Understanding The Structure of Nucleons

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Physics Seminar

Juniata College

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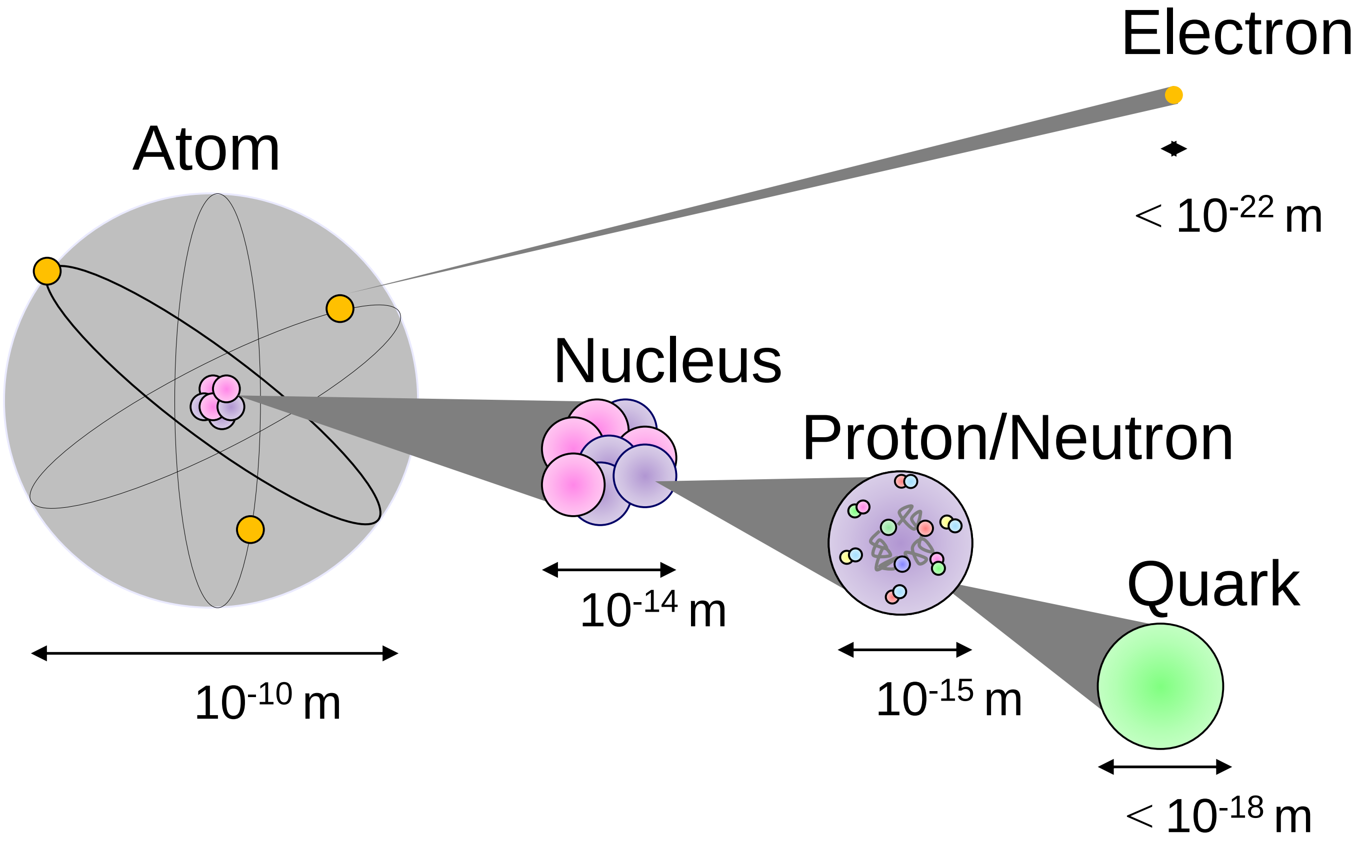
University of New Hampshire

Today's Discussion

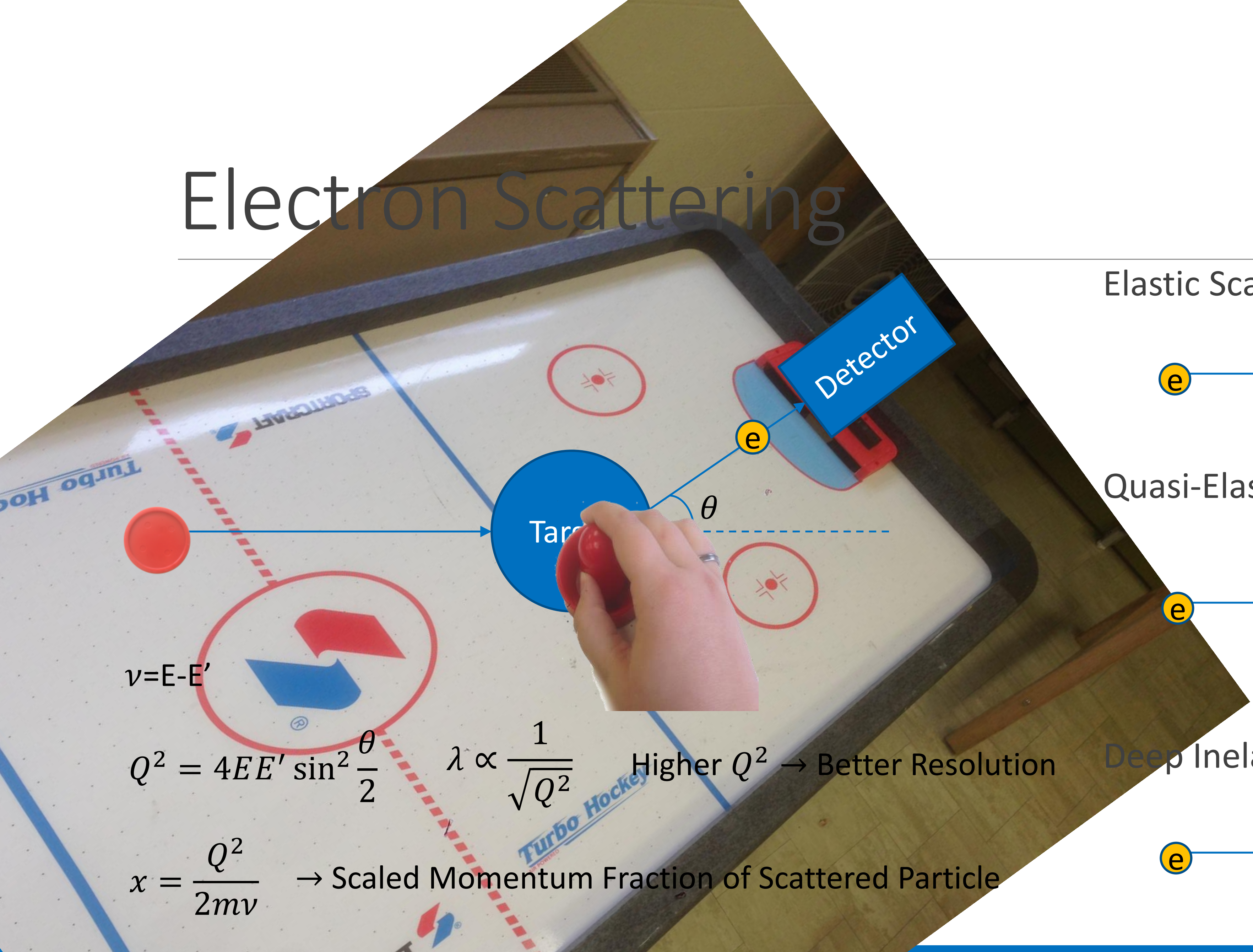
- The Structure of Matter – A Brief Overview
- Electron Scattering Experiments
- Nucleon Structure:
  - Electromagnetic Form Factors
  - Structure Functions
  - The Future through Tensor Polarization

The Structure of Matter



A sense of scale: http://htwins.net/scale

Electron Scattering



ν=E-E'

$$Q^2 = 4EE'\sin^2\frac{\theta}{2}$$

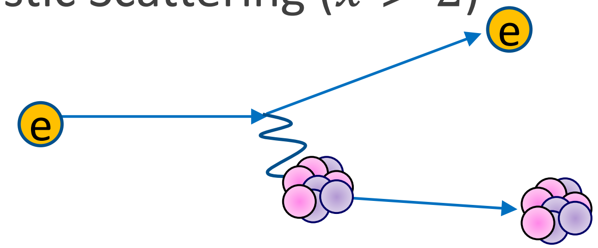
$$\lambda \propto \frac{1}{\sqrt{Q^2}}$$

Higher Q^2 → Better Resolution

$$x = \frac{Q^2}{2m\nu}$$

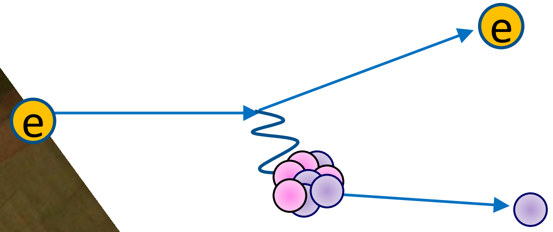
→ Scaled Momentum Fraction of Scattered Particle

Elastic Scattering ($x > 2$)



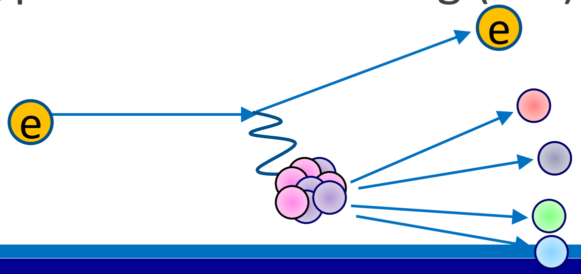
Probes Nuclear Effects

Quasi-Elastic Scattering (QE) ($x \sim 1$)



Probes Nucleon Effects

Deep Inelastic Scattering (DIS) ($x < 0.7$)



Probes Quark Effects

Electron Scattering at Jefferson Lab

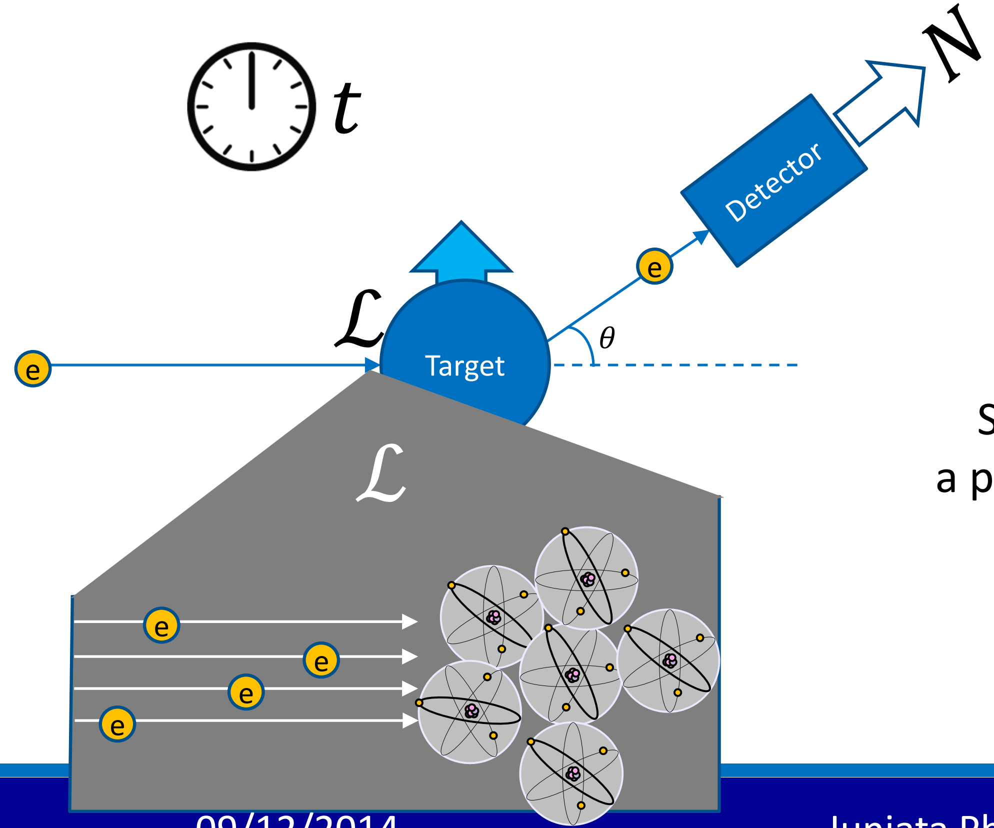
- Fixed target electron accelerator
- Almost completed 12 GeV upgrade
- World leader in polarized beam and polarized targets
- Mission includes: “To deliver discovery-caliber research by exploring the atomic nucleus and its fundamental constituents, including precise tests of their interactions”

Electron Scattering – Measuring Structure

Scattering electrons from nuclei (consisting of protons and neutrons)

We measure the cross section, which can be thought of as normalized counts $(N = \mathcal{L}t\sigma)$

$$\left(\sigma = \frac{N}{\mathcal{L}t}\right)$$



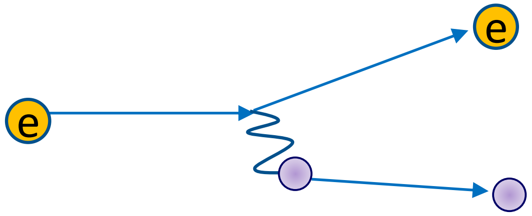
$$\sigma = \sigma_{\text{Mott}} \boxed{\left[\frac{Q^2}{4M^2} G_M^2(Q^2) + \epsilon G_E^2(Q^2)\right]}$$

