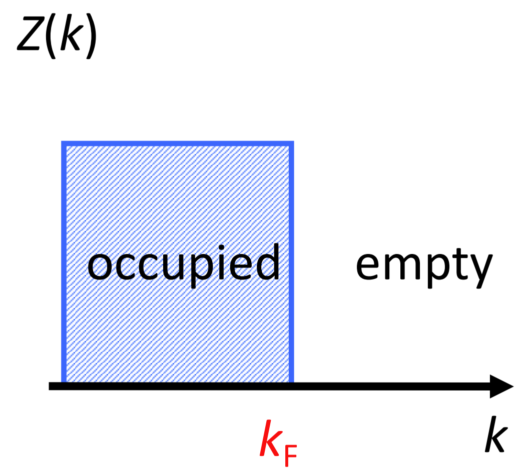
# Independent particle shell model



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




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

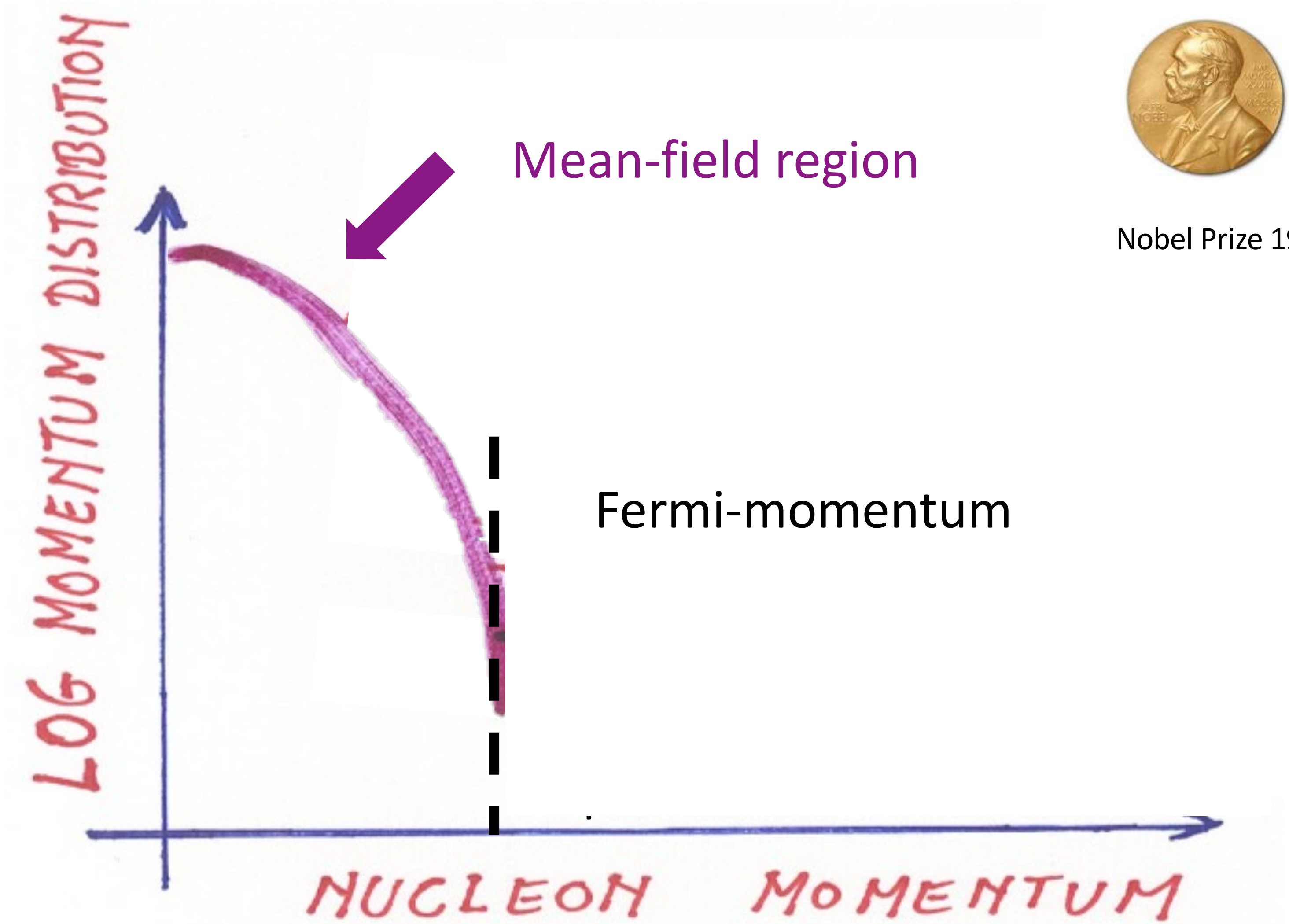



<u>Pauli's principle:</u>

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

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

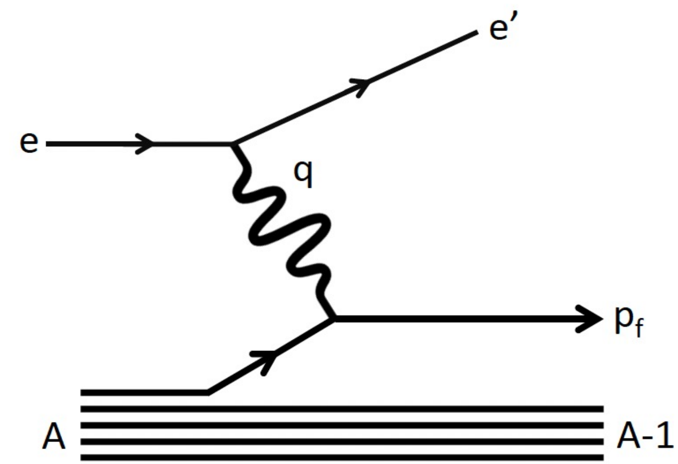
# Momentum distribution:




Nobel Prize 1963

# (e,e'p) Plane Wave Impulse Approximation (PWIA)

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



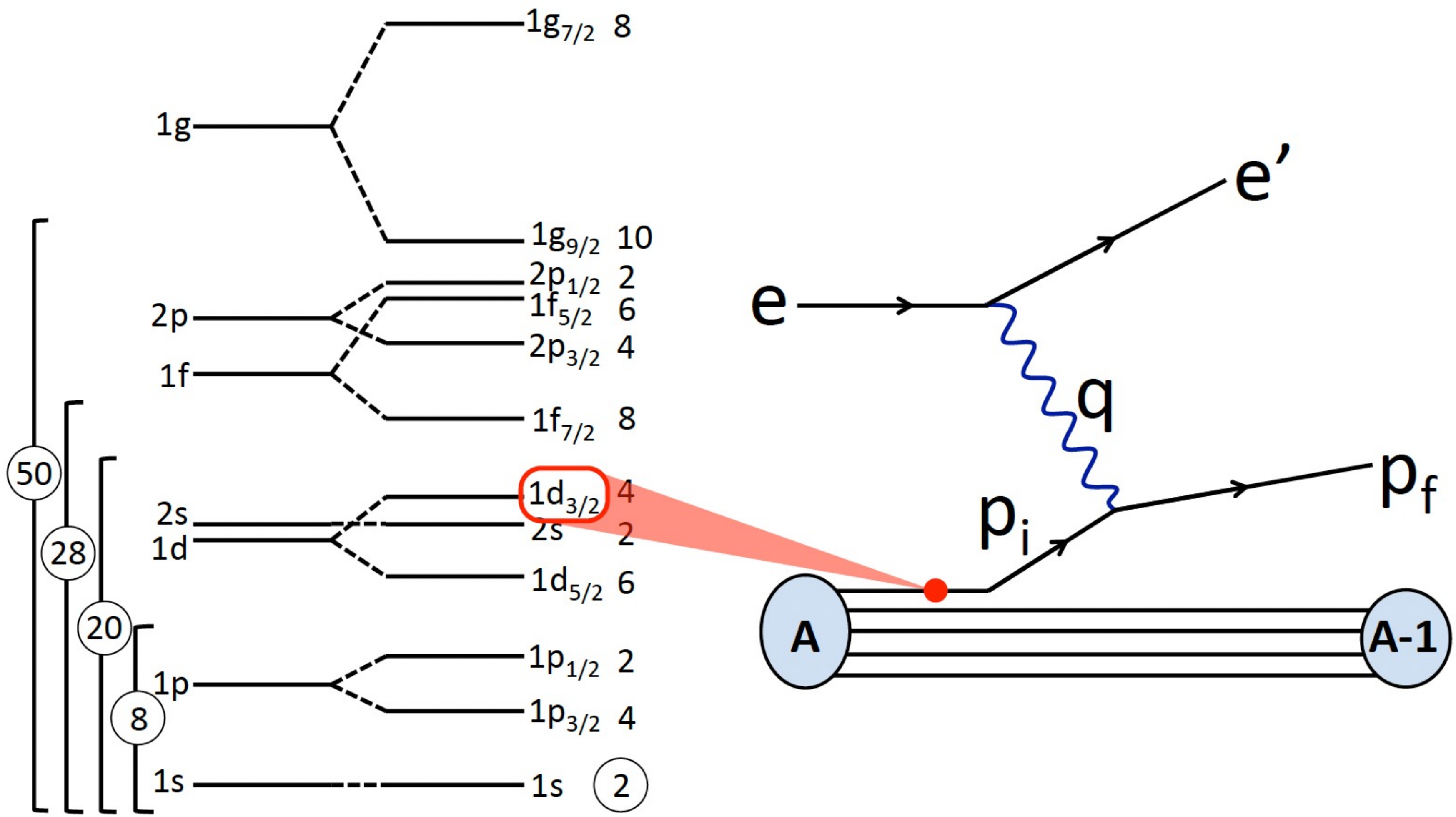

- Missing energy, $E_m = \nu - T_{pf} - T_{A-1}$
- Missing momentum, $p_m = q - p_f$

PWIA implies: $p_i = -p_m$, $|E| = E_m$

Cross-section factorization

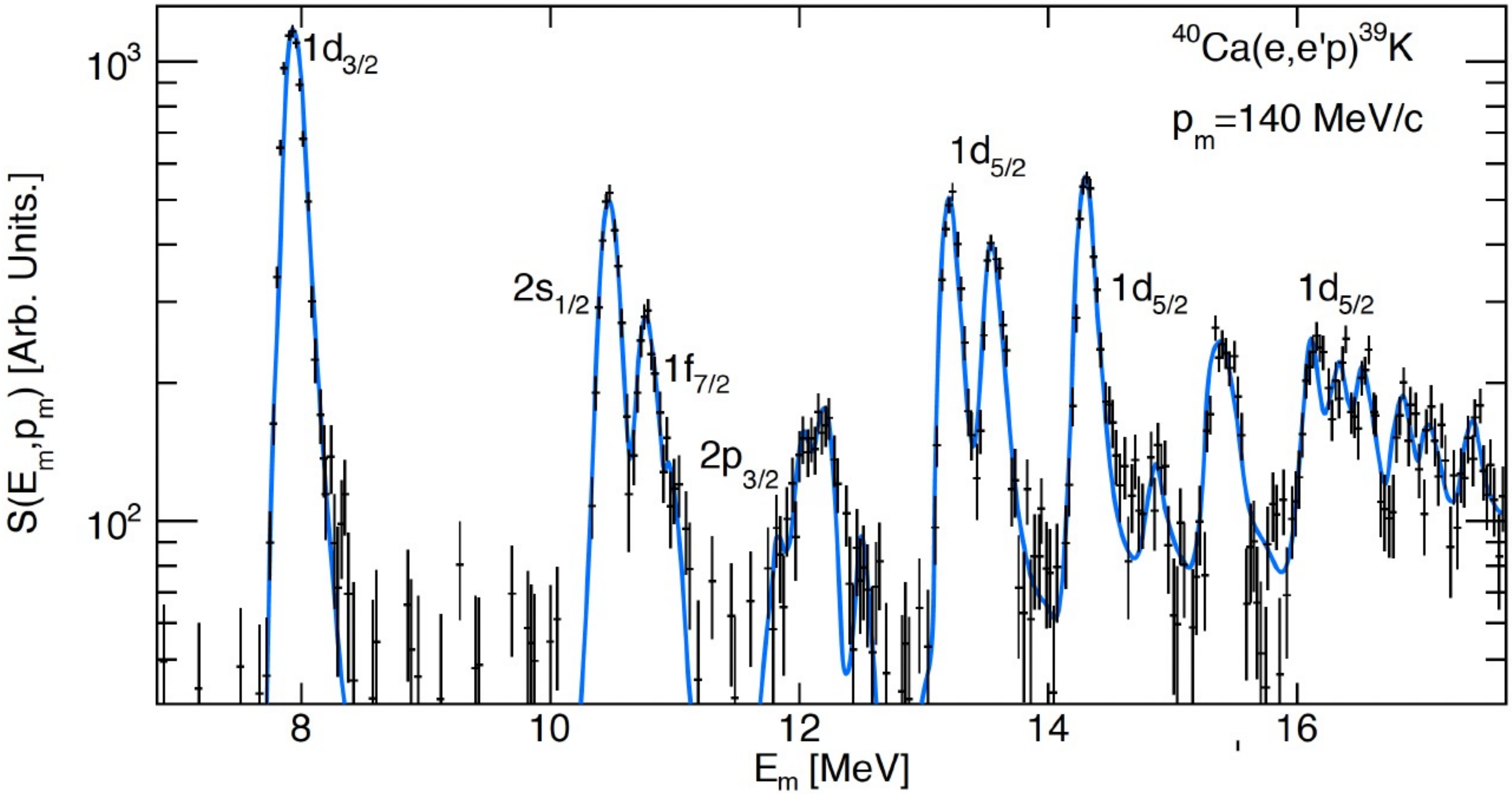
$$\sigma = K\, \sigma_{ep}\, S(|\overrightarrow{P_i}|, E_i)$$