Scattering from
a point-like nucleon

Deviation from
a point-like nucleon

With polarized spins, can also measure asymmetries

$$A = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \sim \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$



Electromagnetic Form Factors

Scatter electrons from a proton or a neutron

$$\sigma = \sigma_{\text{Mott}}\left[\frac{Q^2}{4M^2}G_M^2(Q^2) + \epsilon G_E^2(Q^2)\right]$$

Scattering from
a point particle

Deviation due
to magnetic moment
distribution

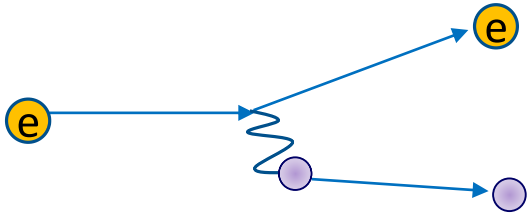
Deviation due
to charge distribution

At $Q^2 = 0$,

- $G_M^p \rightarrow \mu_p$ $\qquad G_M^n \rightarrow \mu_n$
- $G_E^p \rightarrow 1$ $\qquad G_E^n \rightarrow 0$

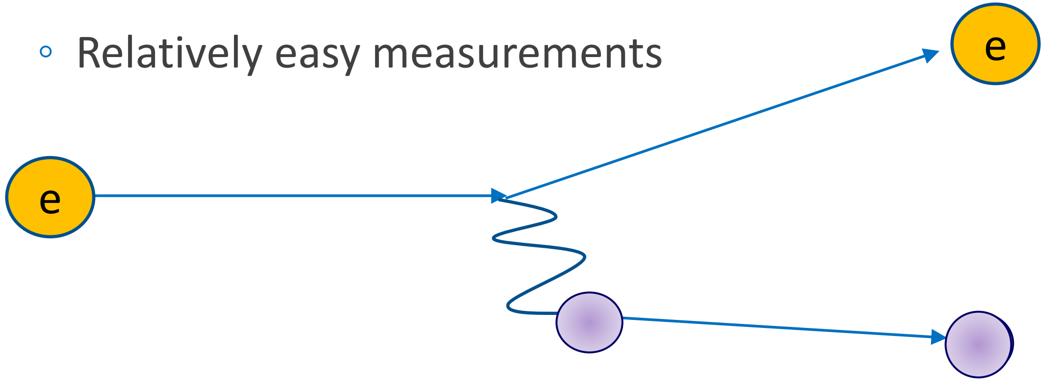
Higher Q^2 → Better Resolution

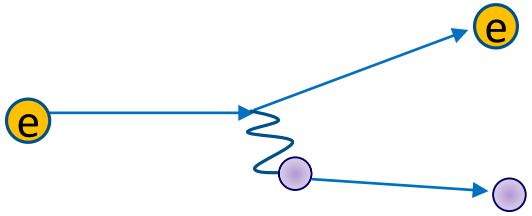
Changes with Q^2 indicate substructure



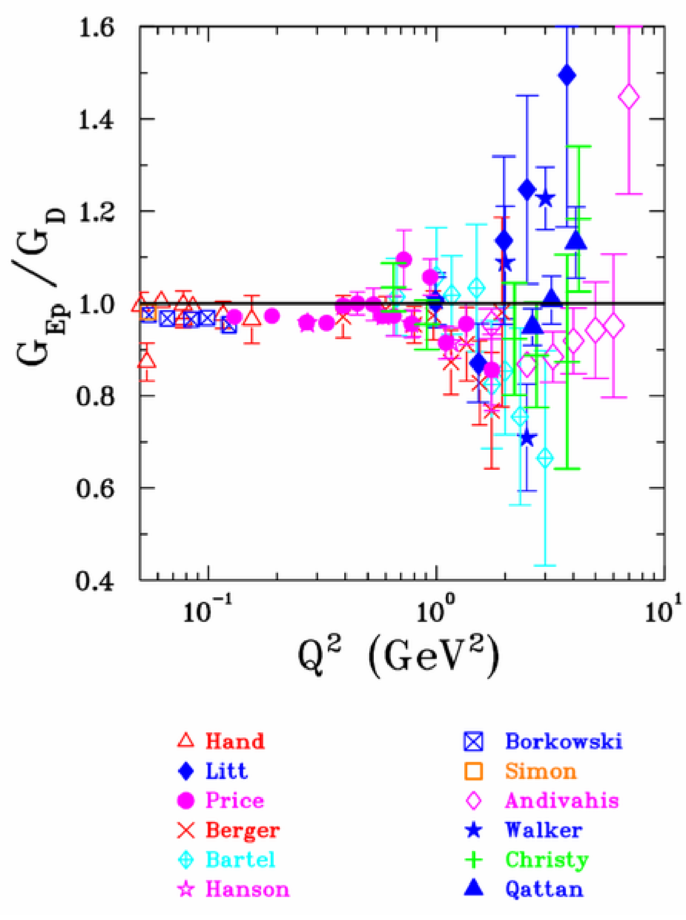
Proton Form Factors

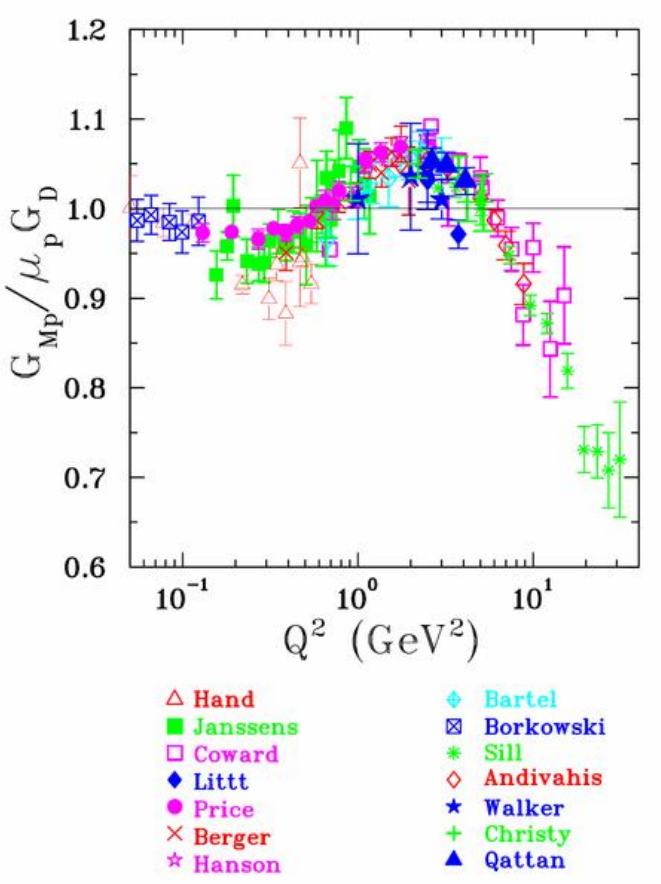
- Free proton targets available – ^{1}H
- Protons are charged, so normal spectrometers can isolate them
- Counting number of particles detected gives the cross section
- Since two unknowns (G_E^p and G_M^p), take two measurements to solve for them
- Relatively easy measurements

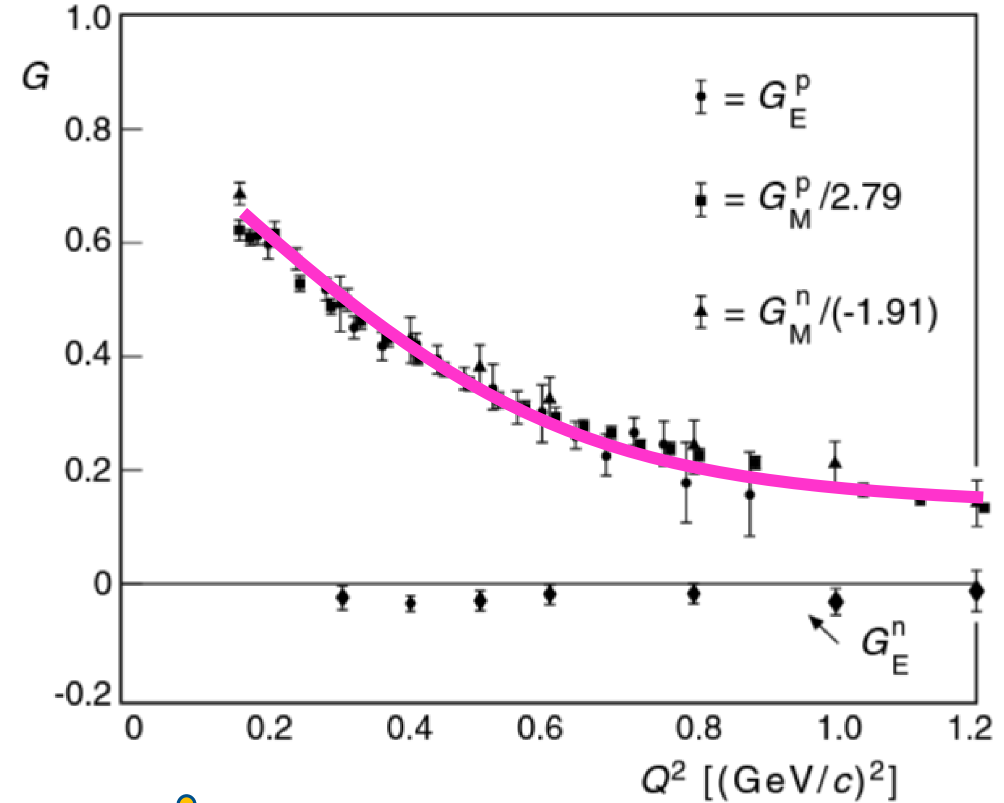


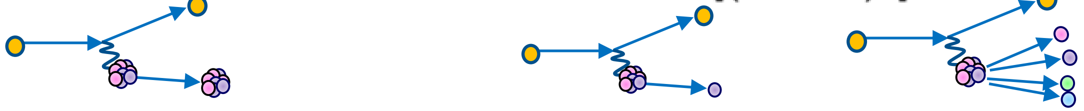


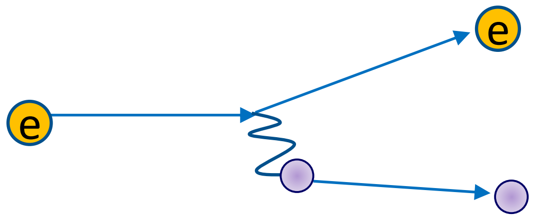
Proton Form Factors – World Data











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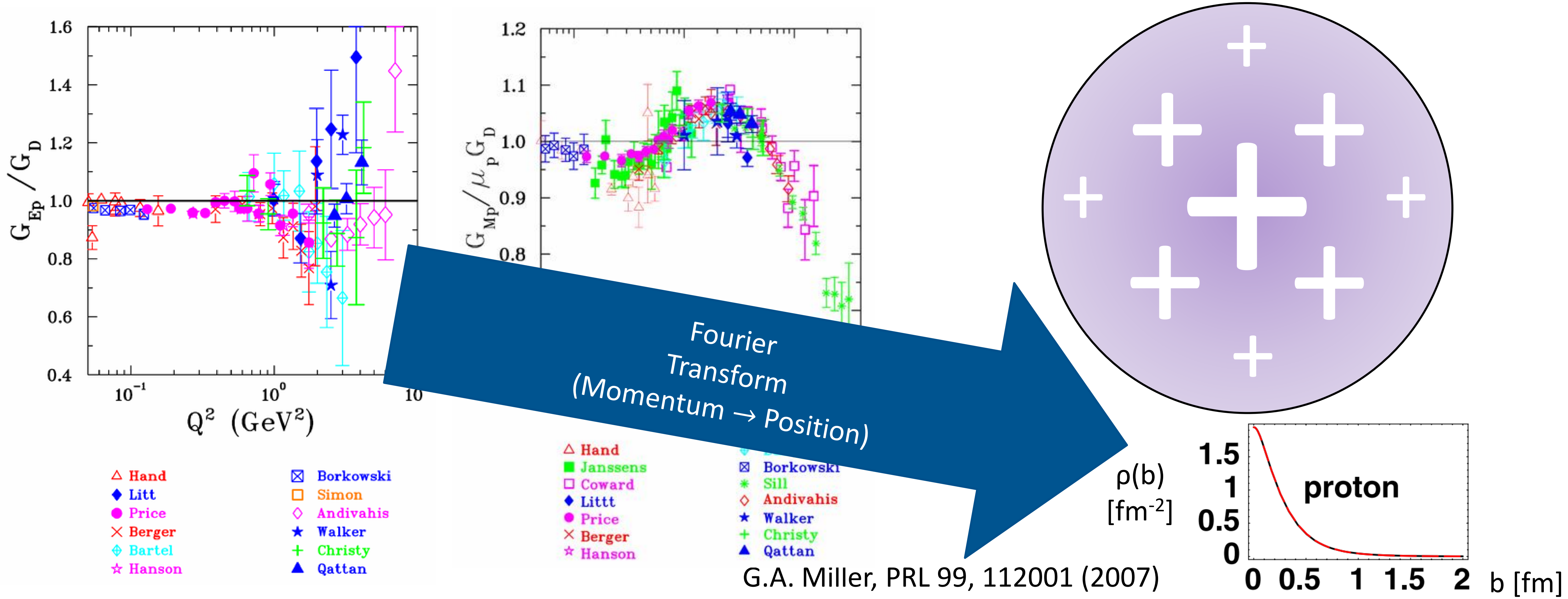
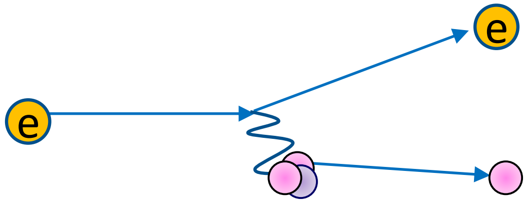


Fourier Transform (Momentum → Position)

G.A. Miller, PRL 99, 112001 (2007)



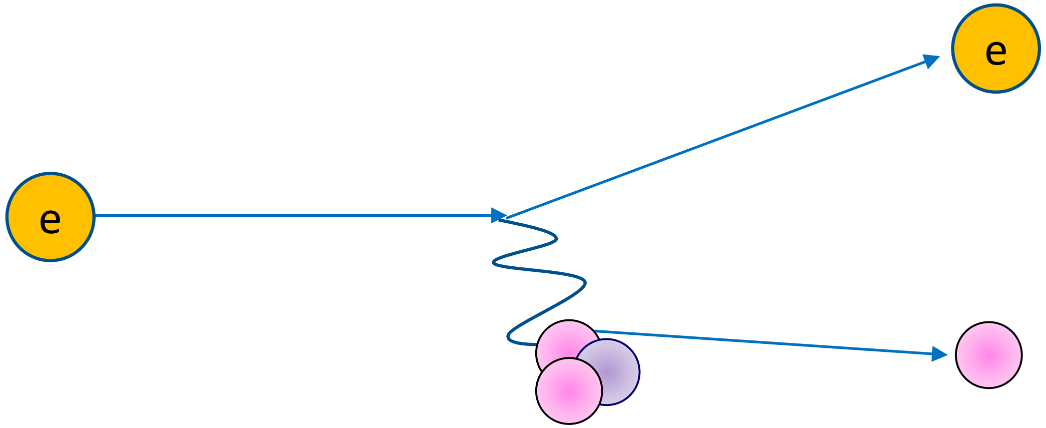
Neutron Form Factors

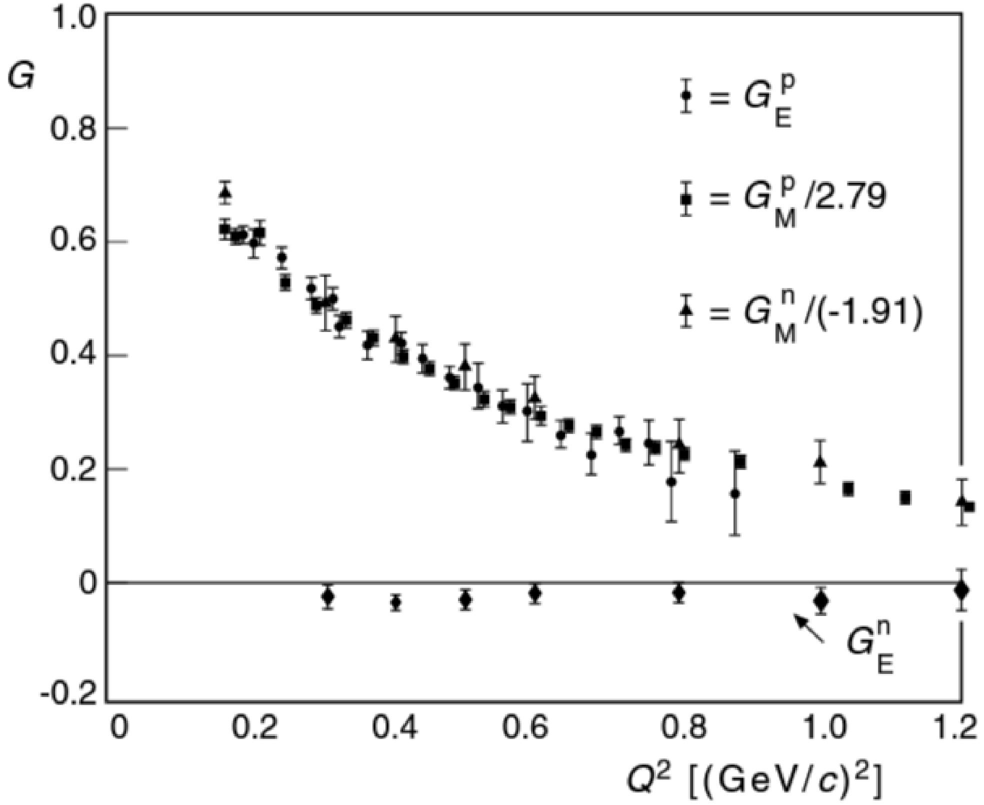
Electric form factor is much smaller

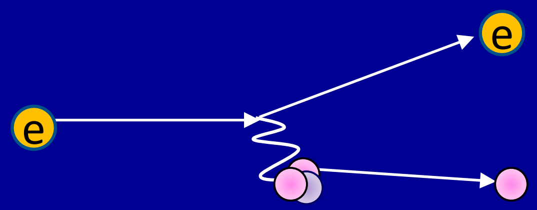
No free neutron target is available

- Requires small-nuclei targets, such as ^2H or ^3He

Neutrons, being neutral, cannot be directly detected using standard spectrometers

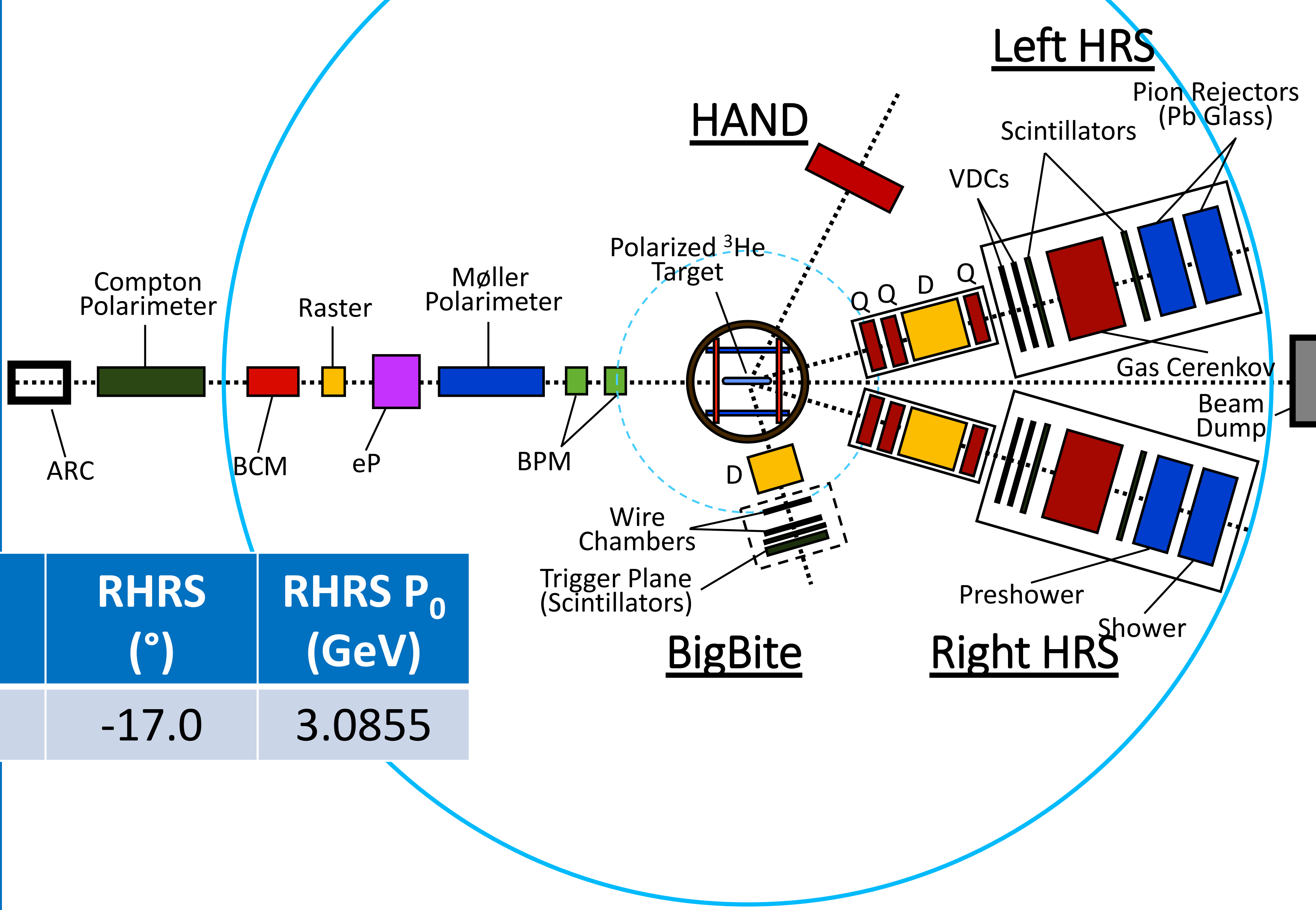




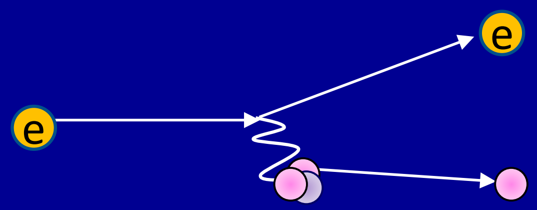


Neutron Form Factor, G_E^n Measurement

JLab's Hall A



Target Pol.	Q^2 $(\mathrm{GeV}/c)^2$	E_0 (GeV)	RHRS (°)	RHRS P_0 (GeV)
Vertical	0.95	3.605	-17.0	3.0855



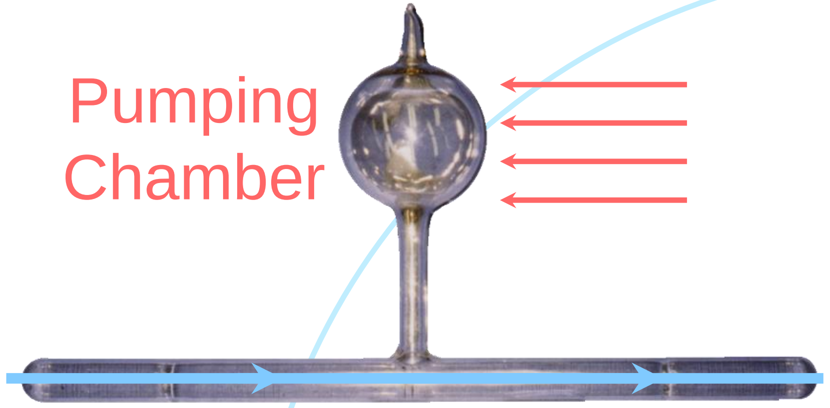
Neutron Form Factor, G_E^n Measurement

Polarized ^{3}He Target

- Optically pumped Rb and K vapor used to polarized ^{3}He via spin exchange (SEOP)
- NMR and EPR used to measure P_t
- N present in cell to absorb photons from spin-exchange

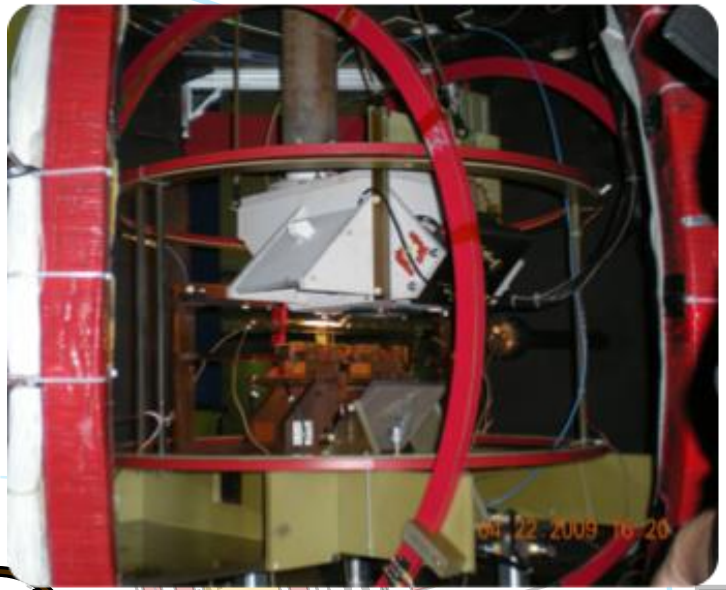
$$D_N = \begin{array}{l} 5.3 \pm 0.8\% \text{ at } Q^2 = 0.1 \\ 2.4 \pm 0.3\% \text{ at } Q^2 = 0.5 \\ 2.8 \pm 1.2\% \text{ at } Q^2 = 1.0 \end{array}$$

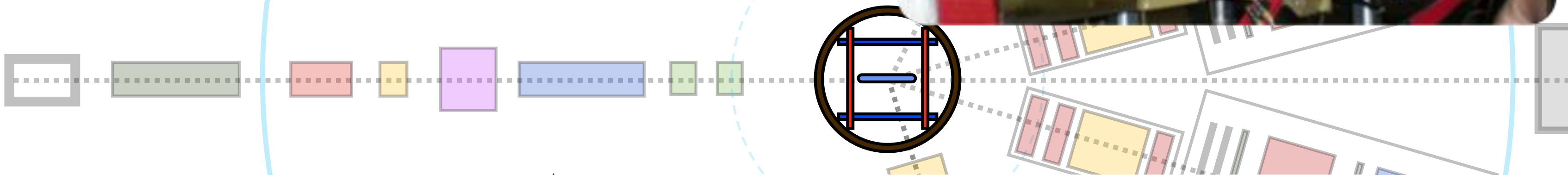
- Achieved P_t of $51.4 \pm 0.4 \pm 2.8$ %
- Details in Y. Zhang, Ph.D. Thesis, Rutgers, 2013