# (e,e'p) scattering off shell orbitals



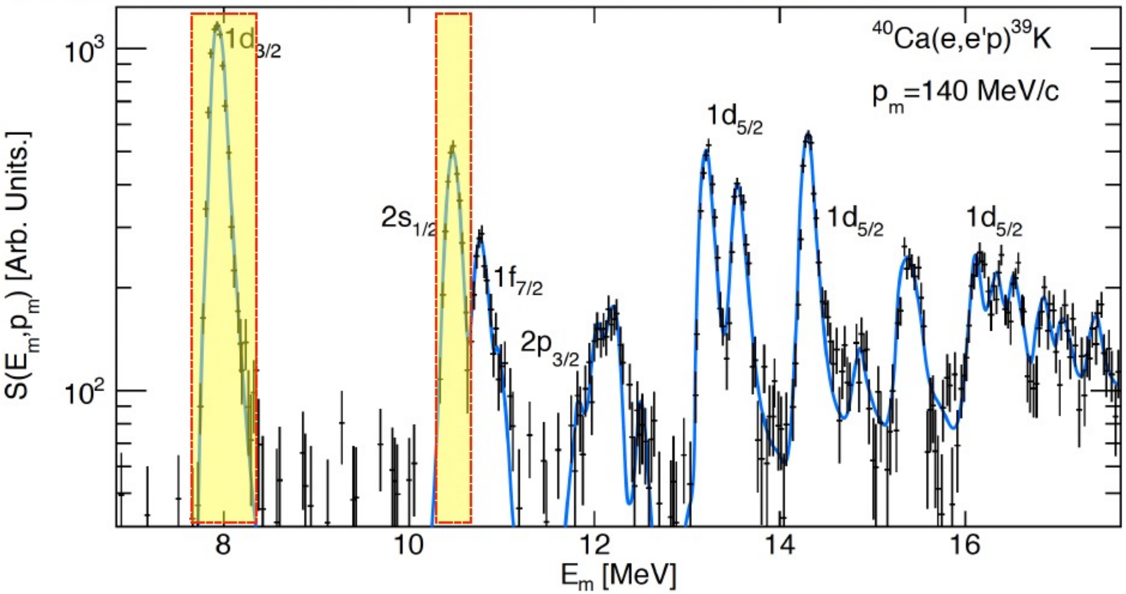
# (e,e'p) scattering off shell orbitals

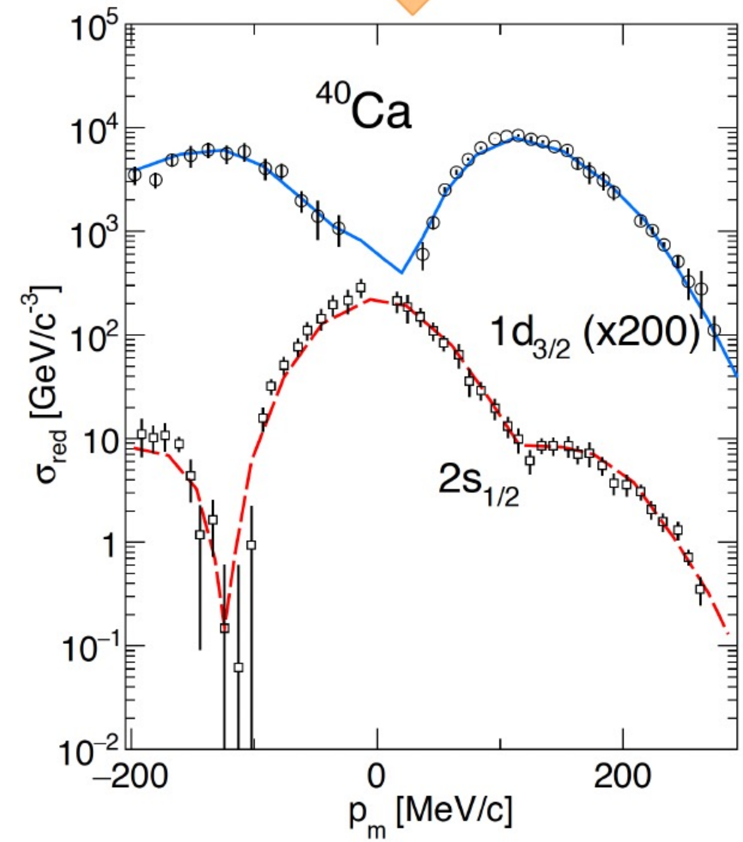
The missing energy spectrum shows shells occupancy




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

# (e,e'p) scattering off shell orbitals



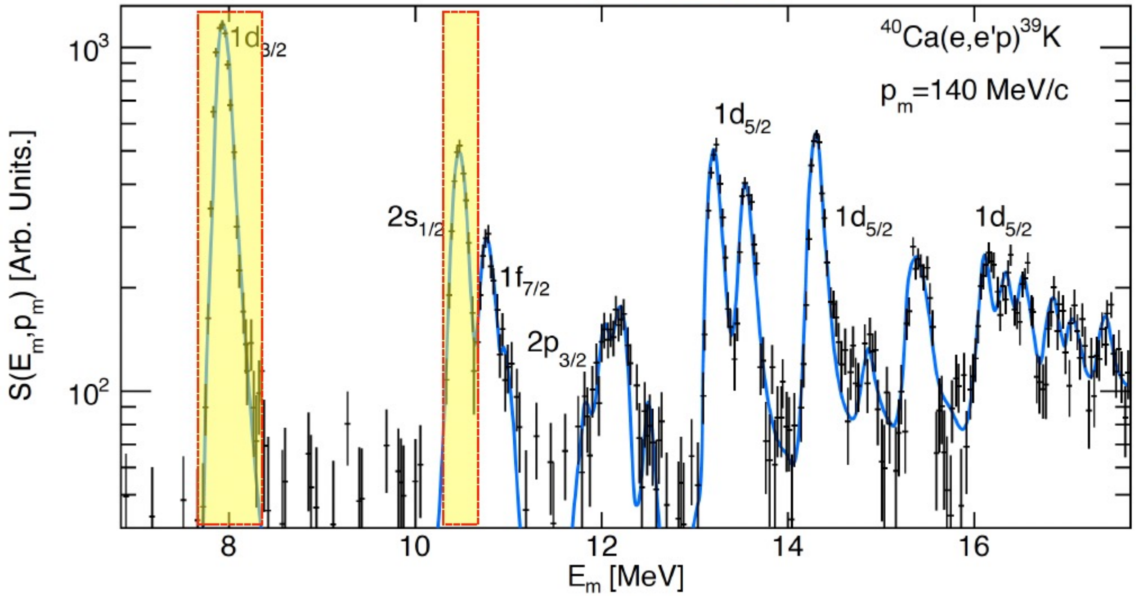



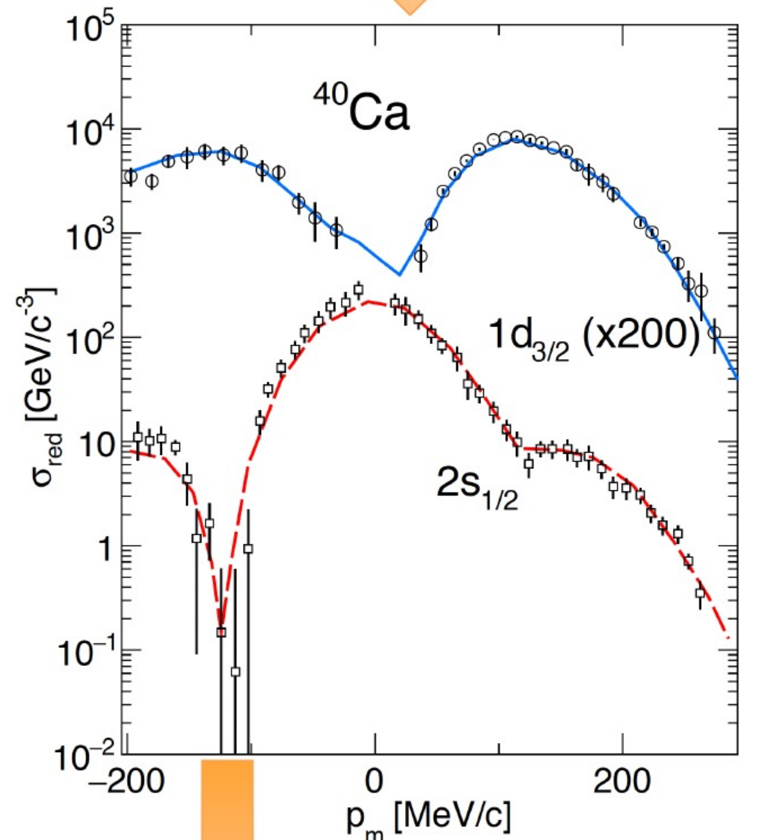

Compare to Shell Model predictions:

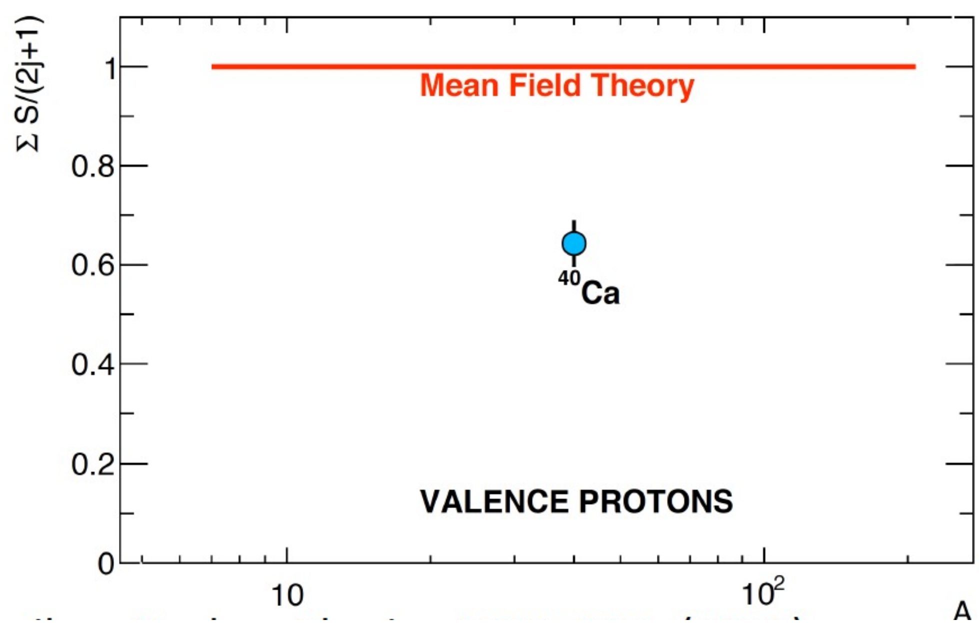
- Shapes well described
  - Normalization…