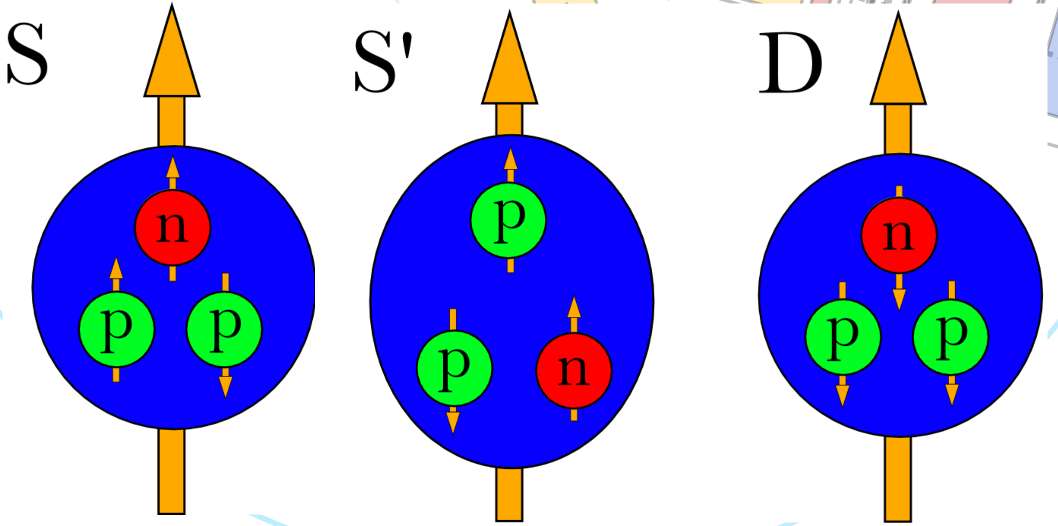


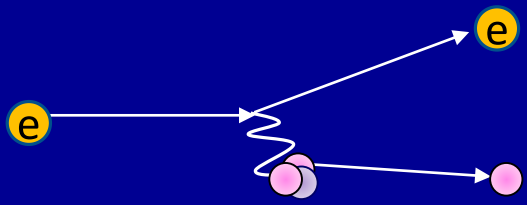
Pumping Chamber

Target Chamber
(Nuclear Physics Happens Here)





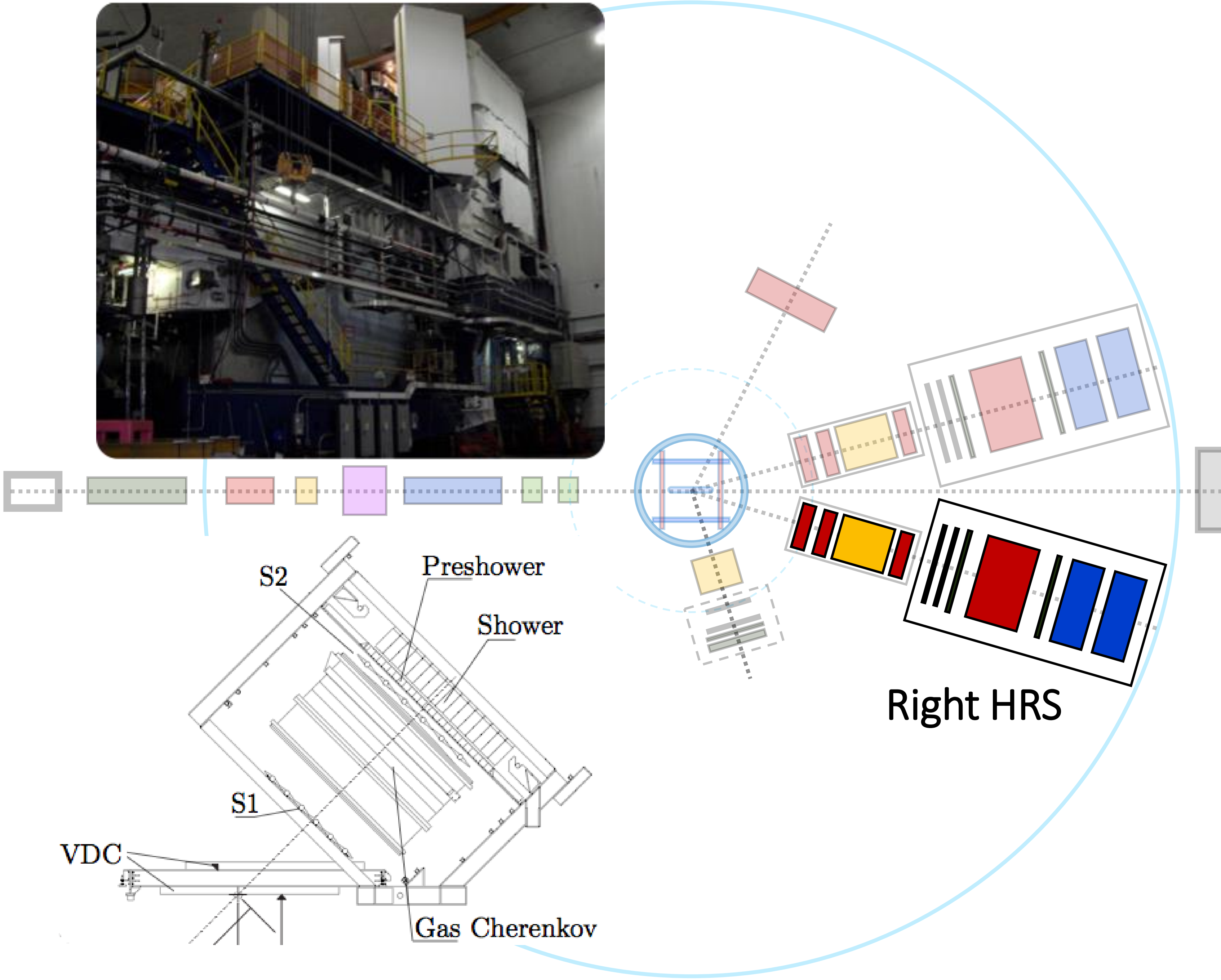


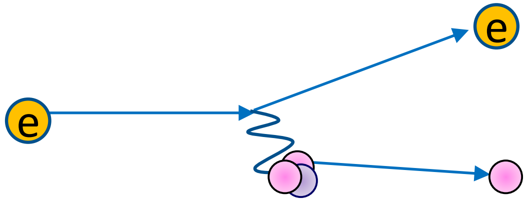


Neutron Form Factor, G_E^n Measurement

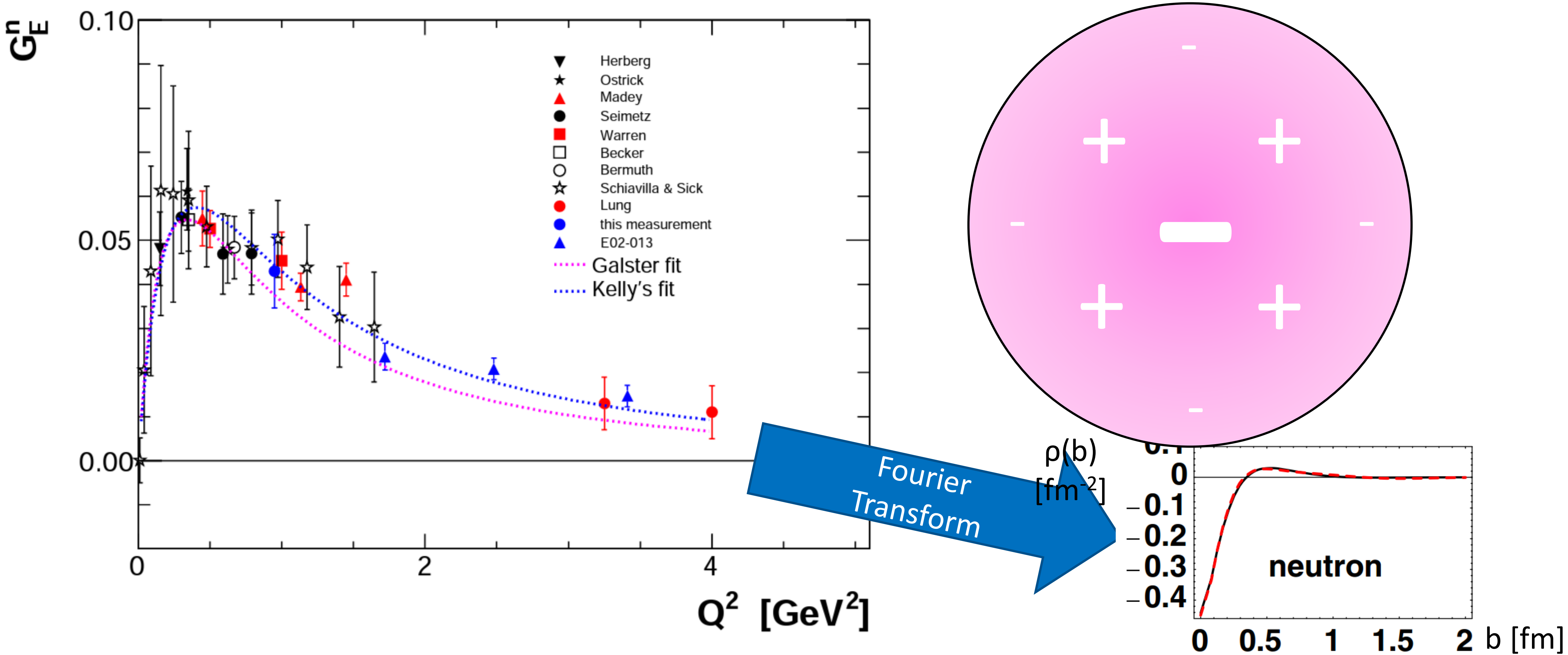
Right HRS

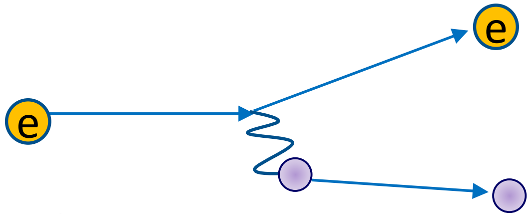
- Detected scattered electrons from ^{3}He($e,e'n$) and ^{3}He(e,e')
- Detector package included VDCs, trigger scintillators, gas Cherenkov, and lead-glass calorimeters

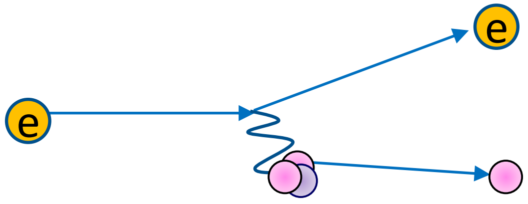




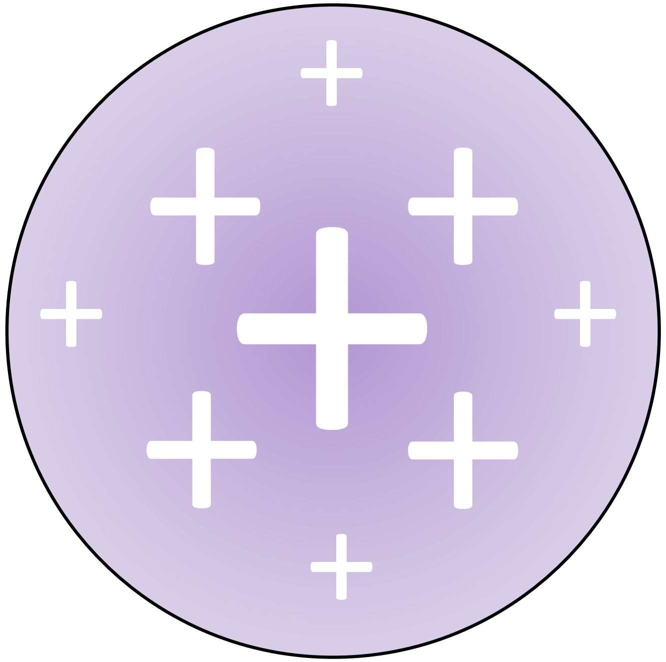
Neutron Form Factors – World Data



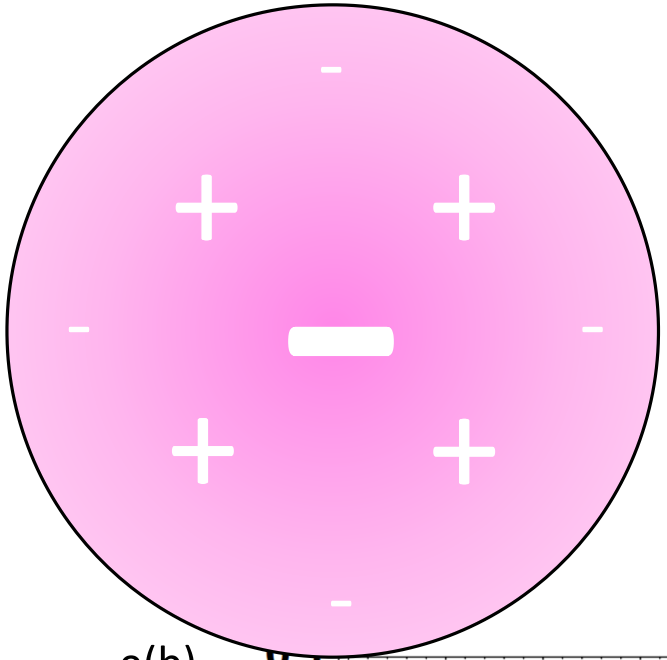


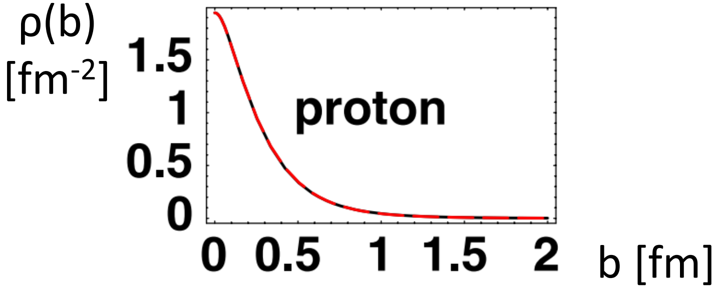


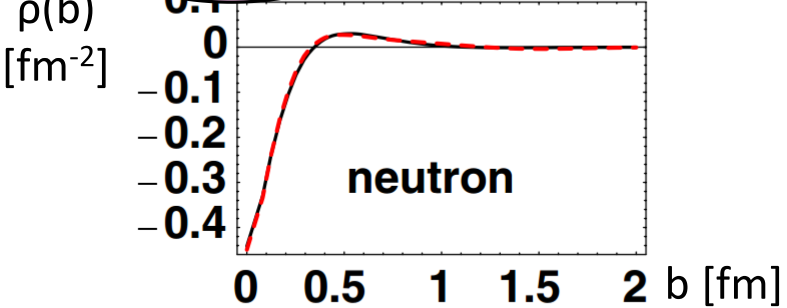
Electromagnetic Form Factors

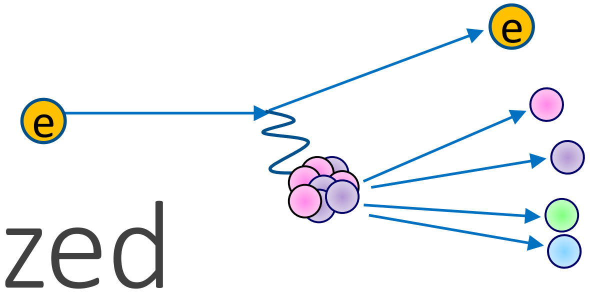


Constituents of nucleons are charged particles









Structure Functions - Unpolarized

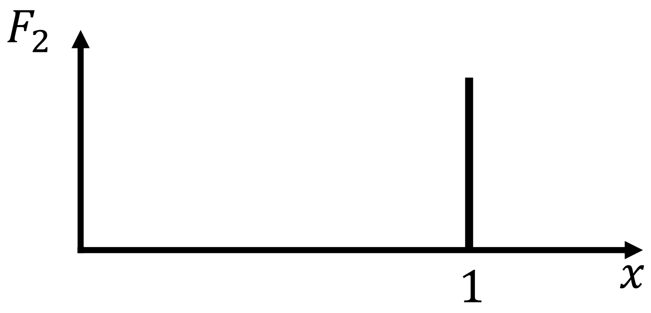
Structure functions describe deviations from point-like structure

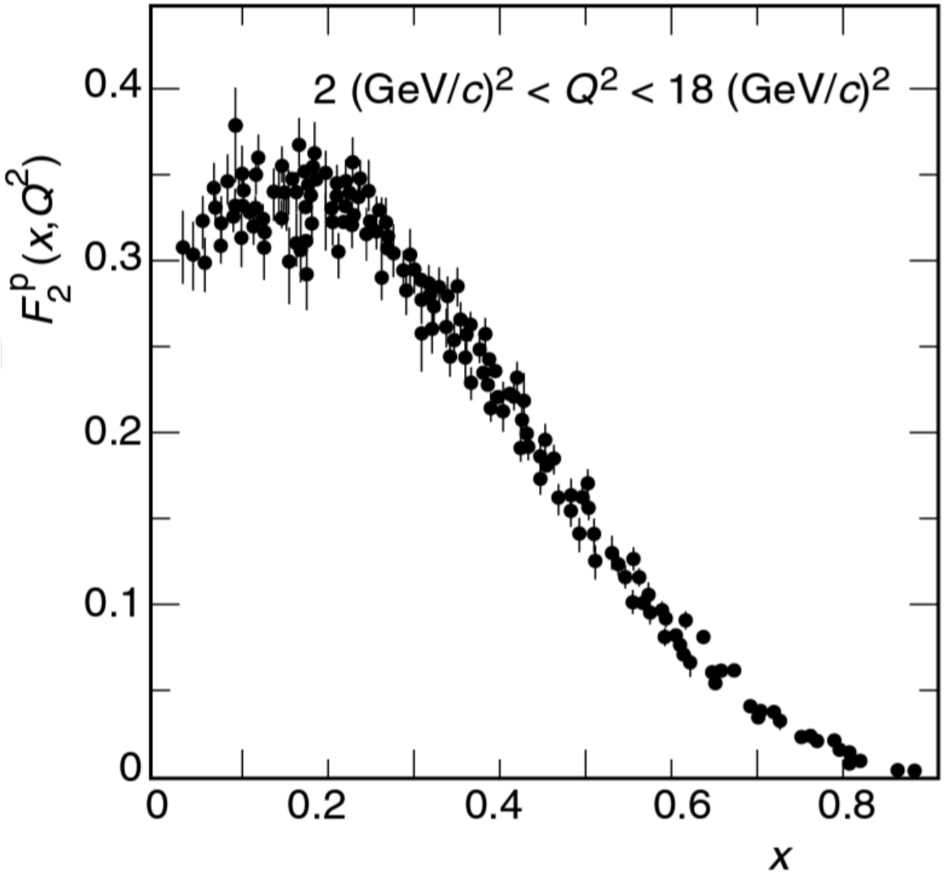
$$\sigma = \sigma_{\text{Mott}} \boxed{\left[\frac{2}{Mc^2}F_1(x,Q^2)\tan^2\frac{\theta}{2} + \frac{1}{\nu}F_2\,(x,Q^2)\right]}$$

Scattering from a point-like nucleon

Gives insight to proton substructure

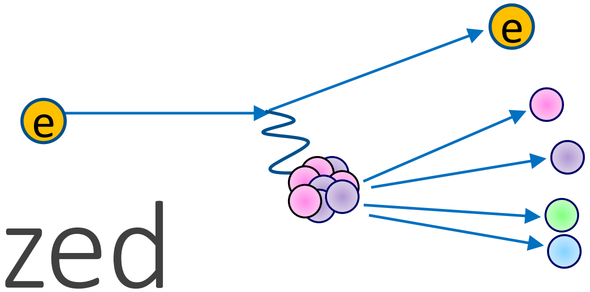
Deviation fro
a point-like nuc





F. Halzen and A. Martin, *Quarks and Leptons*

B. Povh *et al*, *Particles and Nuclei*



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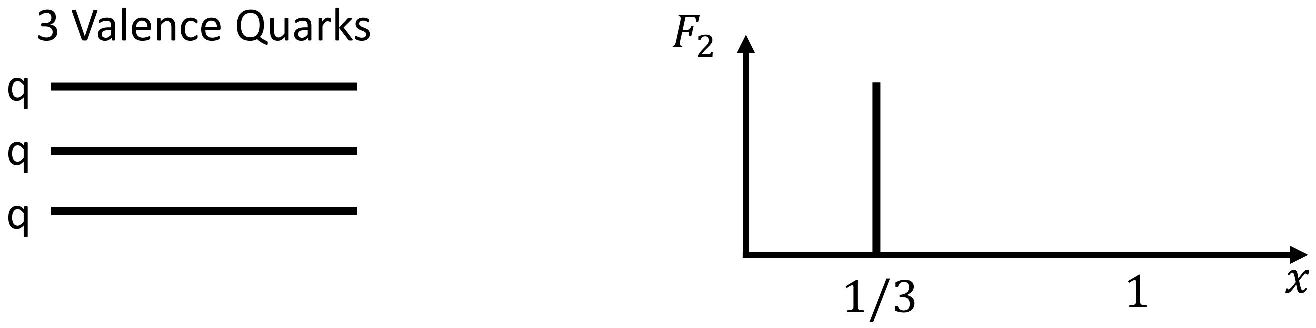
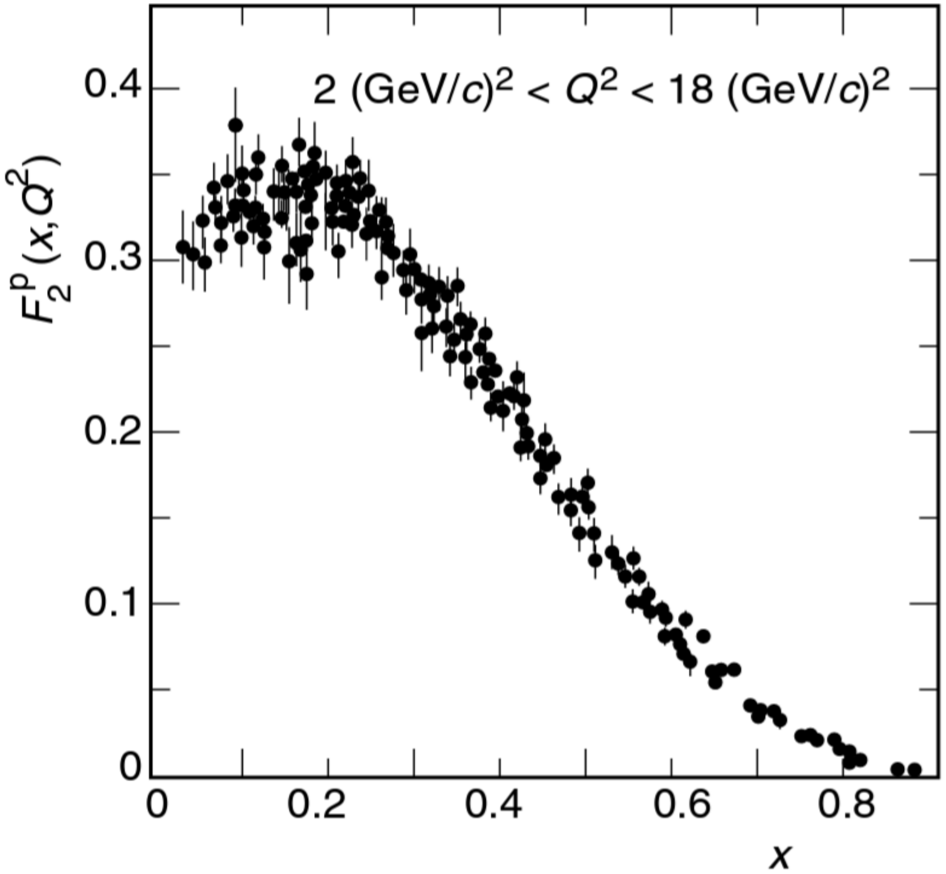
Gives insight to proton substructure





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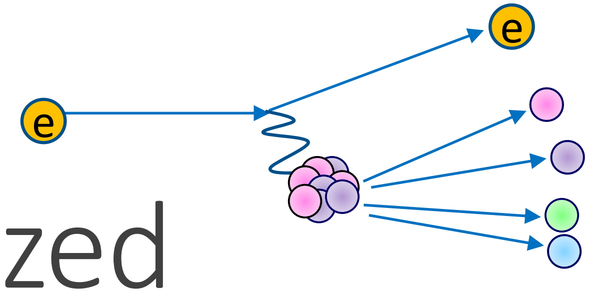

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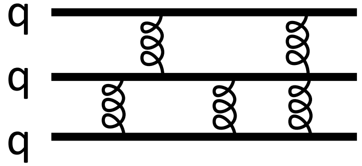
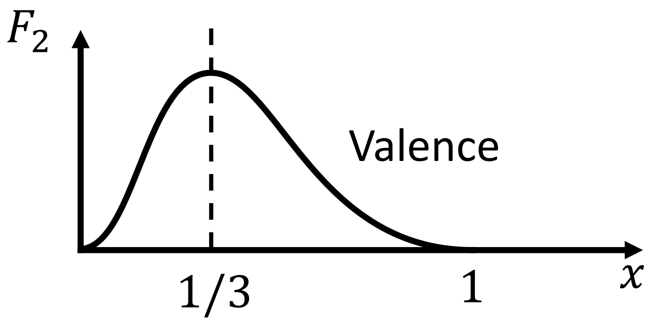
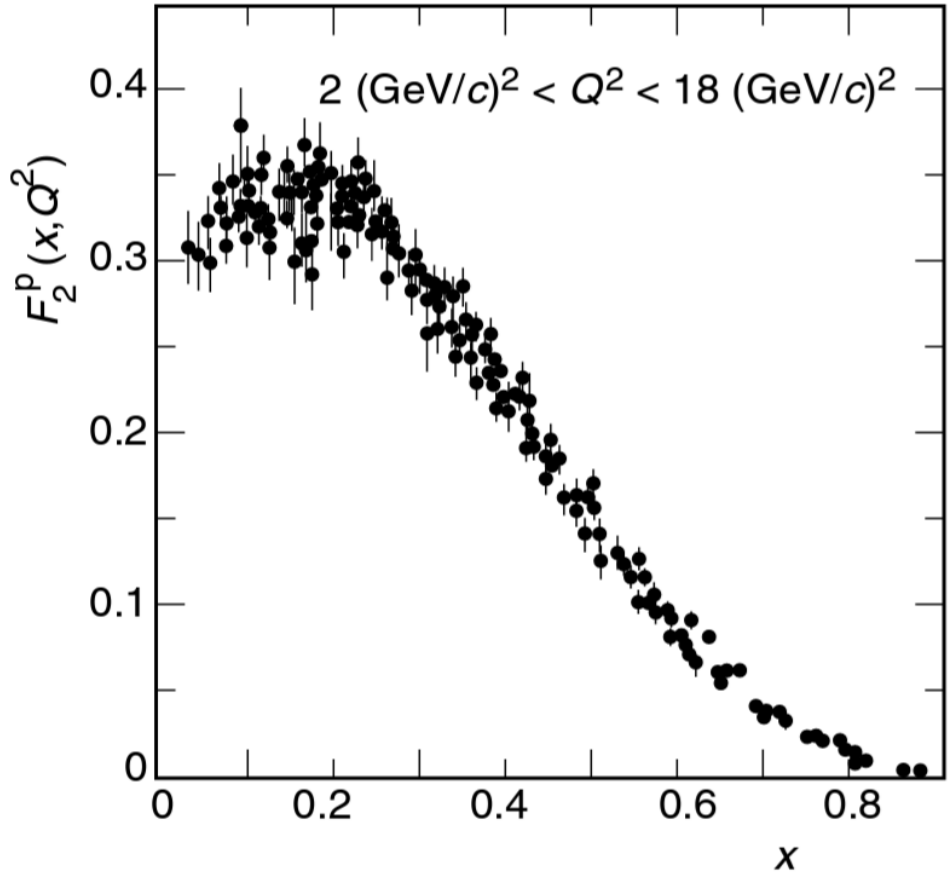
Gives insight to proton substructure