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

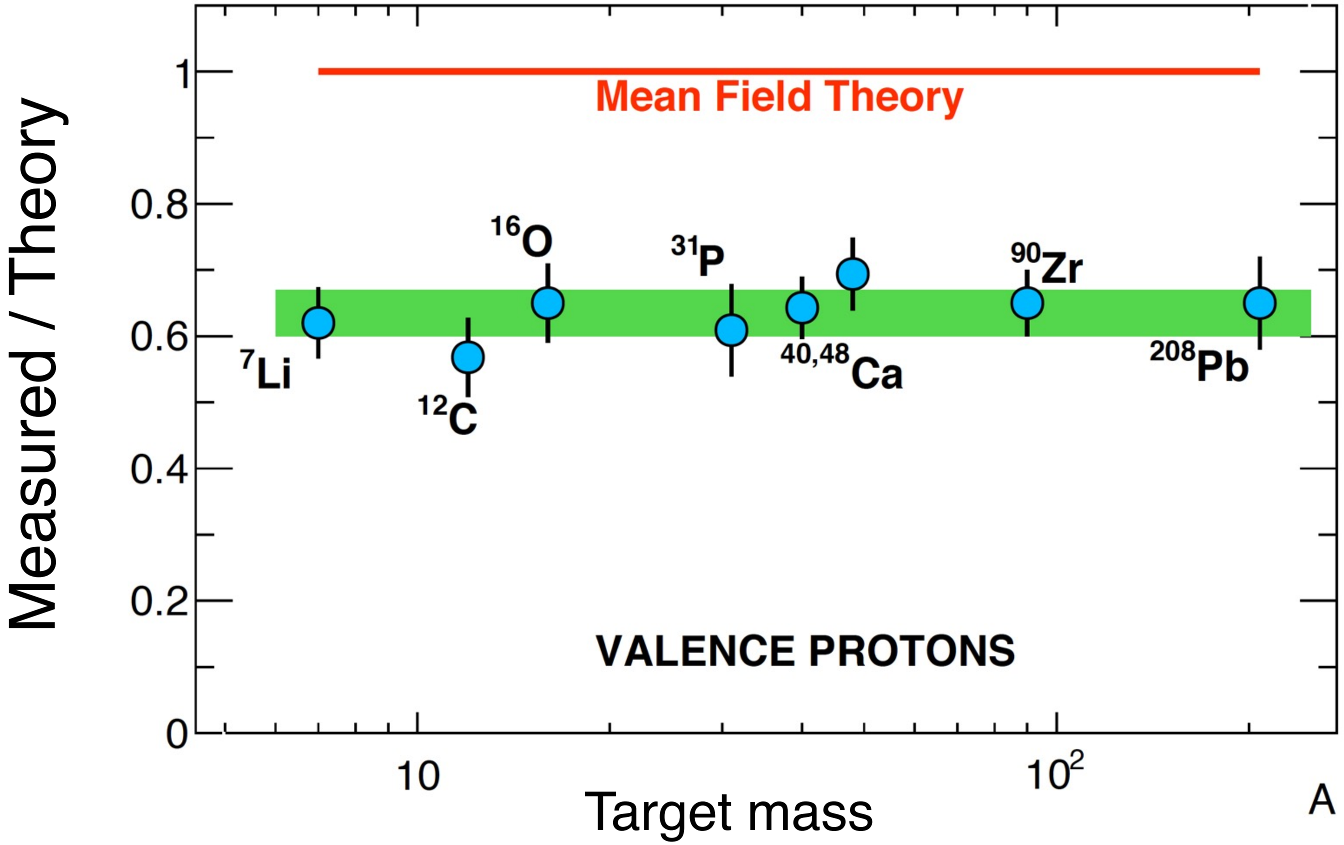
# (e,e'p) scattering off shell orbitals



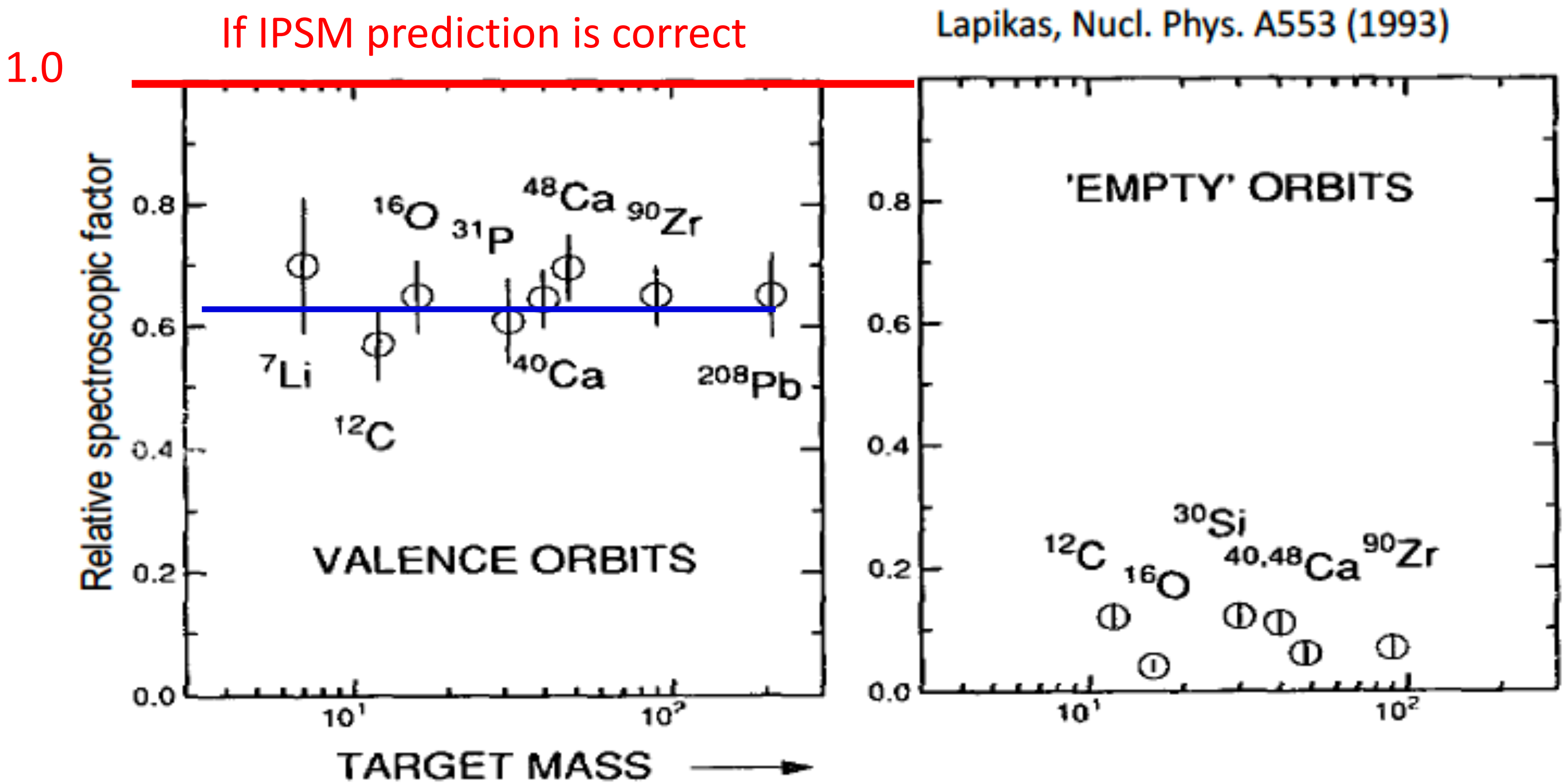



# Nucleon went missing??




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

# Nucleons went missing?




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

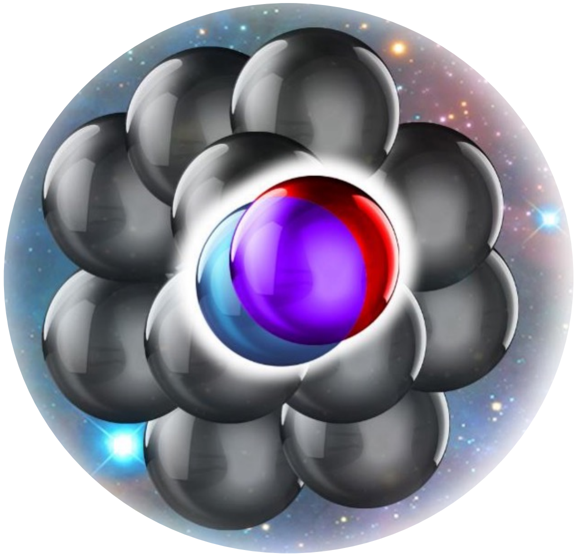
$$H = \underbrace{\left[T + V_M\right]}_{\text{IPSM}} + \underbrace{\left[V_{2-body} + V_{3-body} + \ldots - V_M\right]}_{\text{neglected in IPSM}}.$$

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

# Welcome to SRCs

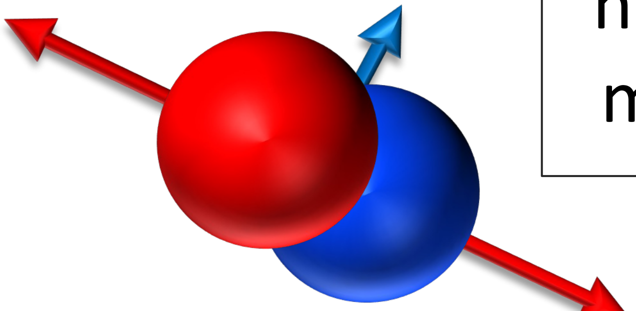
# What are Short Range Correlations (SRCs) ?

r-space



Nucleon pairs that are close together in the nucleus

k-space

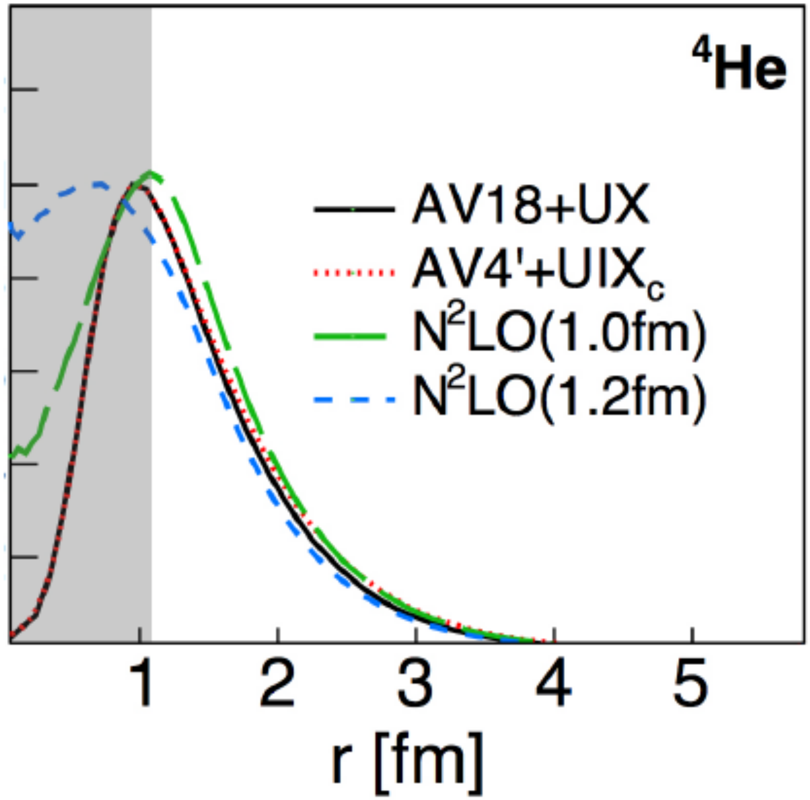


high ***relative*** and lower ***c.m.*** momentum compared to $k_F$

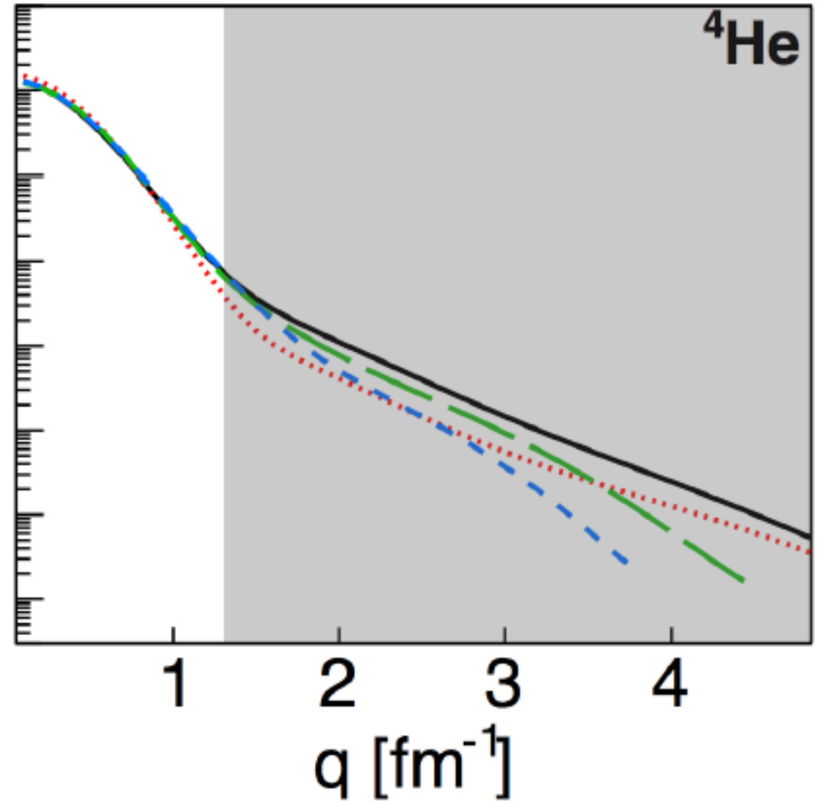
*More on this in next lectures*

# NN interaction at short distance

Probability to find two nucleons with relative distance r




Probability to find two nucleons with relative momentum q.



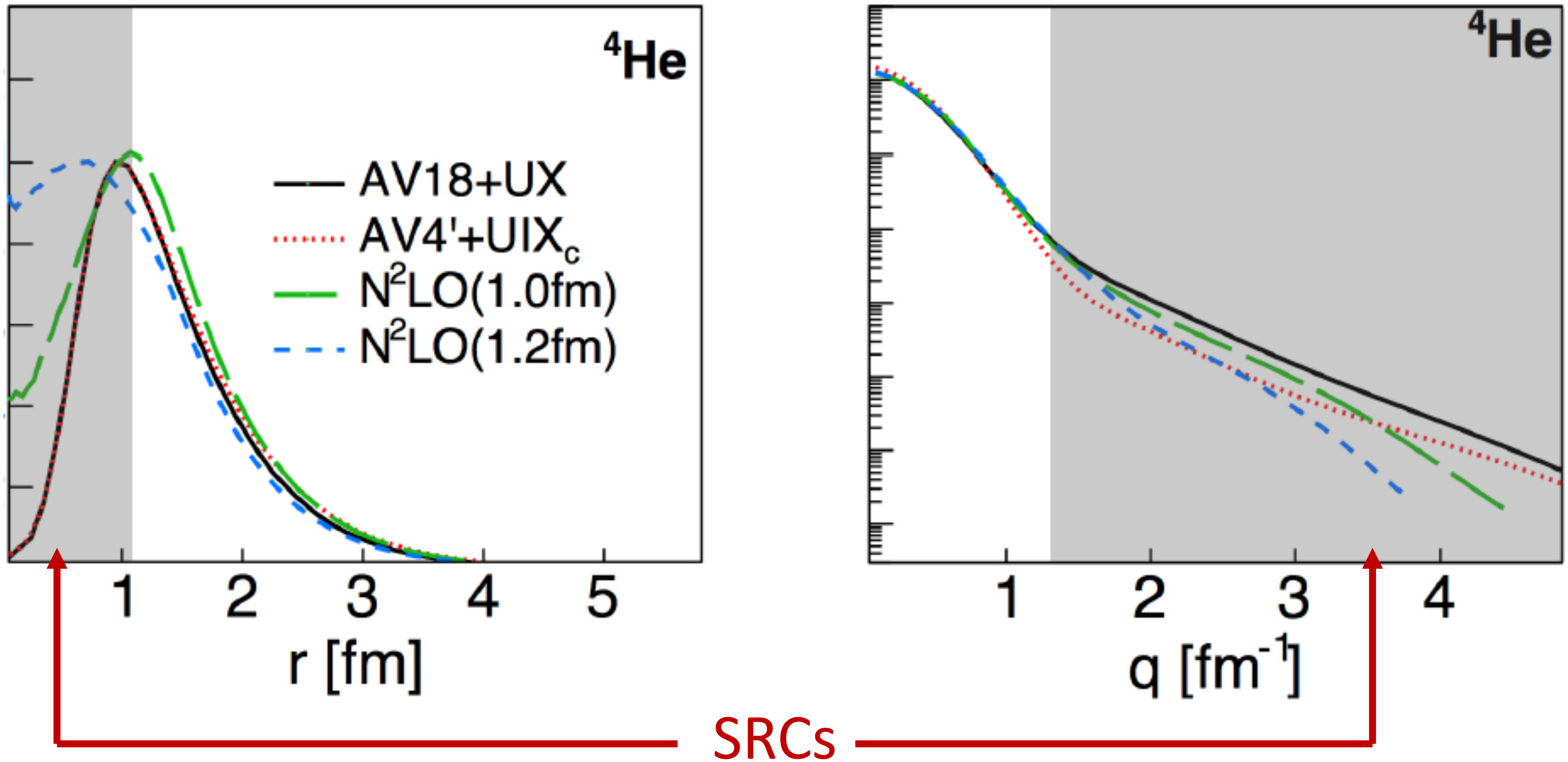

200 MeV/$c$ ≈ 1 fm$^{-1}$

Need to put these to test

# Large model dependence at small-r/high-k

Probability to find two nucleons with relative distance r

Probability to find two nucleons with relative momentum q.

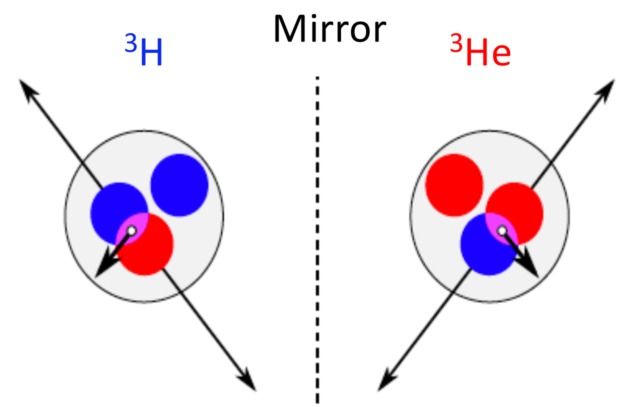



Need to put these to test

# Why light nuclei?

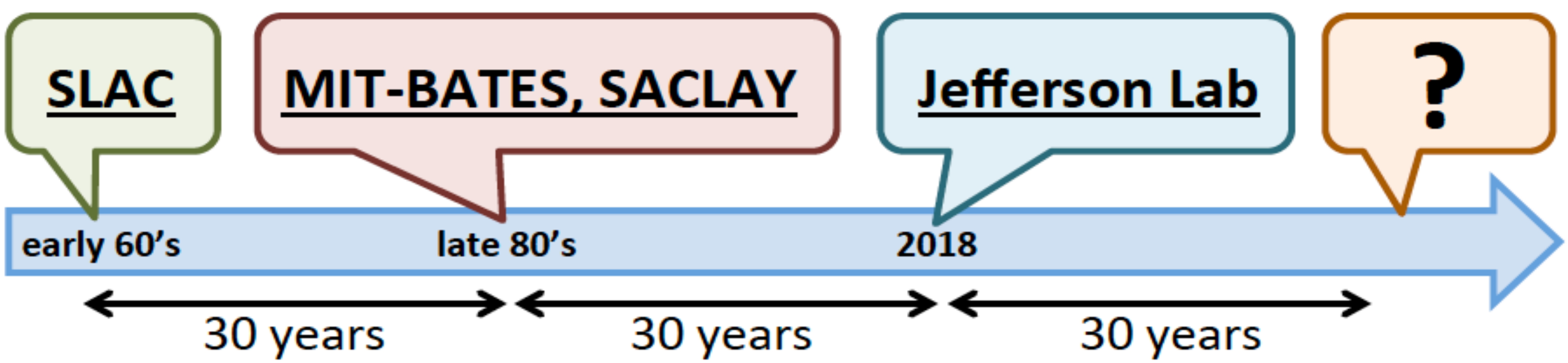
3-Body system:

- Exactly calculatable
- Test & benchmark theory

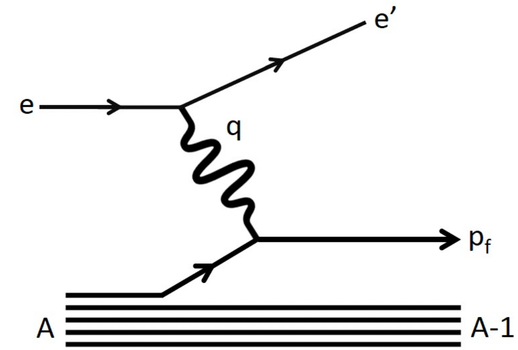



Why Tritium?