3 Interacting Quarks





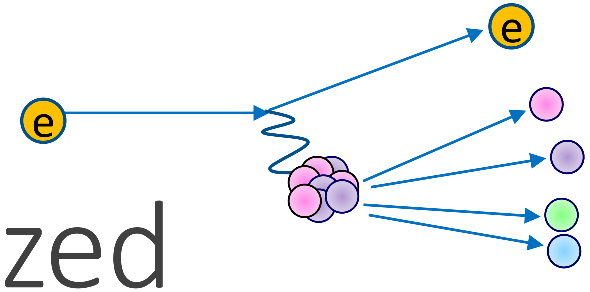


F. Halzen and A. Martin, *Quarks and Leptons*

B. Povh *et al*, *Particles and Nuclei*

Structure Functions - Unpolarized

Higher Q^2 → Better Resolution
If no change with Q^2, no substructure



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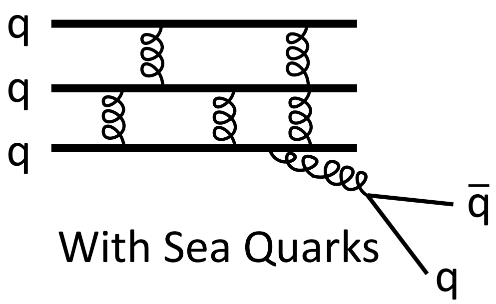
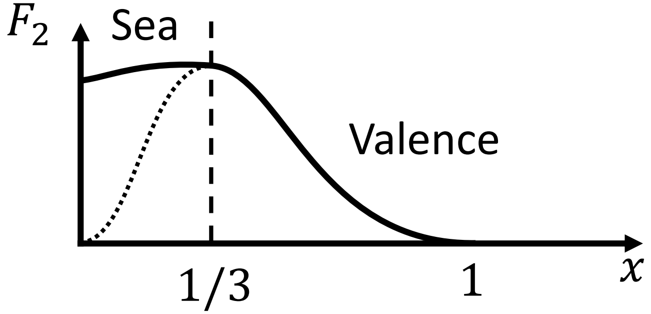
Gives insight to proton substructure

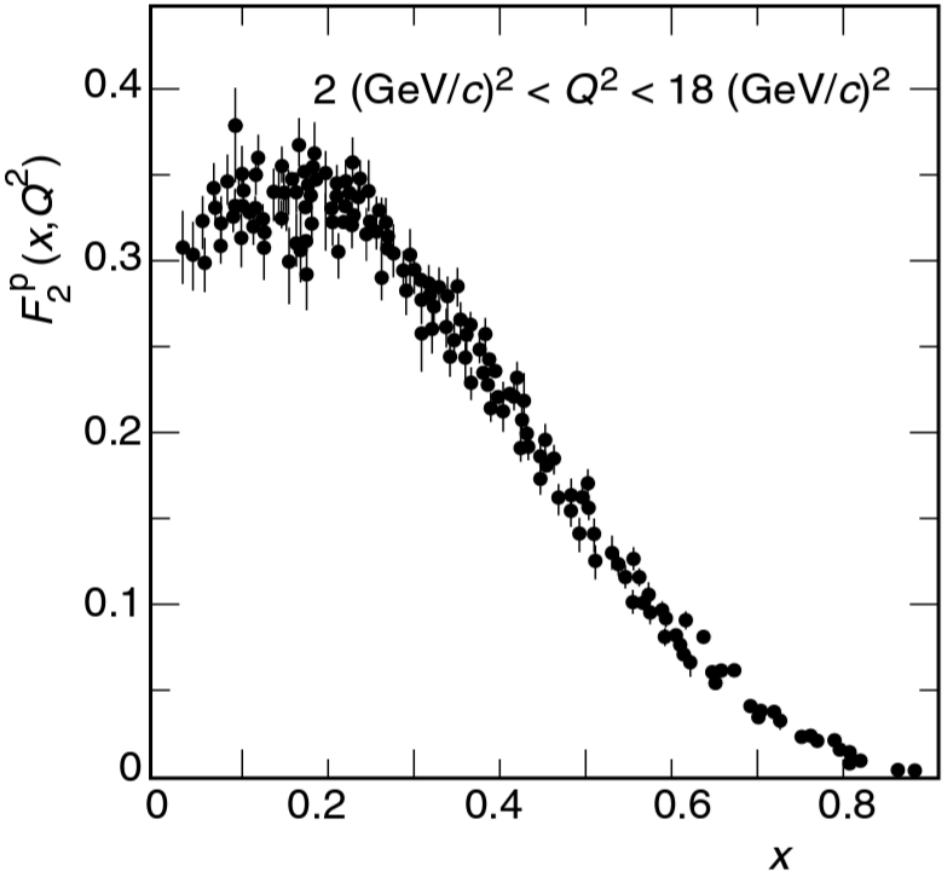


3 Interacting Quarks

With Sea Quarks

F. Halzen and A. Martin, *Quarks and Leptons*





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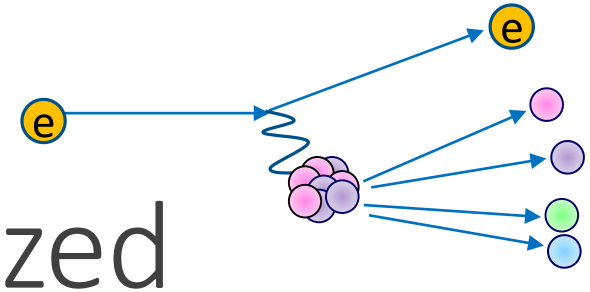

Structure Functions - Unpolarized

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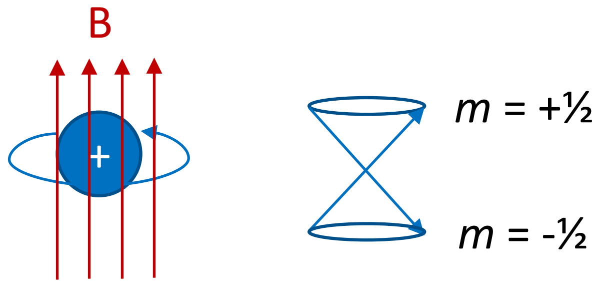
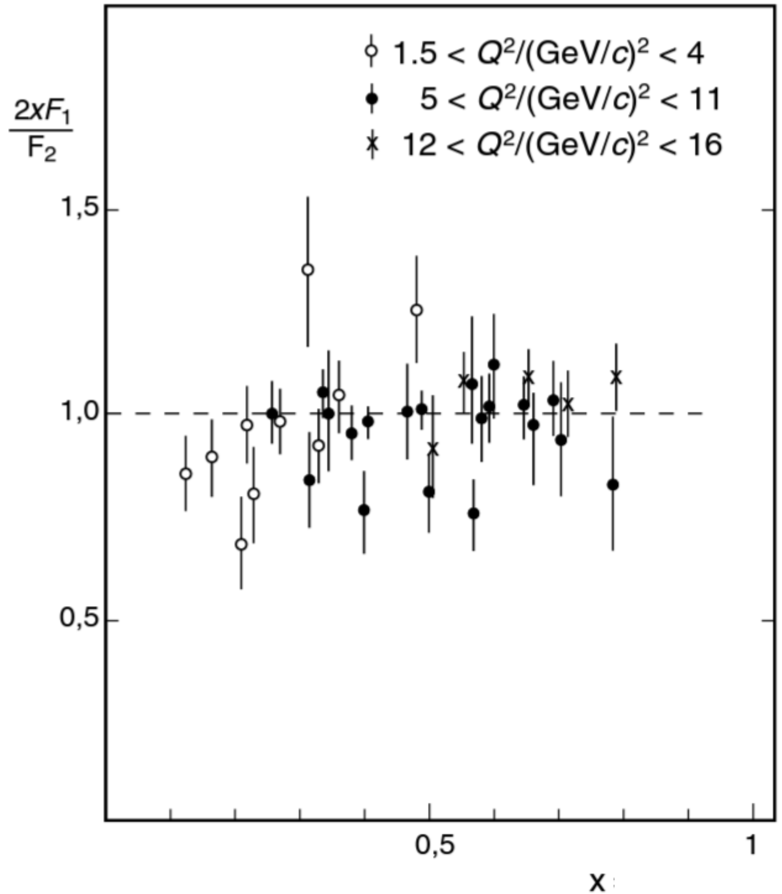
Derives from magnetic interaction

For spin ½ particles, $\frac{F_1(x)}{F_2(x)} x = \frac{1}{2}$

$$\frac{2xF_1(x)}{F_2(x)} = 1$$

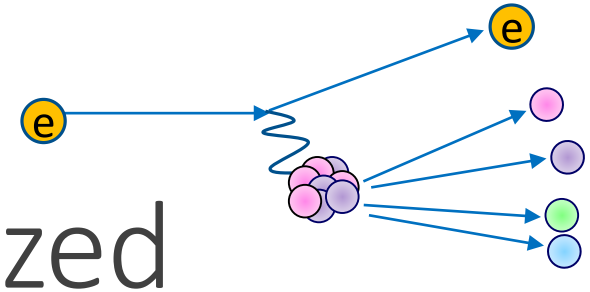


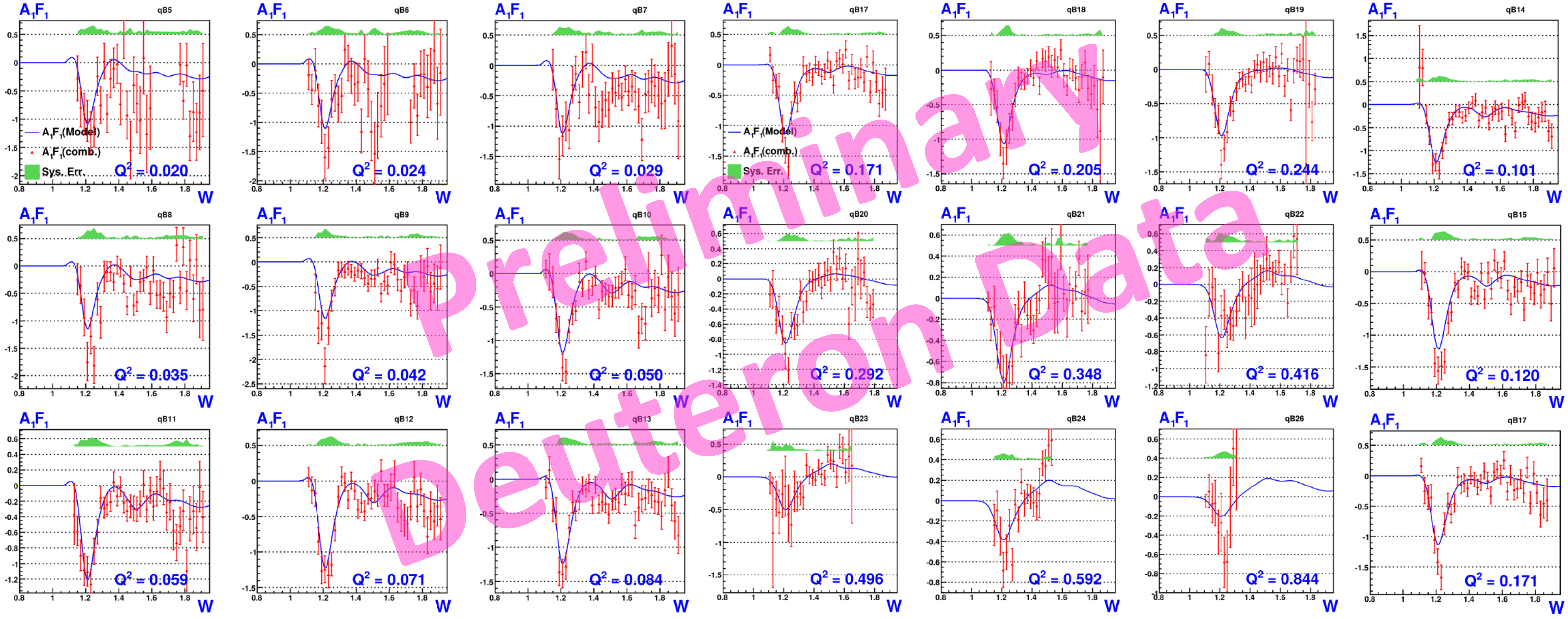


B. Povh *et al*, *Particles and Nuclei*

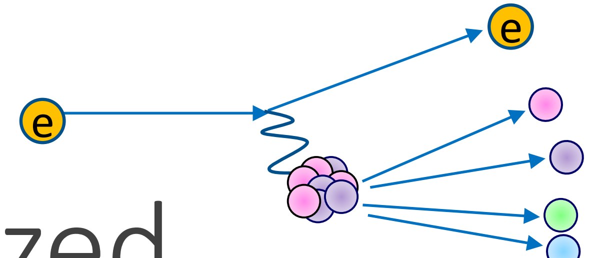
K. Adhikari, Ph.D. thesis, ODU

Structure Functions - Unpolarized





Preliminary Deuteron Data



Structure Functions - Unpolarized

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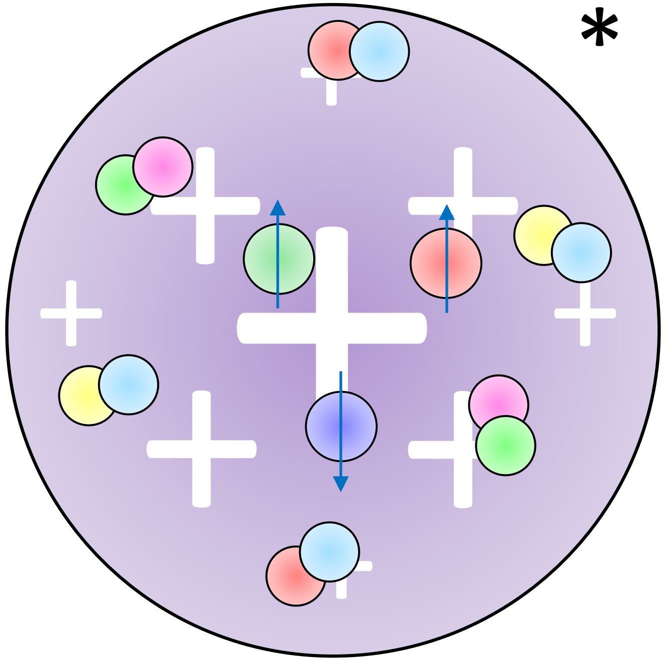
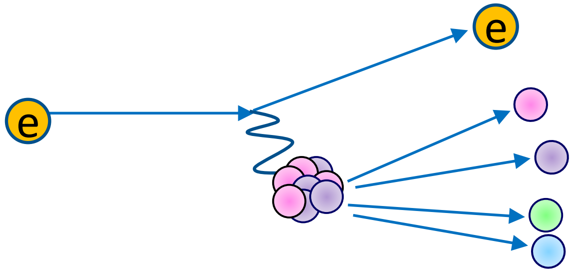
From F_1 and F_2 we learned that

- Nucleons are made up of three valence point-like particles
- These three particles are spin-½
- These particles interact with a "quark sea"



* From F_1 and F_2, we know they're in there, but not where they are



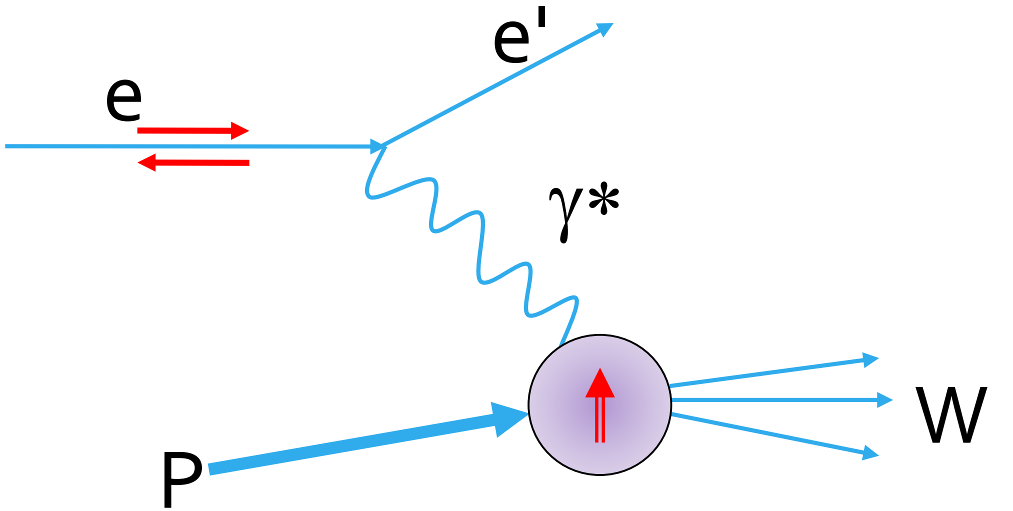
Structure Functions - Polarized

Structure functions describe deviations from point-like structure

$$\sigma = \sigma_{\mathrm{Mott}}\left[\frac{2}{Mc^2}F_1(x,Q^2)\tan^2\frac{\theta}{2} + \frac{1}{\nu}F_2\,(x,Q^2)\right]$$

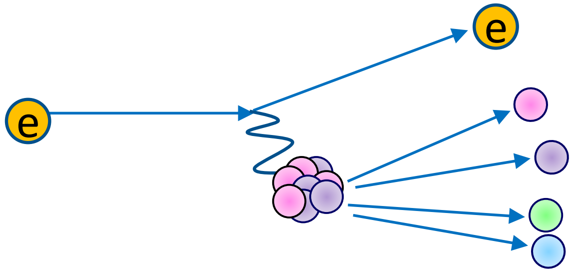
$$\sigma = \frac{\alpha^2 E'}{Q^4 E}L_{\mu\nu}W^{\mu\nu}$$

$$W^{\mu\nu} = -\alpha F_1 + \beta F_2$$
$$+i\gamma g_1 + i\delta g_2$$



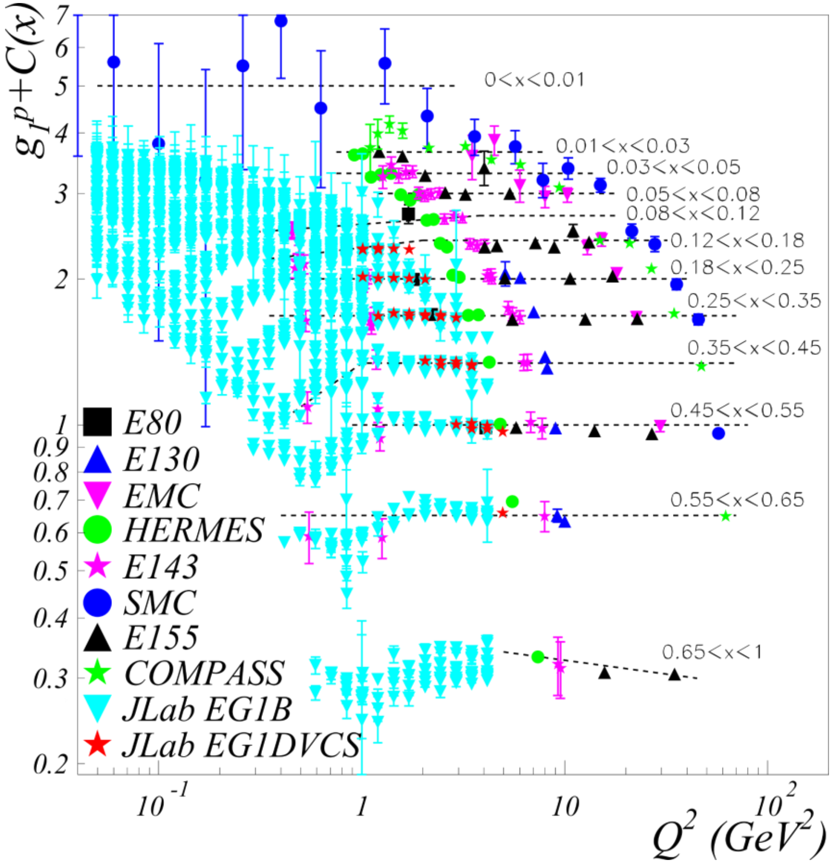
Scattering on Unpolarized Nucleons

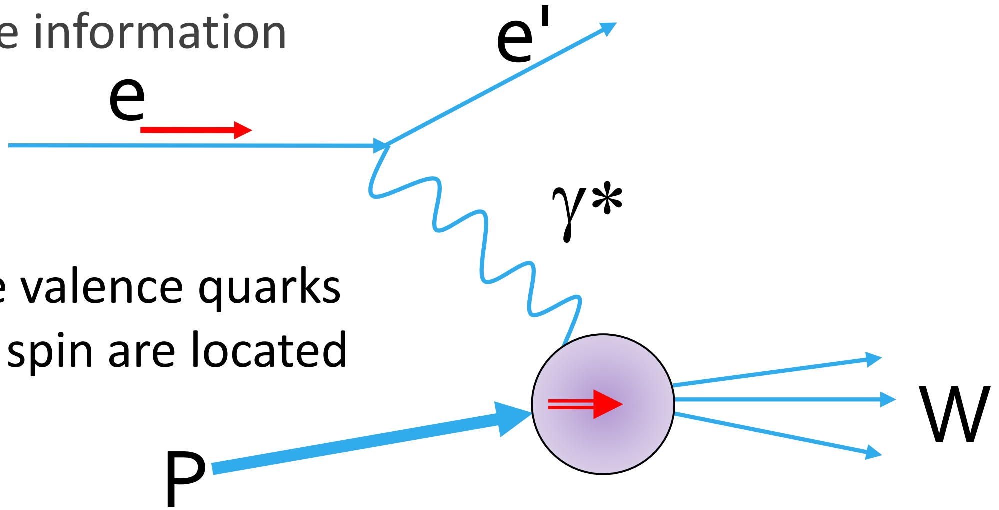
Scattering on Polarized Nucleons (spin up or down)



Structure Functions - Polarized

Using a polarized target, we can gain access to more information



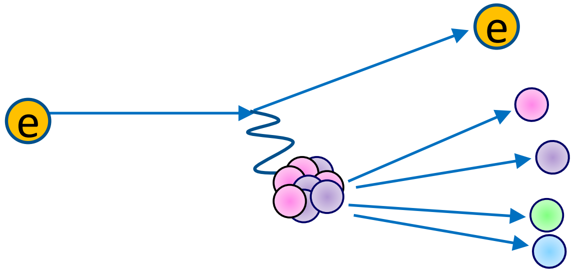


Tells us where valence quarks with a certain spin are located

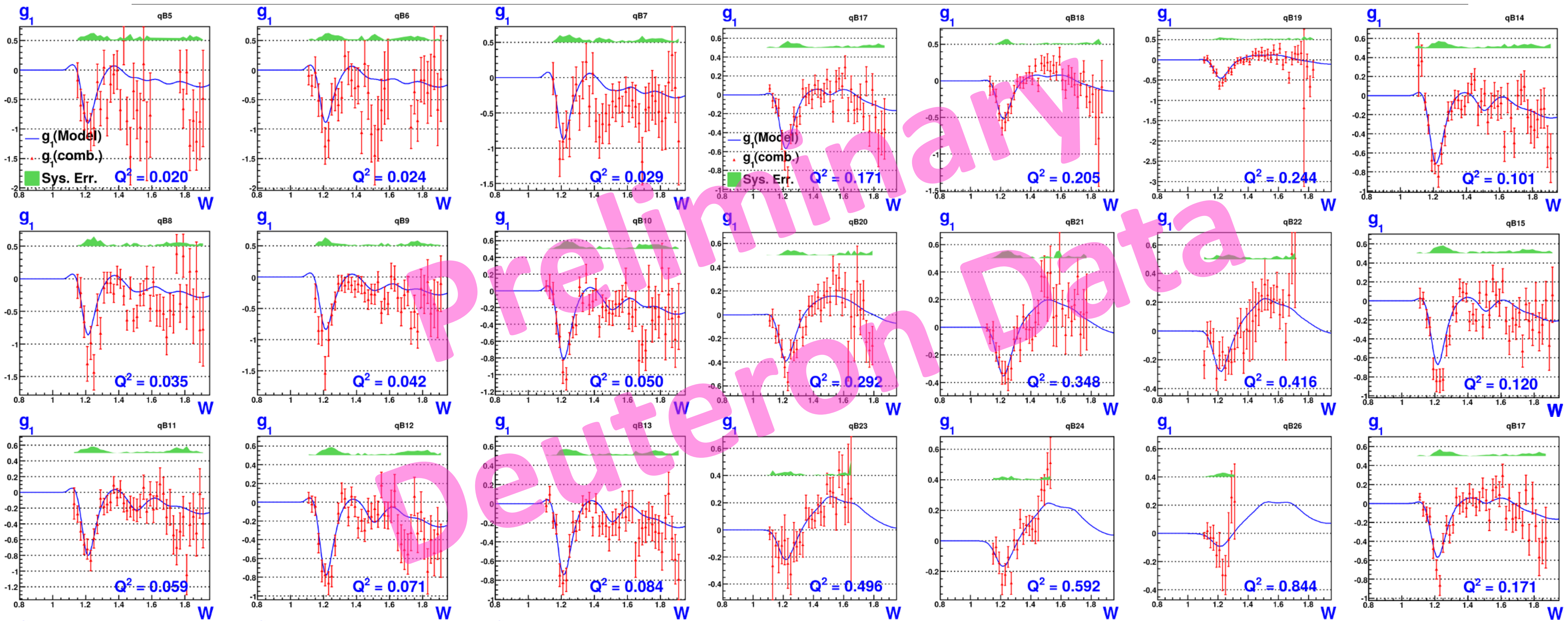
$$\Delta\sigma = \sigma_{++} - \sigma_{+-}$$

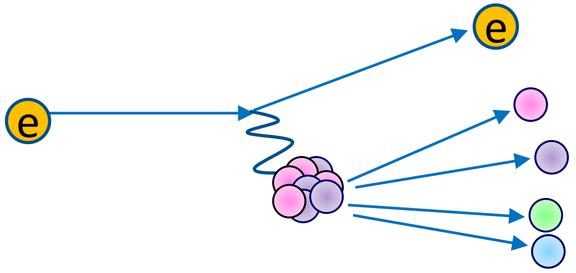
$$\Delta\sigma \propto \frac{1}{2}\sum_i e_i^2\left(q_i^+(x) - q_i^-(x)\right) \equiv g_1(x)$$