- Proton in $^{3}He$ = Neutron in $^{3}H$
- Constraint reaction mechanism



# High $Q^2$: PWIA factorized approximation



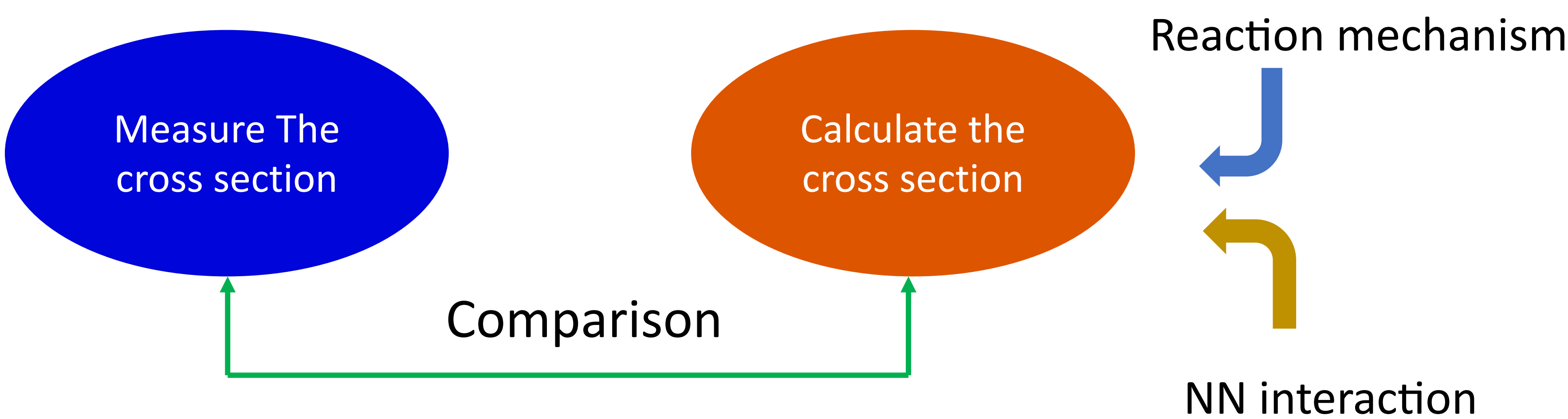

$$\vec{P}_{miss} = \vec{P}_f - \vec{q}$$

## Cross-section (Observation) (e,e'p)

$$\frac{d^6\sigma}{d\omega dE_p d\Omega_e d\Omega_p} = K\sigma_{ep} S(|\vec{p}_i|, E_i)$$

Experient:

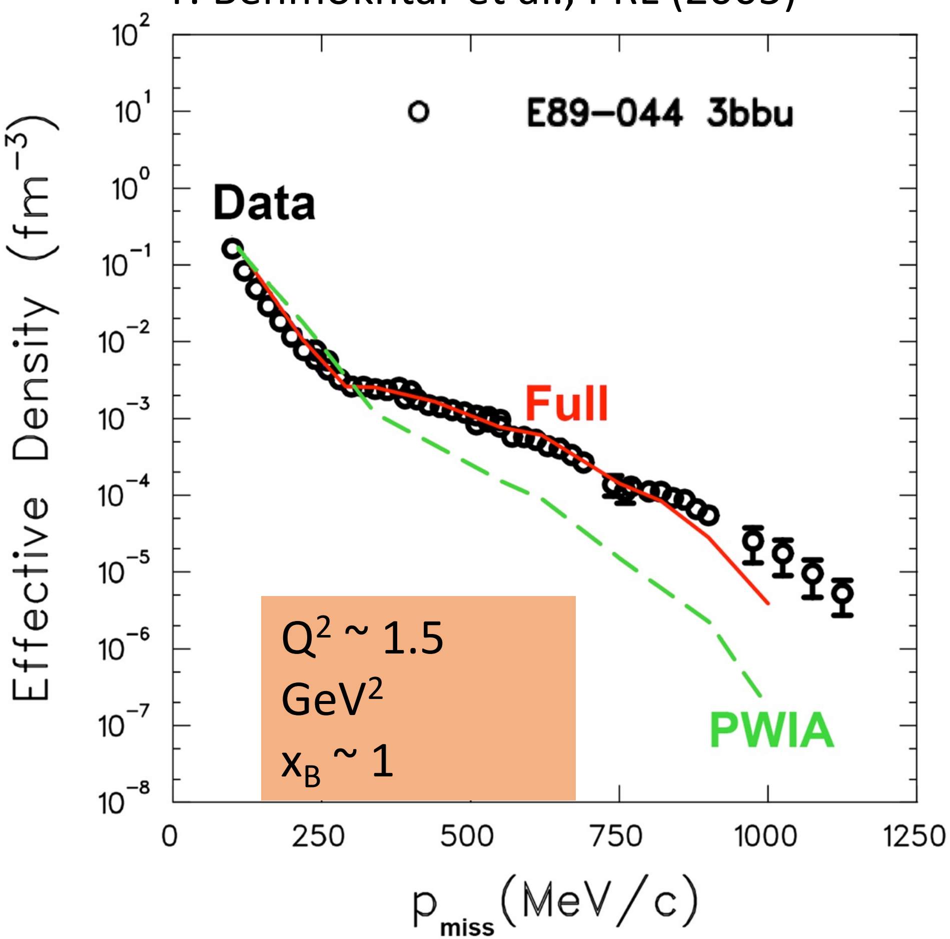
Theory

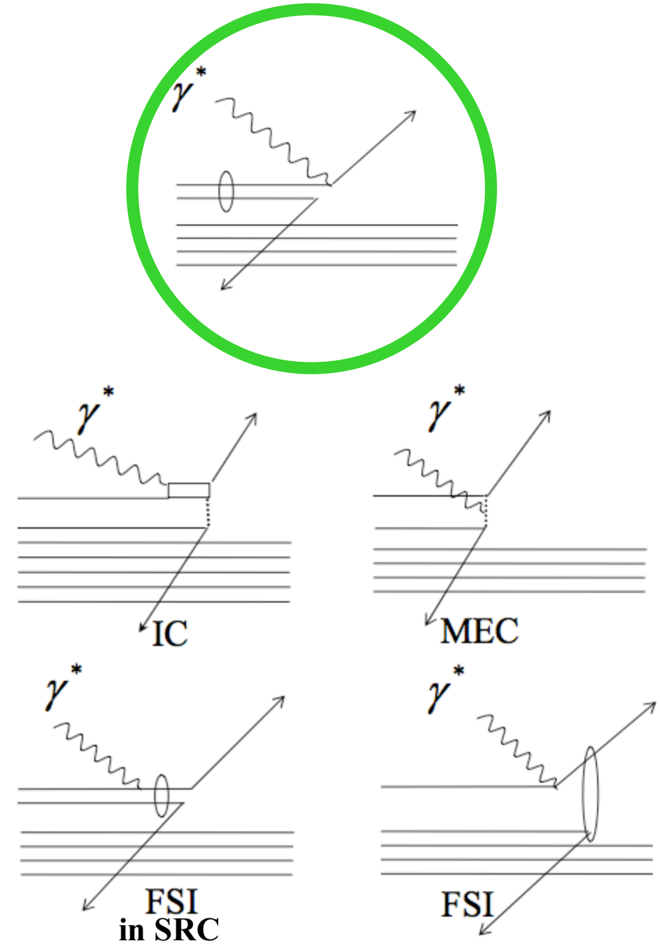



CD-Bonn NN potential

# Non-QE mechanisms contribution

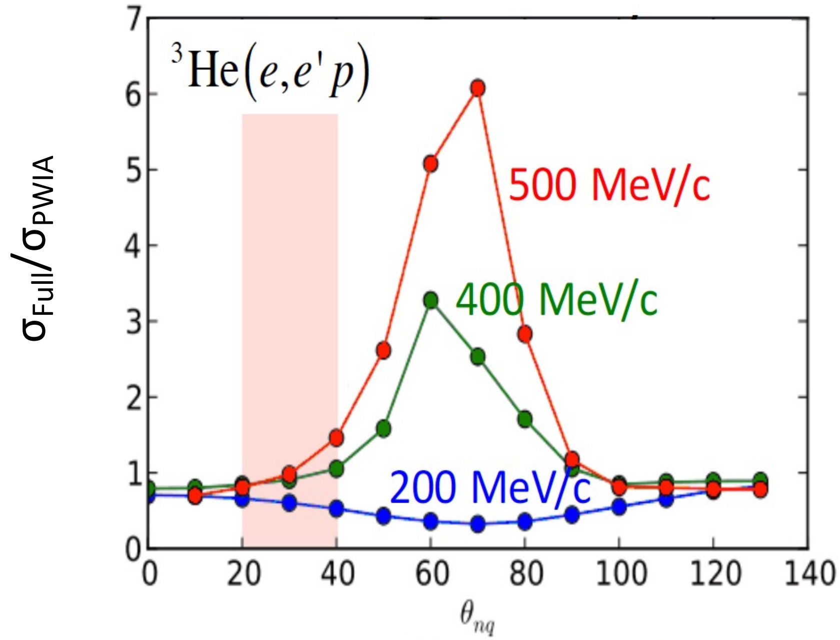
F. Benmokhtar et al., PRL (2005)

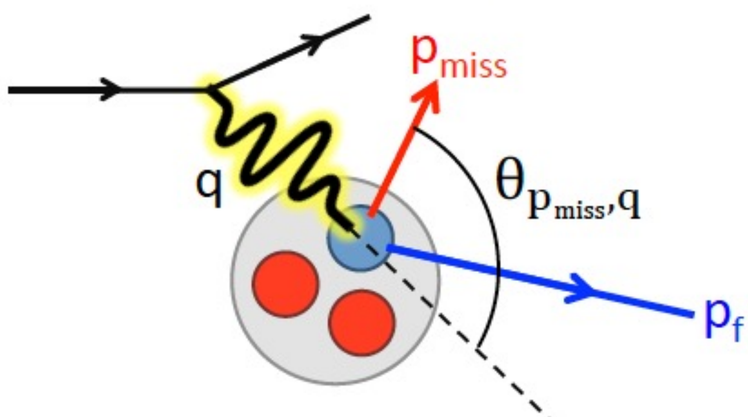


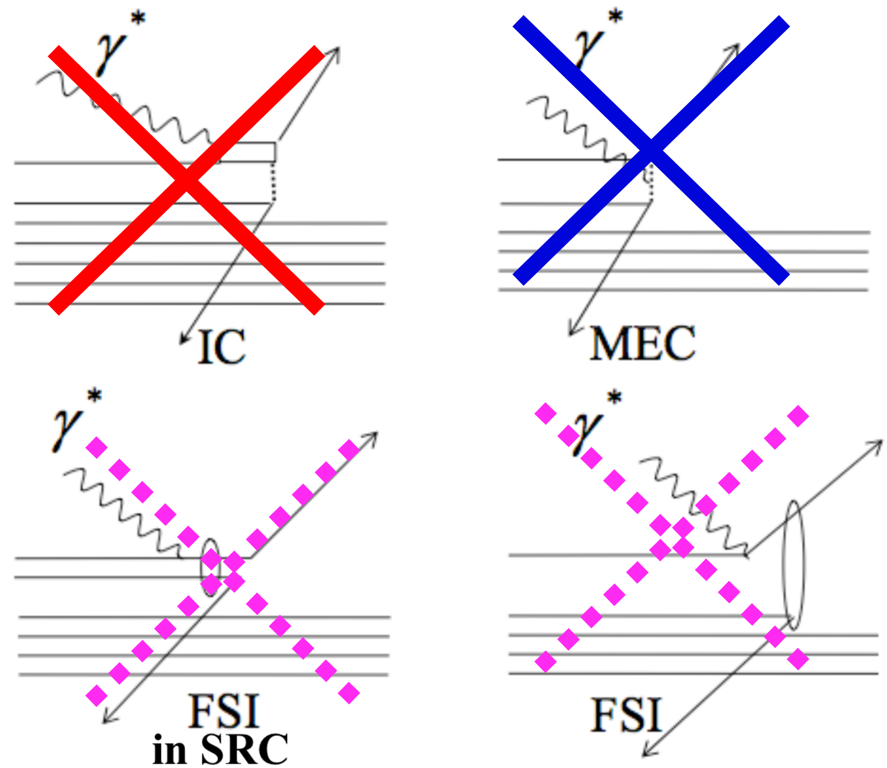

❑Non-QE mechanisms can be minimized using selected kinematic region

# Minimizing non-QE mechanisms



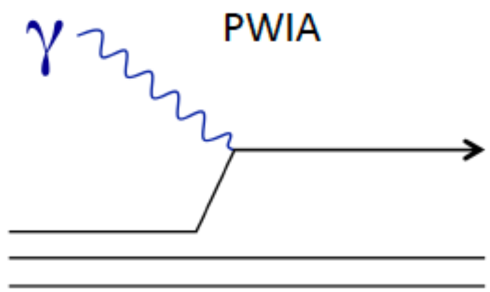

$X_B > 1$ $Q^2 > 2$ GeV$^2$

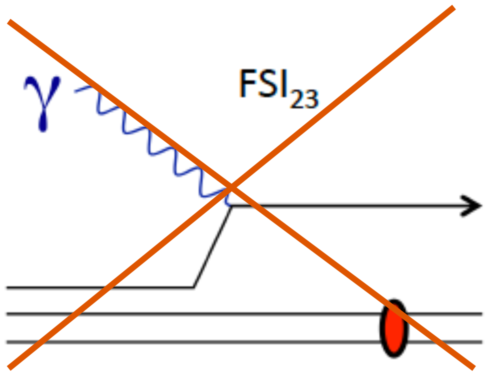


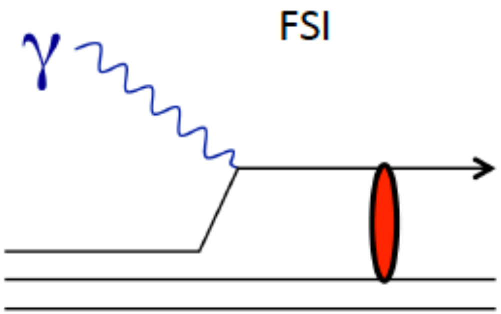

$\theta_{qr} < 35^o$

Boeglin et al., PRL 107 (2011) 262501

# Compare to different theory calculation




**Cracow:**

- ❑ Faddeev-formulation-based calculations
- ❑ Continuum interaction between two spectator nucleons ($FSI_{23}$)

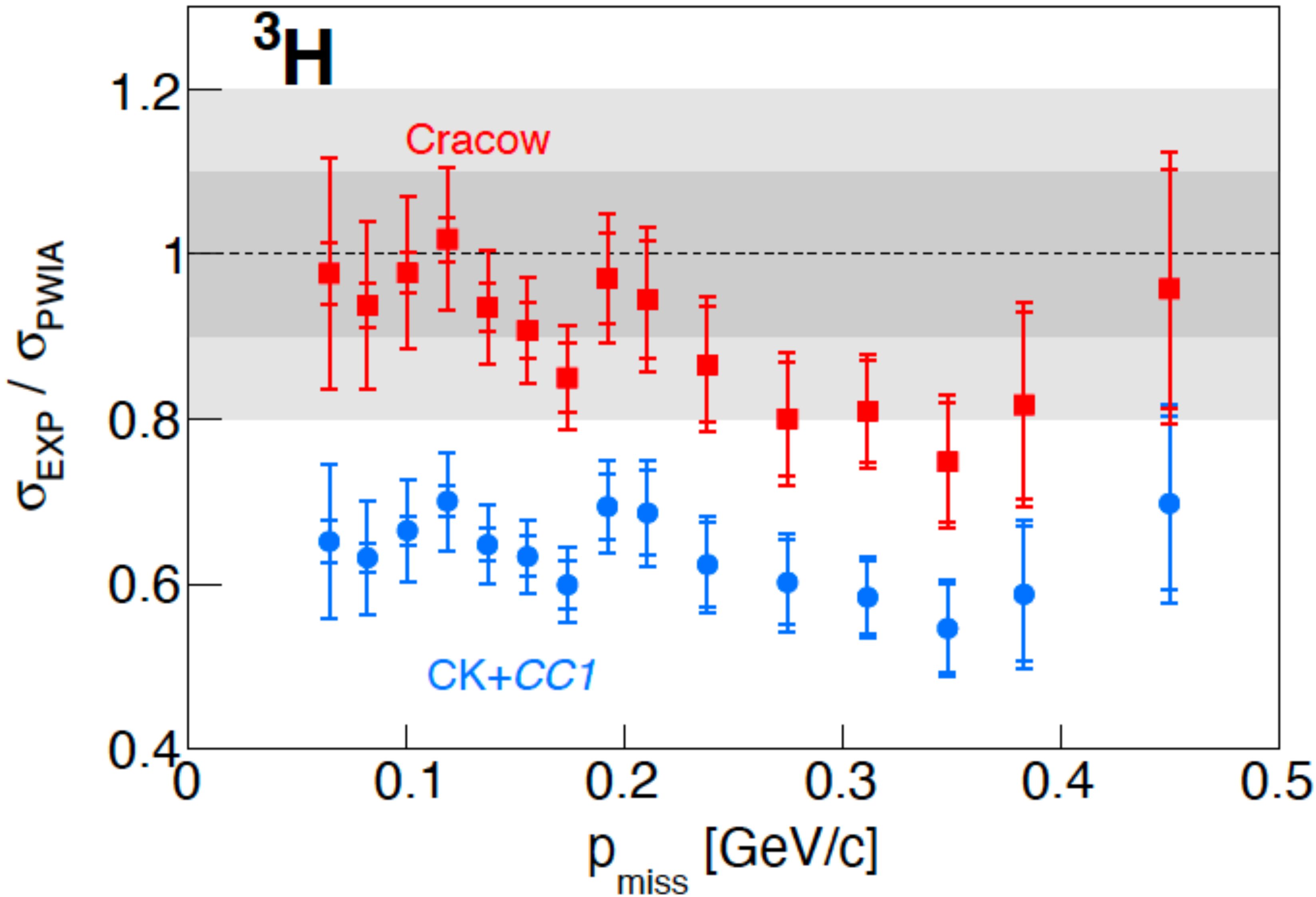
**CK + *CC1*:**

- ❑ $^{3}$He spectral function of C. Cio degli Atti and L. P. Kaptari and electron off-shell nucleon cross-section
- ❑ Including $FSI_{23}$

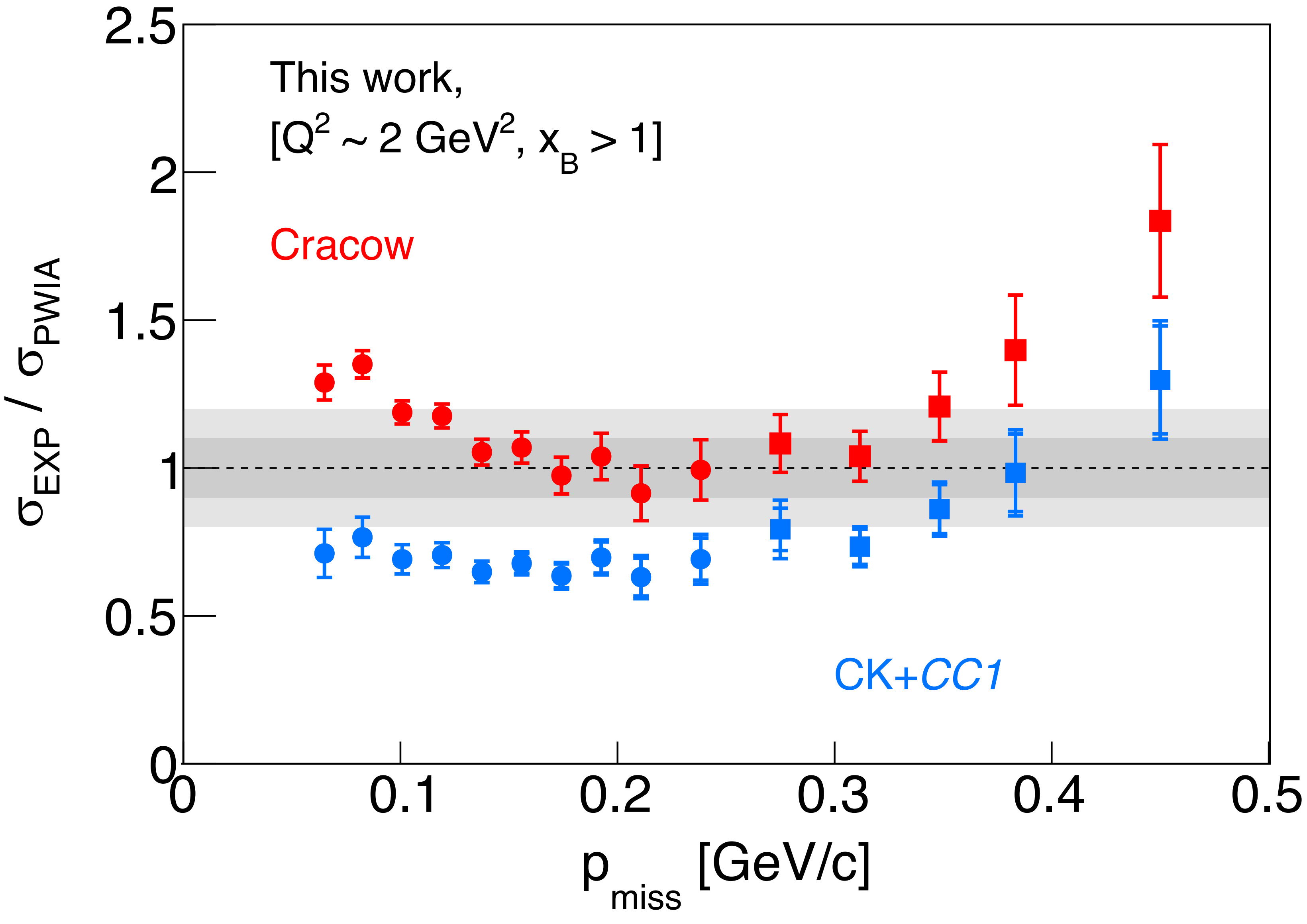
**M. Sargian (FSI):**

- ❑ FSI calculation based on generalized Eikonal approximation
- ❑ Does not include FSI23

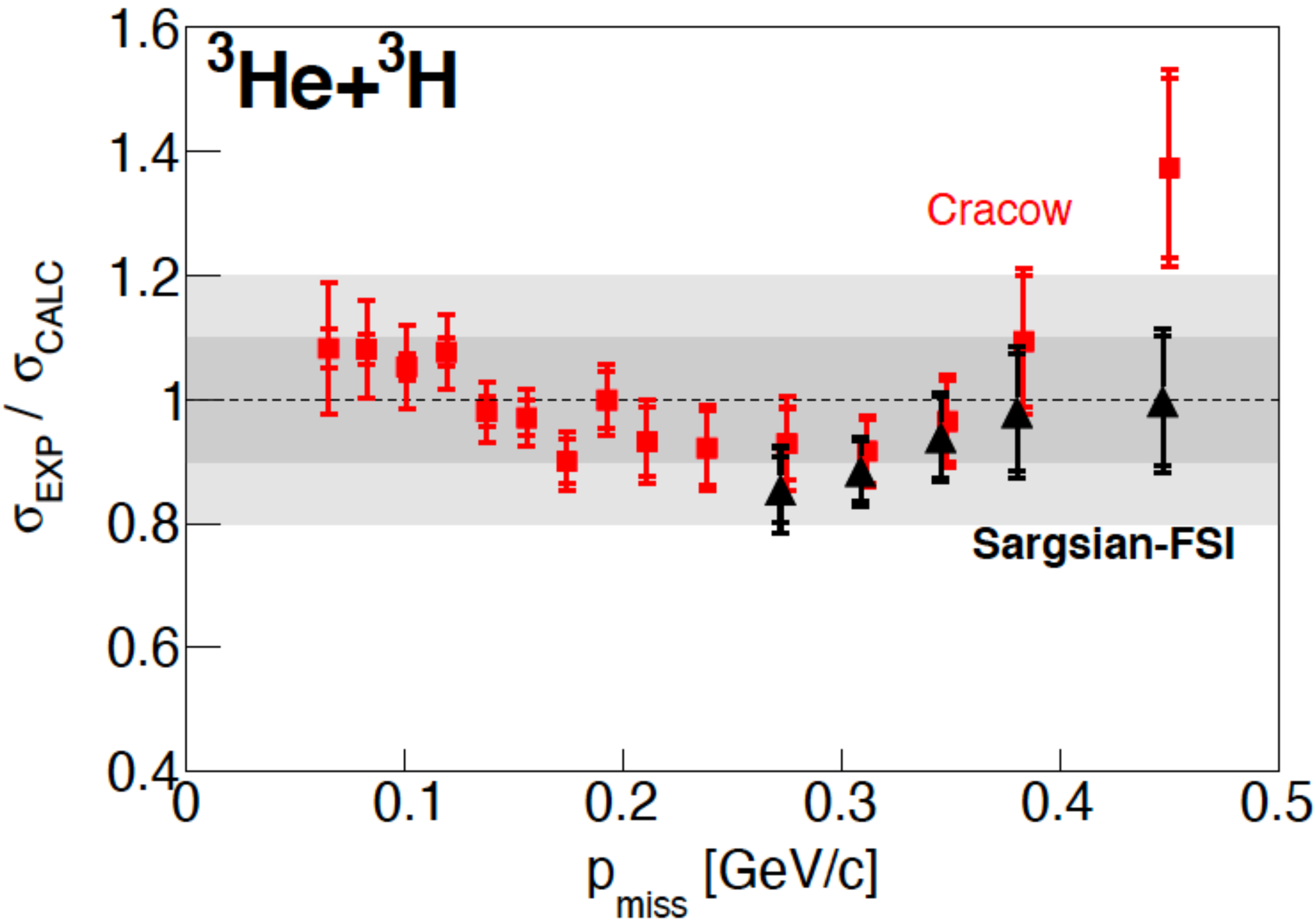
# Exp/PWIA: Cracow and CK+CC1 For $^3H$



# Exp/PWIA: Cracow and CK+CC1 For $^3$He

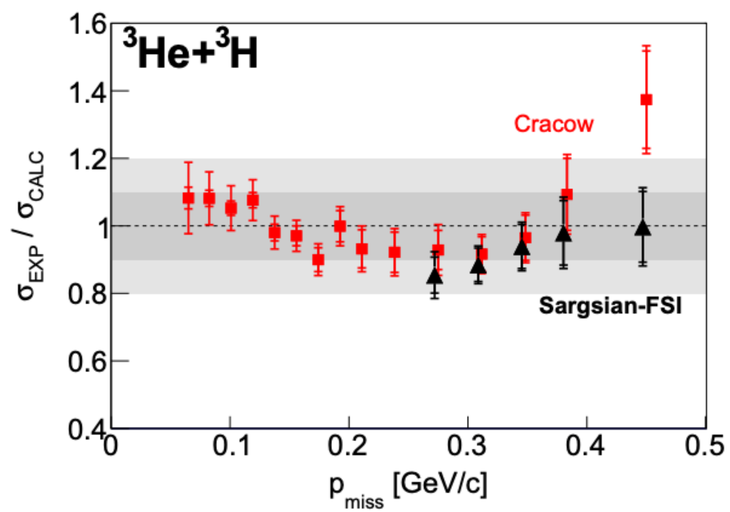


# Isoscalar Sum good better agreement



# What we have learned in A= 3:

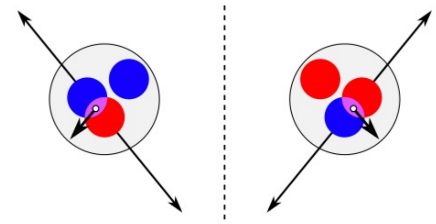
- $^3$H has better agreement to calculation than $^3$He
- Data/PWIA ~ 20% at high Pmiss
- Theory describes $^3$H+$^3$He data within 10% up to Pmiss = 500 MeV/c



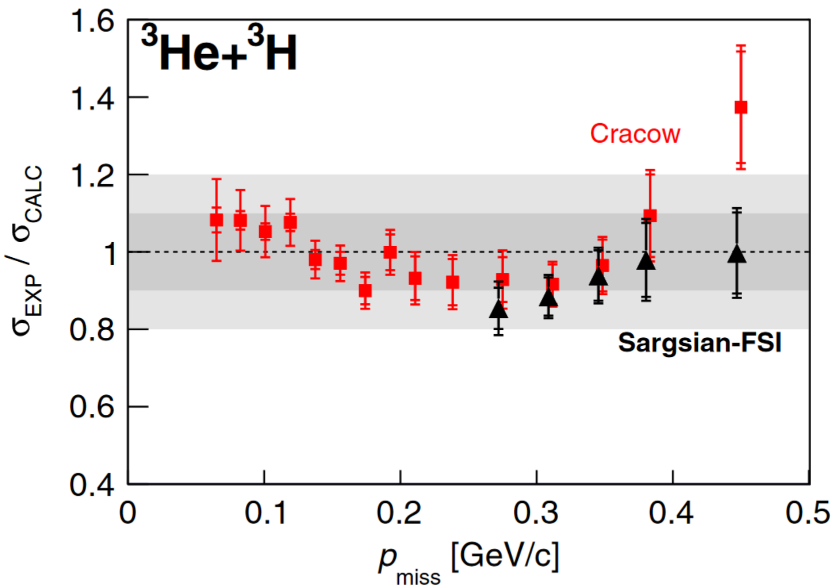

Crucial benchmark for few-body nuclear theory and essential test of theoretical calculation

R. Cruz-Torres, D. Nguyen et al. PRL editor suggestion (2020)

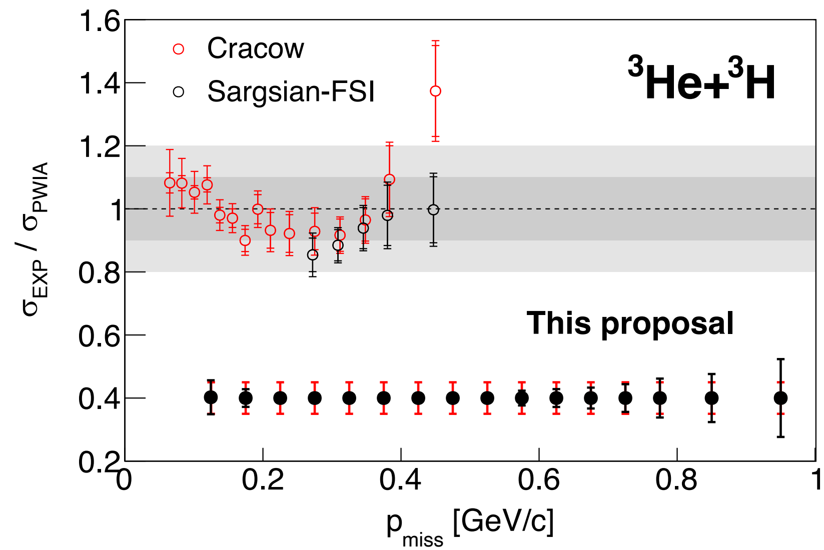
# A=3 nuclei: Ideal systems to test theory calculations




(e.e'p) data from Hall A JLab




Future measurement with CLAS12



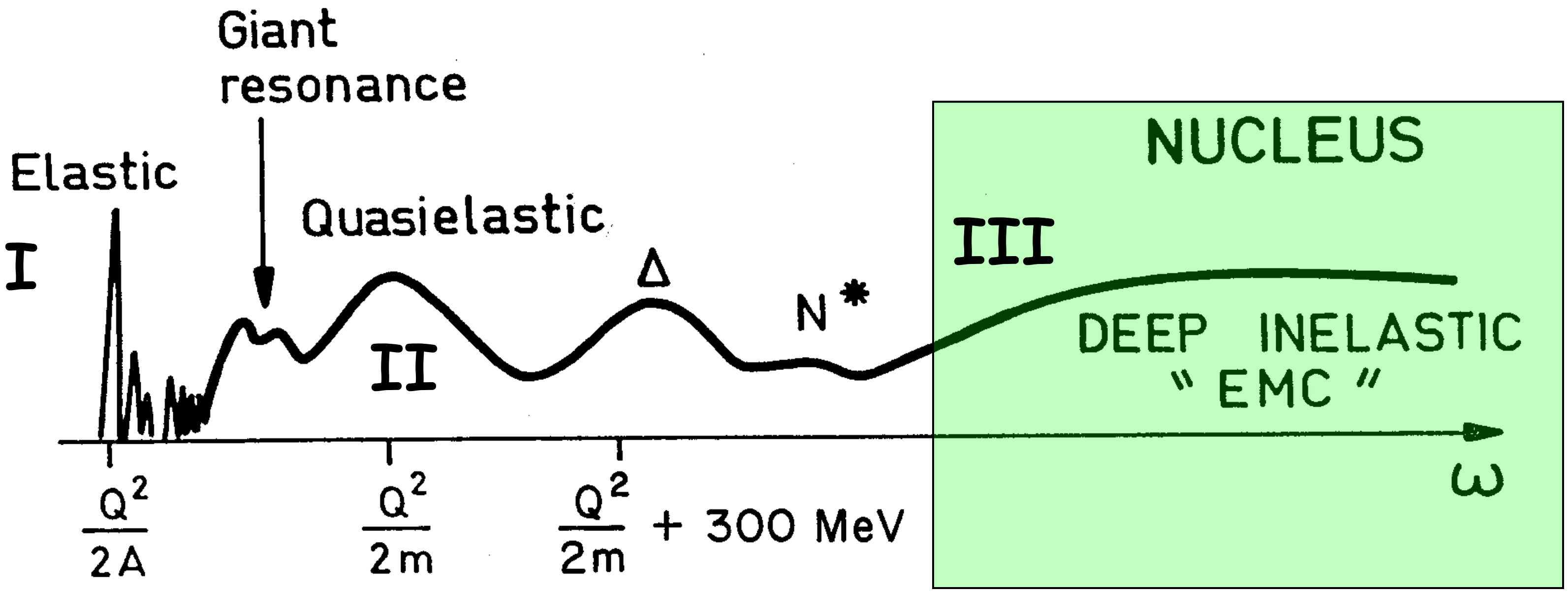

R. Cruz-Torres, D. Nguyen, PRL(2020).
R. Cruz-Torres PLB (2019).

*See Ronen's talk*

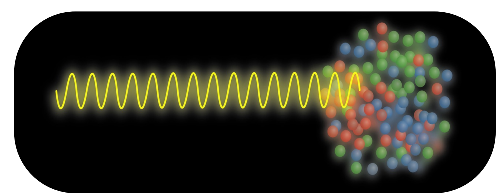
# Quasi-elastic Summary

- Measures shell structure directly
- Provide information on nucleon momentum distribution
- Nucleon went missing, provide the hint to SRCs
- Measurement on light nuclei benchmark theory calculation up to high momentum 500 MeV

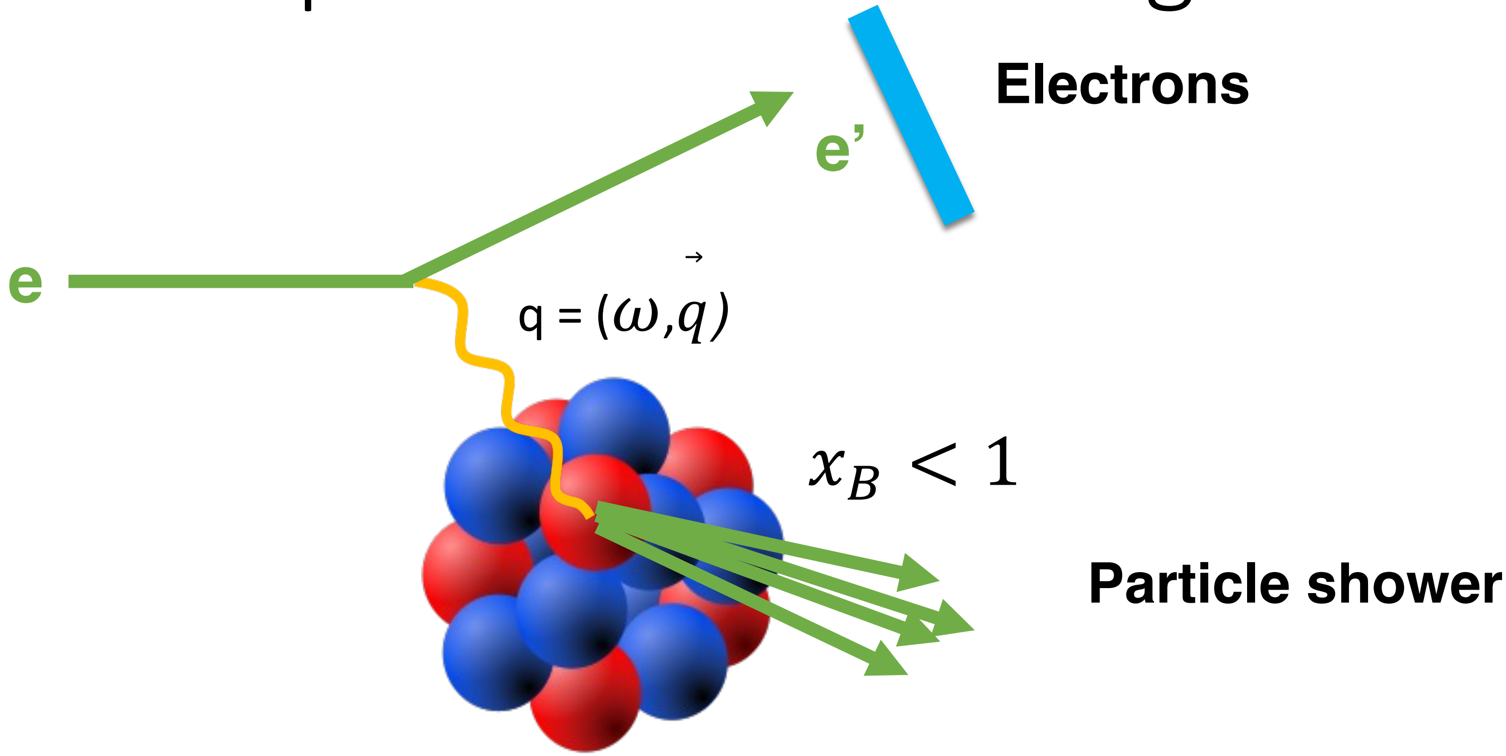
# Overview: Deep Inelastic Scattering (DIS)




- ❑ Structure Functions
- ❑ EMC Effect



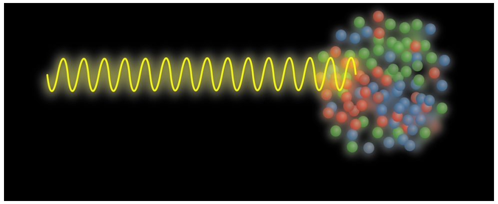
# Deep Inelastic Scattering

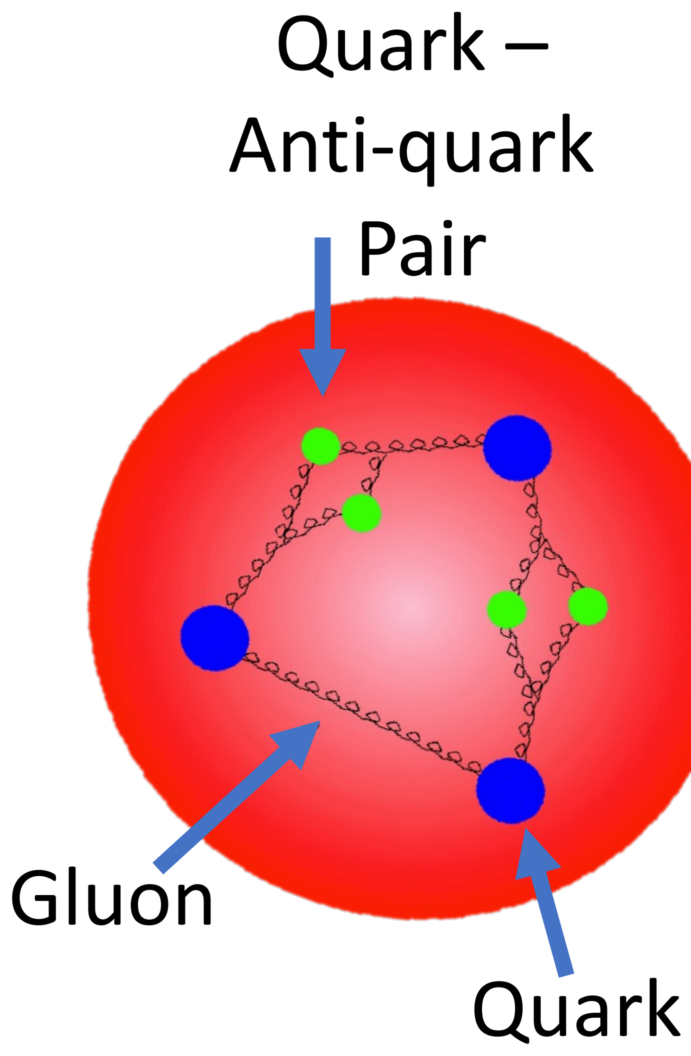



- Interacting nucleon destroyed
- Interaction with Parton (quark) inside the nucleon
- Cross-section depends on **Nucleon structure function $F_2$**

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

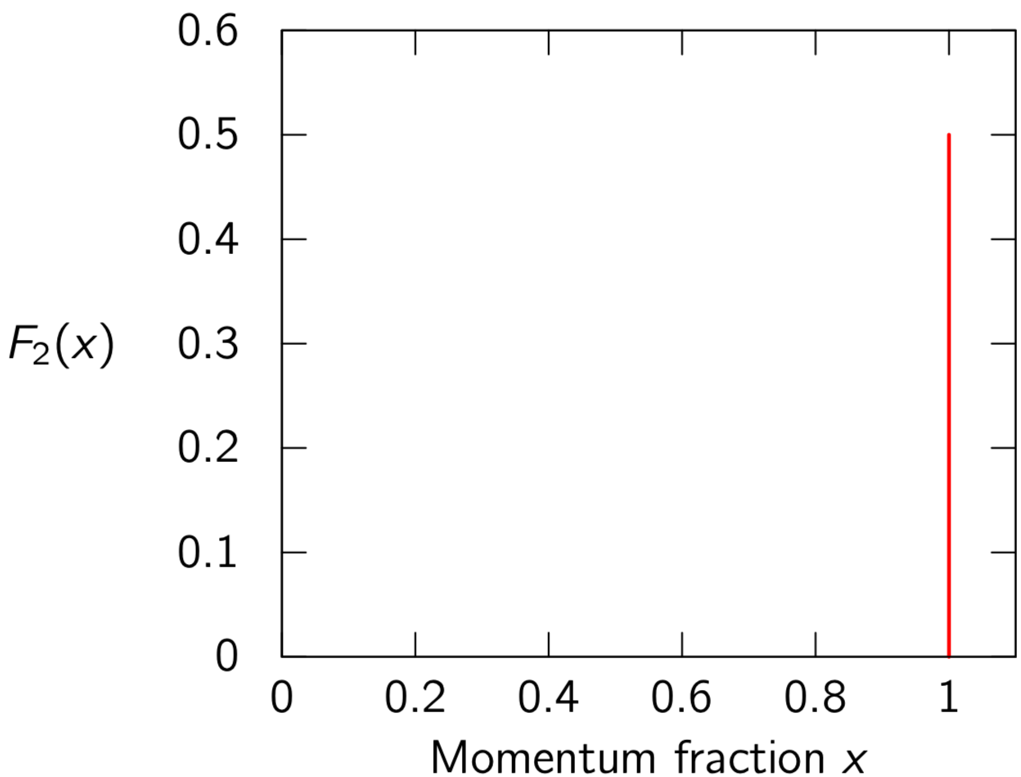
# Partonic Structure



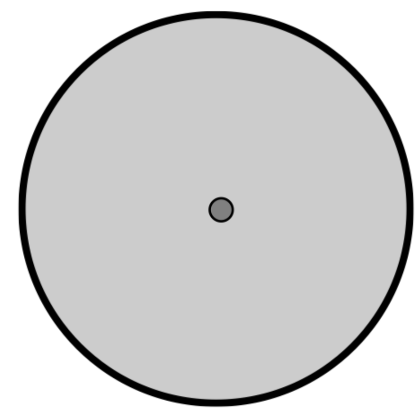


# What $F_2$ can tell us about the nucleon

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




A quark



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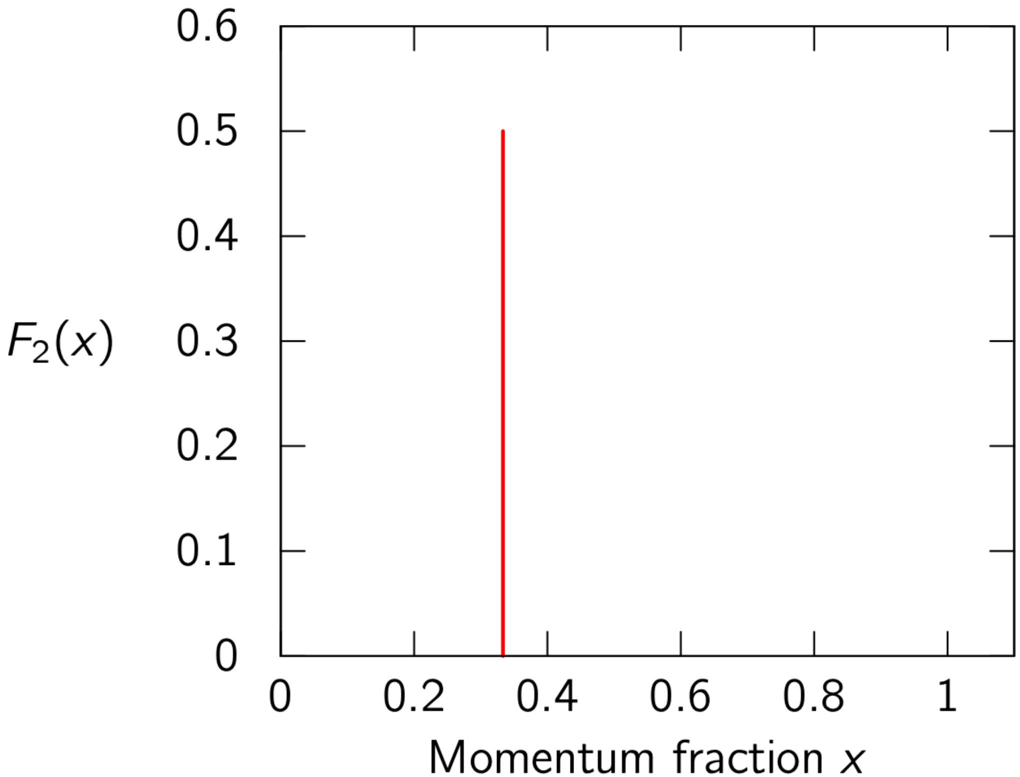
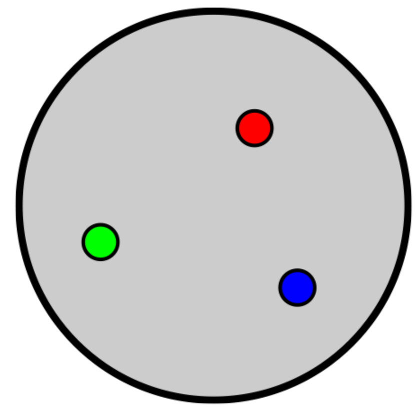



Three valence quarks



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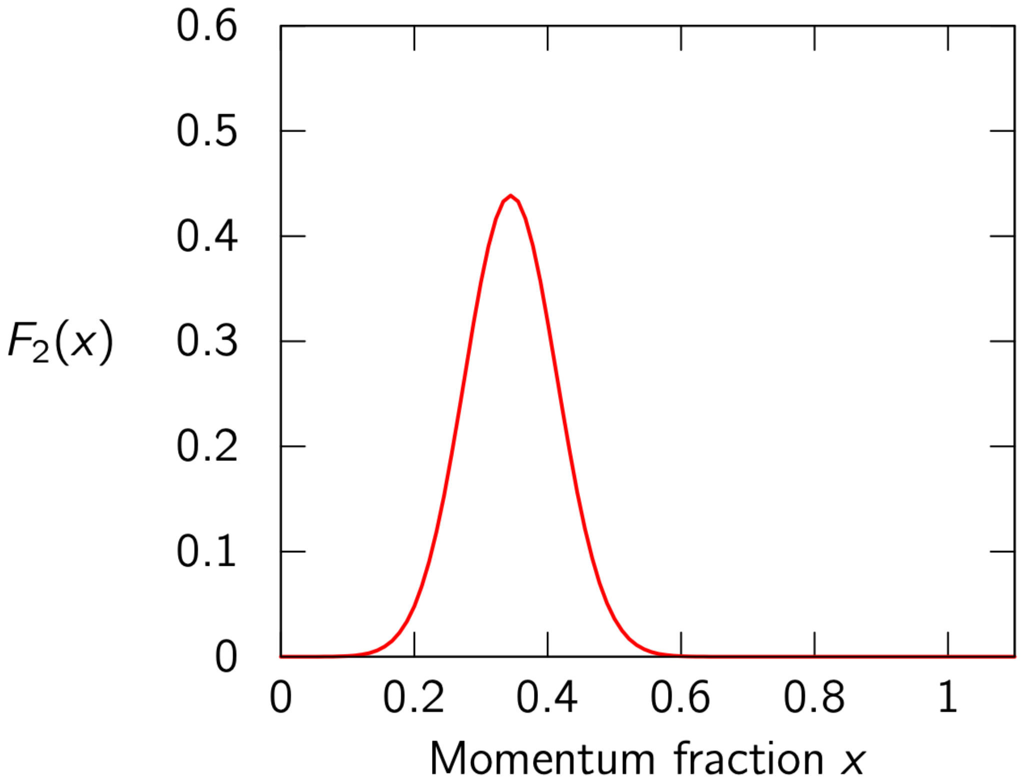
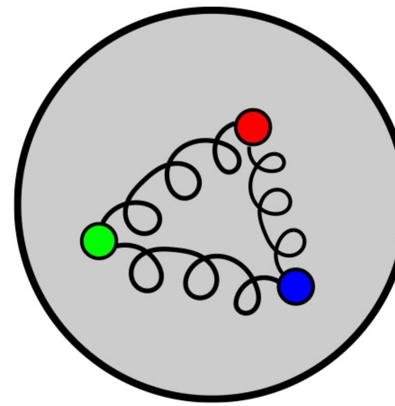
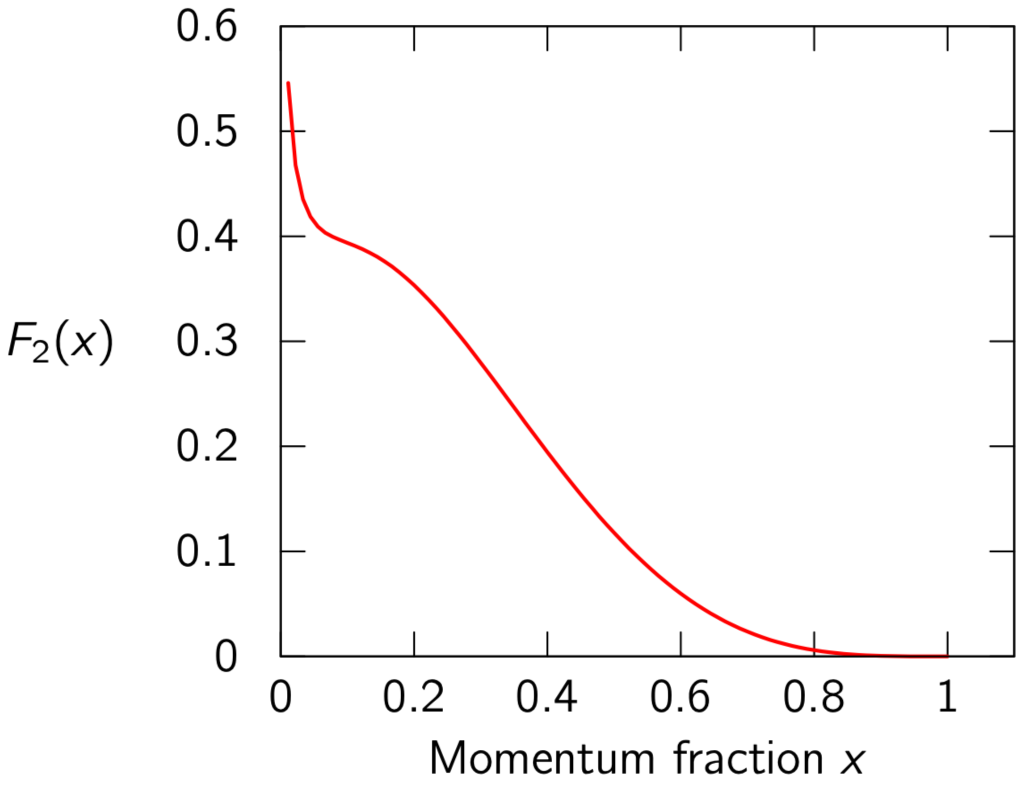


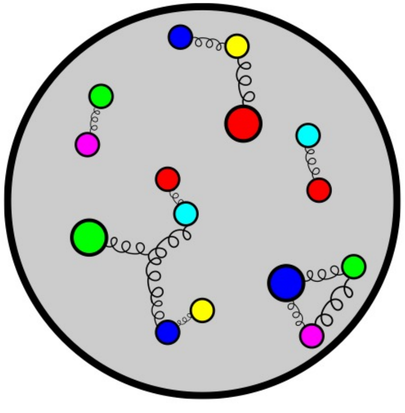

Three bound valance quarks



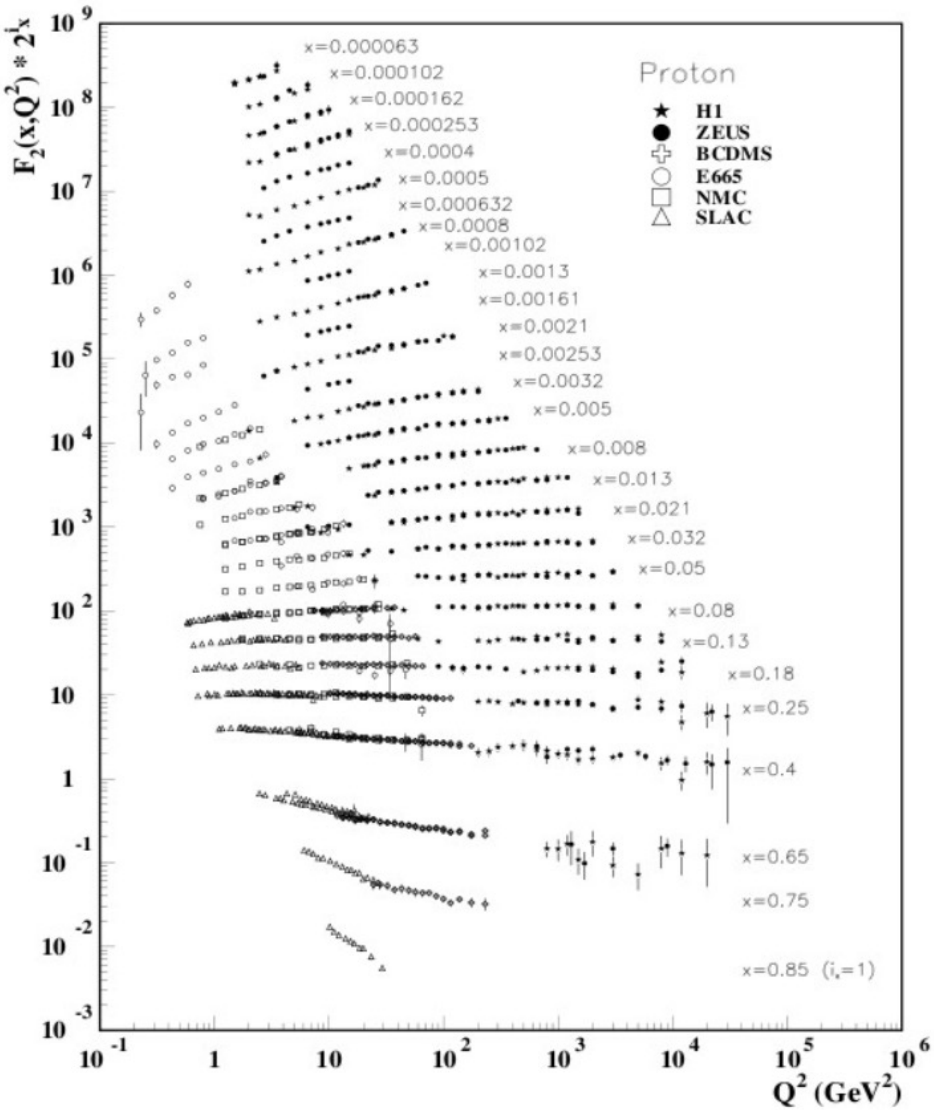
# What $F_2$ can tell us about the nucleon

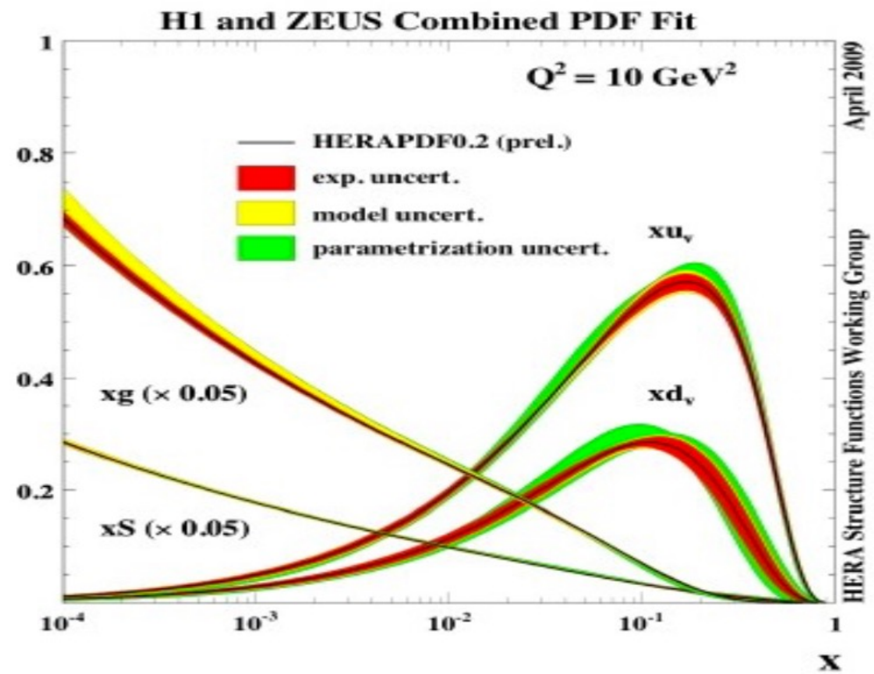
$$F_2\left(x,Q^2\right)=\sum_i e_i^2 \cdot x \cdot f_i(x)$$



# Decade of measurement gives us Proton's $F_2$ and PDFs



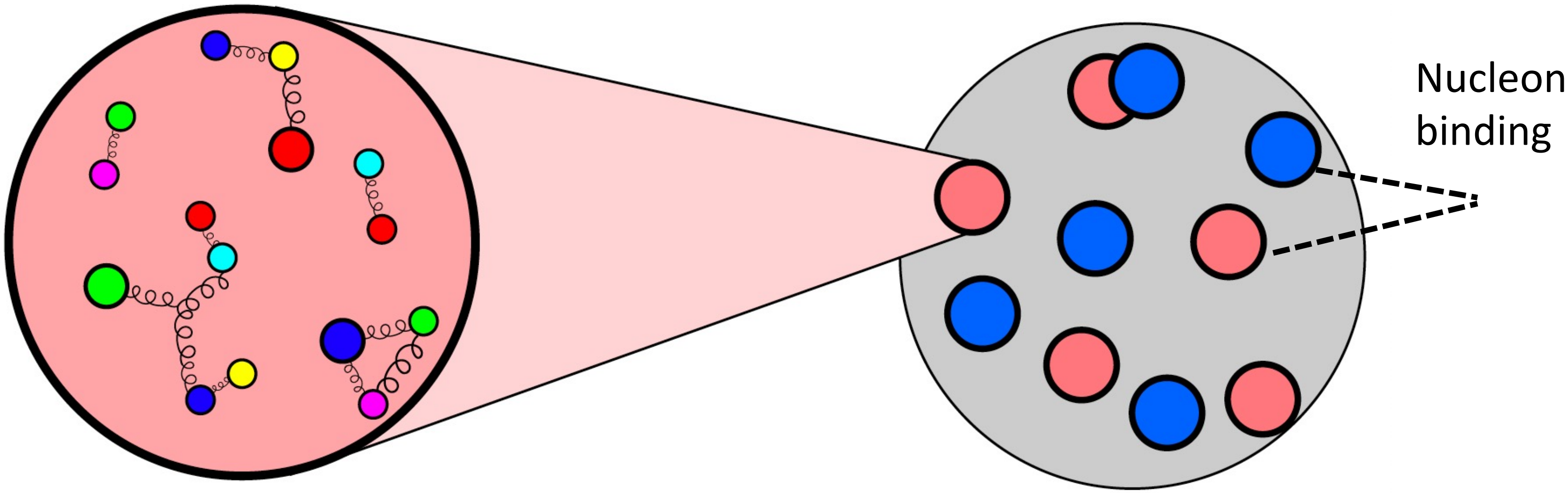
# What is $F_2$ for a nucleus A

$$F_2^A = Z\,F_2^P + N\,F_2^N\;??$$

Questions:

1. Do quarks move differently in Nuclei?
2. Does the nuclear environment affect quark?

# Quark and Nuclei are scale-separated




The scale of GeV

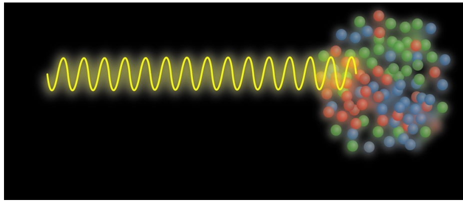
The scale of MeV

**Naive expectation :**

**Bound nucleon = Free nucleon**

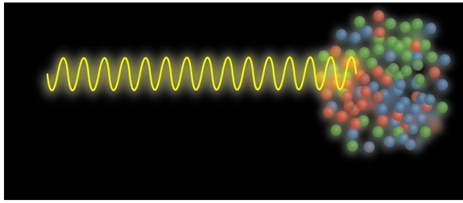
(Except some small Fermi motion correction)

# Partonic – Nucleonic Interplay



**<u>Question:</u>** What is the <u>*simplest*</u> example of nuclear interaction affecting partonic properties?

# Partonic – Nucleonic Interplay



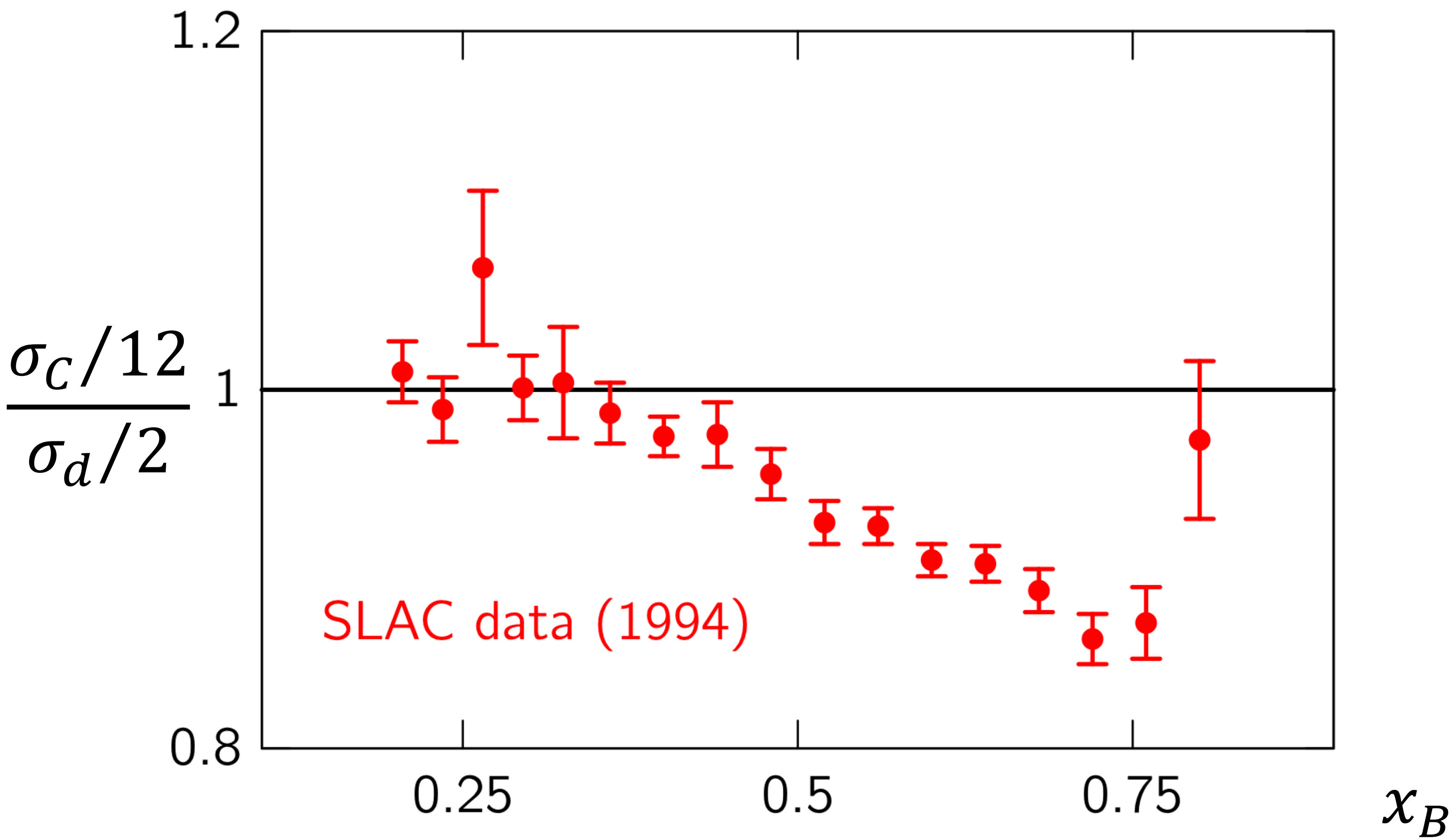
**<u>Question:</u>** What is the *<u>simplest</u>* example of nuclear interaction affecting partonic properties?

**<u>Answer:</u>**

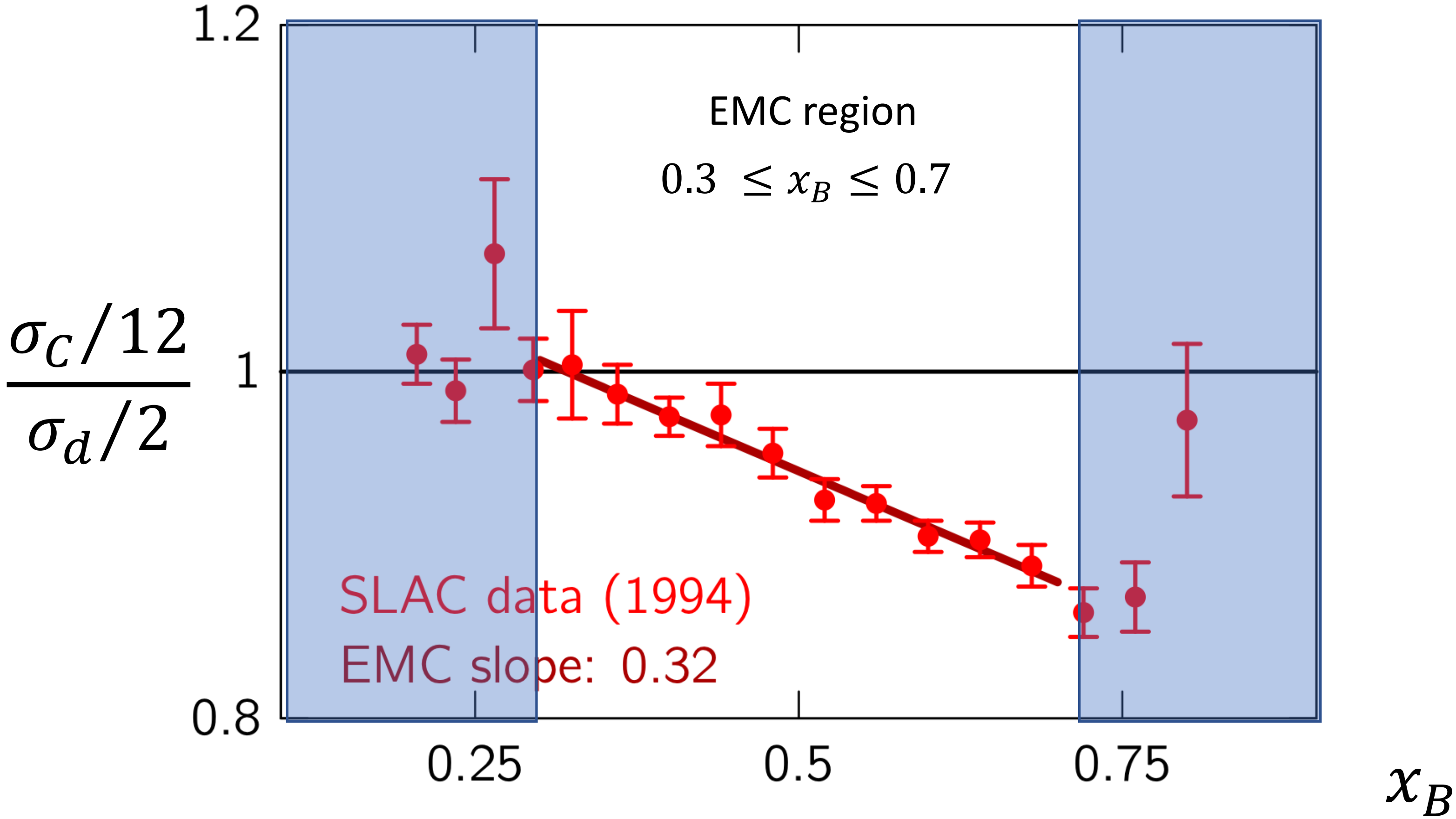
**The nuclear interaction that binds the deuteron also makes the neutron stable.**

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

# The nuclear environment affects quarks!



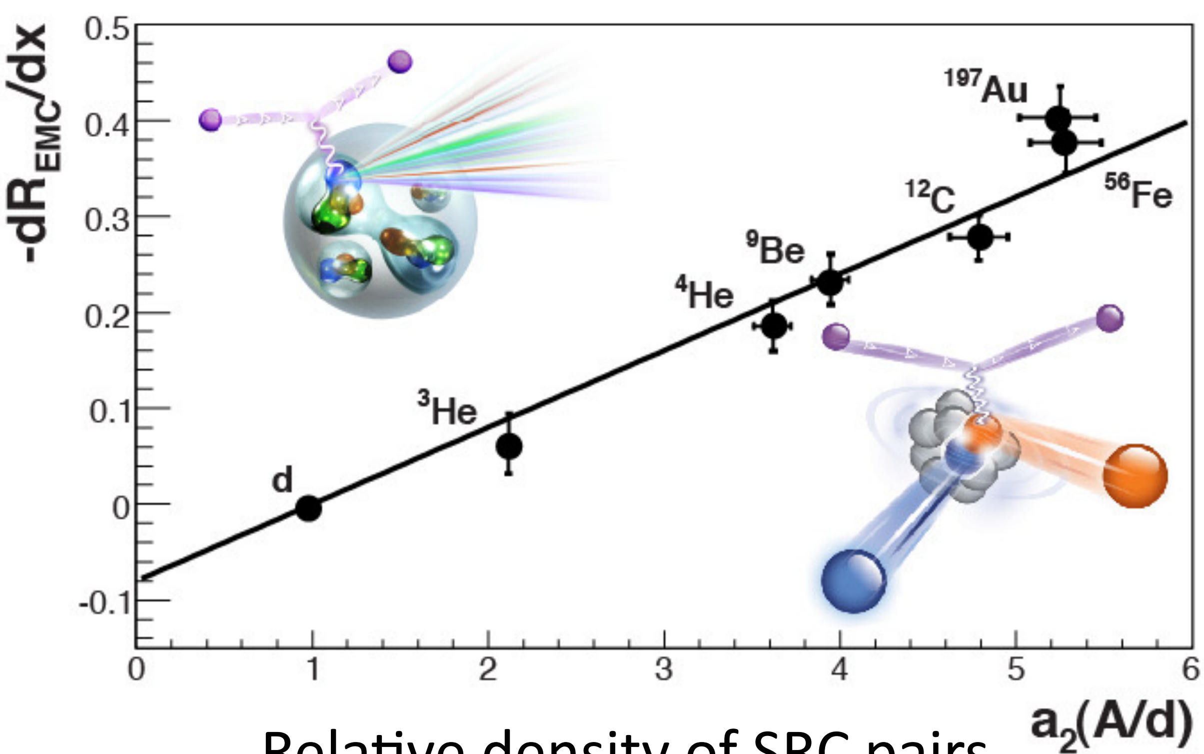
# The EMC effect!




- Size of EMC effect is characterized by the slope

# The frequency of SRC pairs correlates with the strength of the EMC Effect.

Magnitude of the EMC Effect



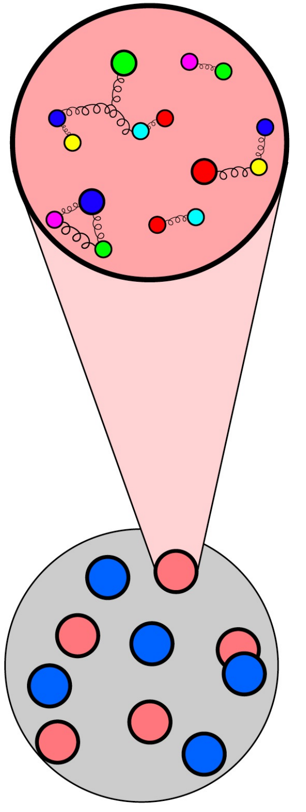

Relative density of SRC pairs

*More on this in next lectures*

Weinstein et al., PRL 106, 052301 (2011)
Hen et al., PRC 85, 047301 (2012)
Arrington et al., PRC 68, 065204 (2012)

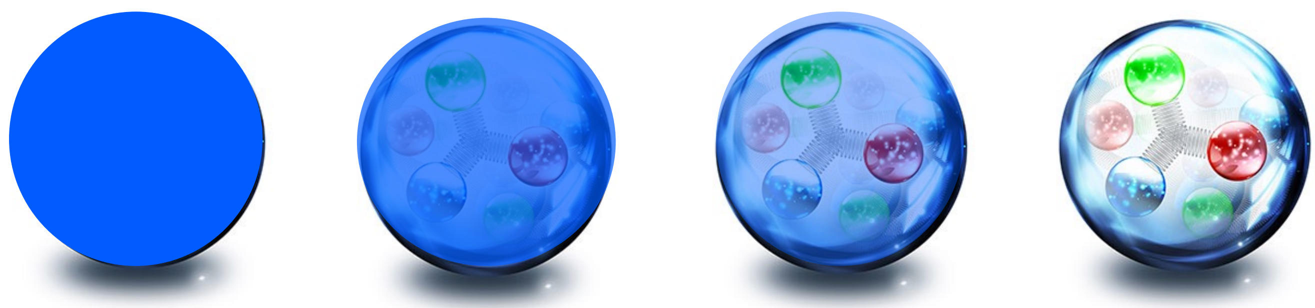
# Deep inelastic scattering summary

- DIS is scattering from a quasi-free quark.
- Structure functions contain the quark momentum density information.
- Bridging between nucleon and parton regiem
- EMC Effect:
  - Bound nucleon # free nucleon
  - Many models try to explain the data.
  - Many experiments try to understand the problem.
  - Hint in correlation EMC vs SRC



# 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