K. Adhikari, Ph.D. thesis, ODU



Structure Functions - Polarized





Structure Functions - Polarized

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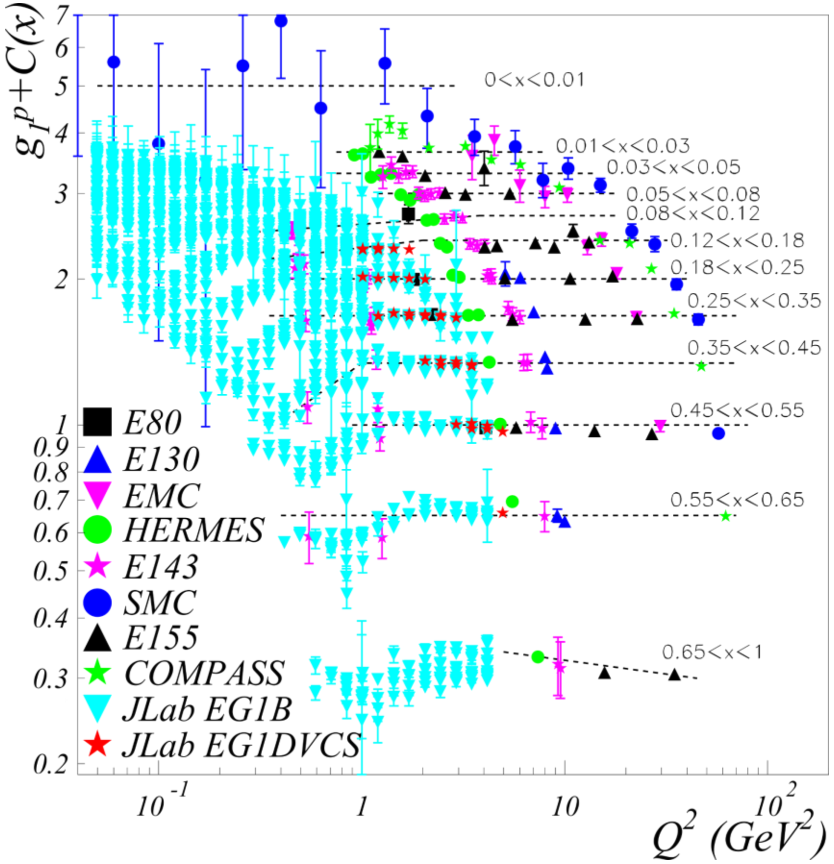

Tells us where valence quarks with a certain spin are located

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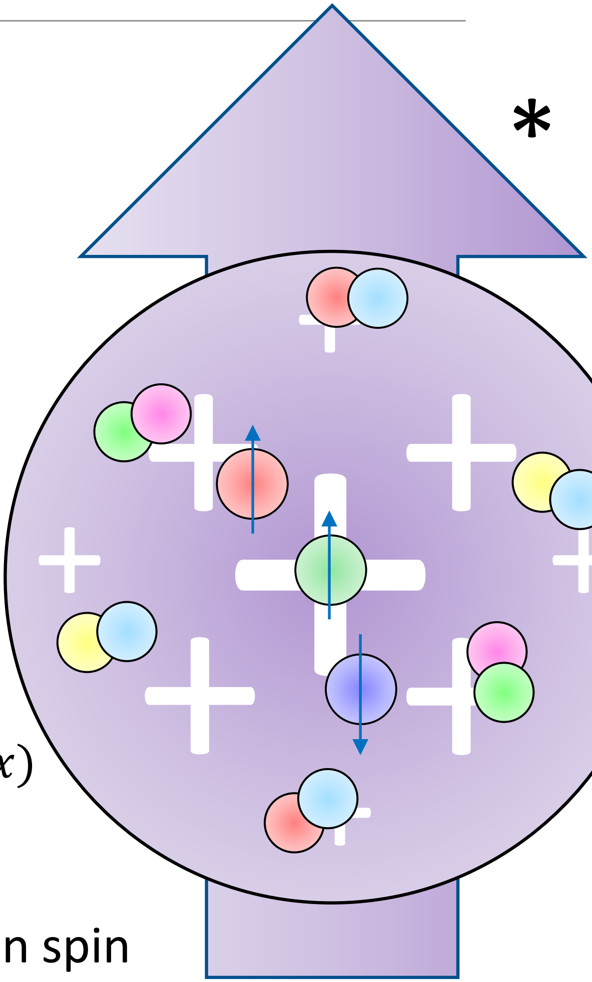
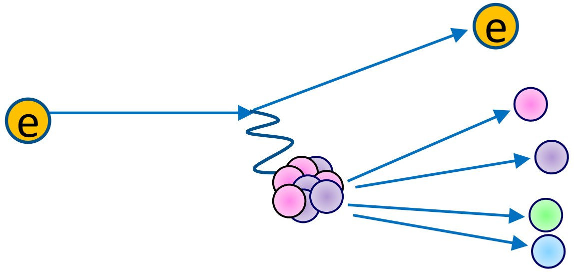


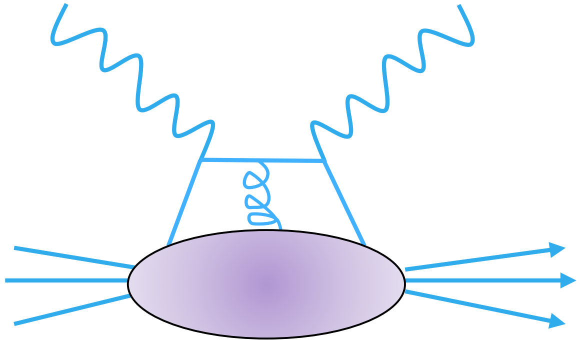
* Sum of valence quark spin ≠ nucleon spin

$$W^{\mu\nu} = -\alpha F_1 + \beta F_2$$
$$+ i\gamma g_1 + i\delta g_2$$



Structure Functions - Polarized

- No simple interpretation for g_2
- High Q^2 → Test of lattice QCD
- High Q^2 → Test of χPT
- Can provide information on polarizability, which might be causing the proton radius problem



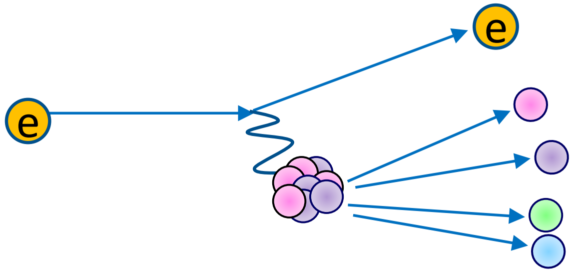
$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$$

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 \frac{dy}{y} g_1(x,Q^2)$$

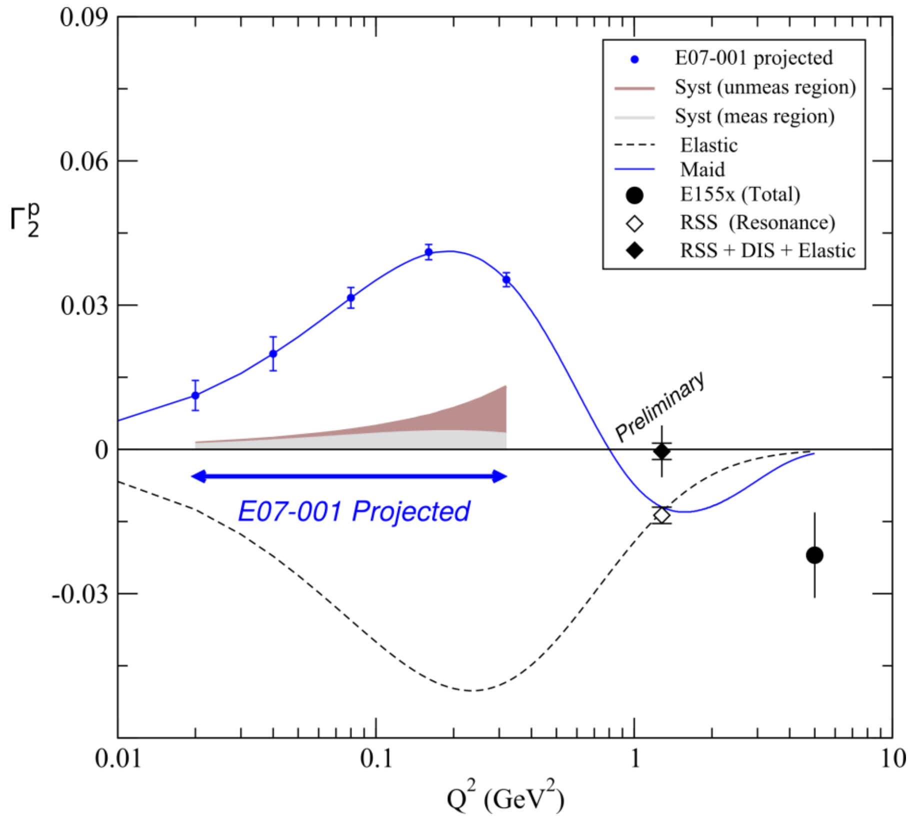
- Leading twist-2 term
- Entirely dependent on g_1

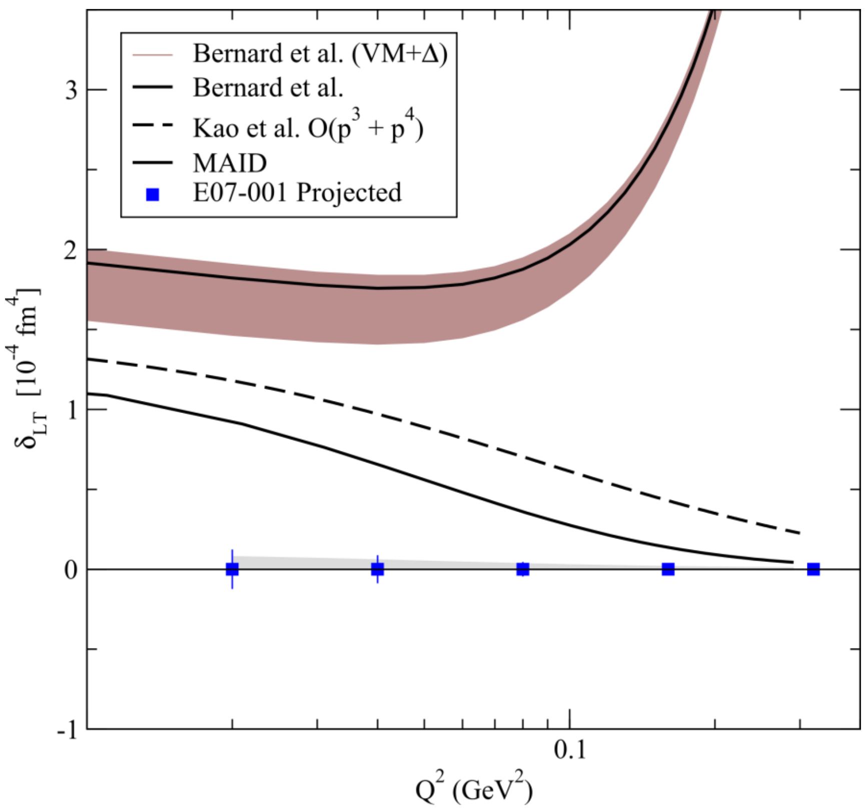
$$\bar{g}_2(x,Q^2) = \int_x^1 \frac{\partial}{\partial y}\left[\frac{m_q}{M} h_T(y,Q^2) + \zeta(y,Q^2)\right]\frac{dy}{y}$$

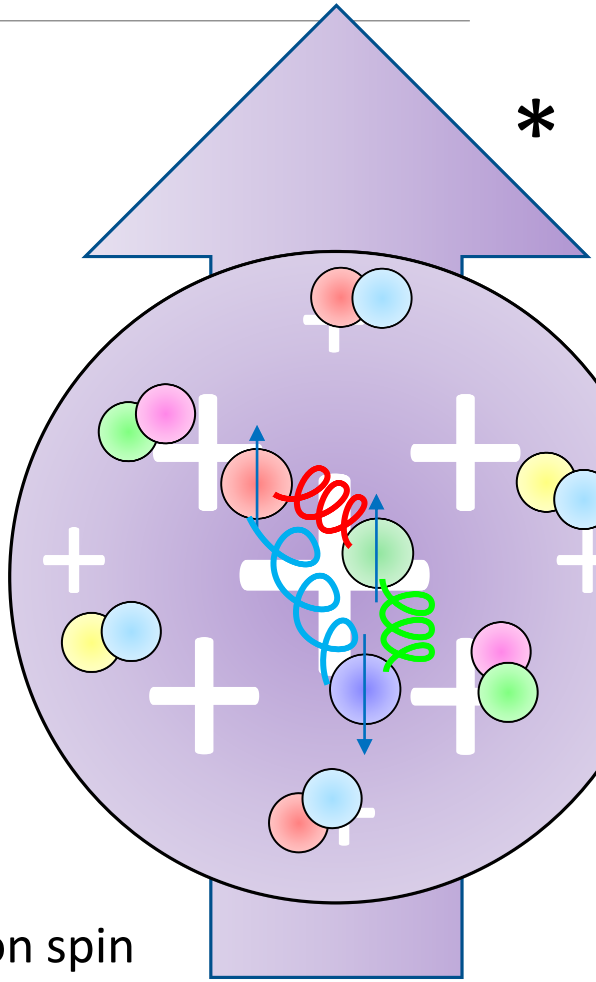
- h_T → Quark transverse polarization distribution
- ζ → Quark-gluon interactions



Structure Functions - Polarized



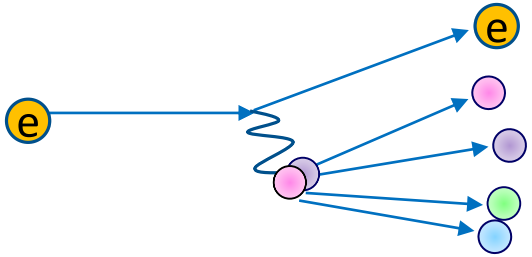




*

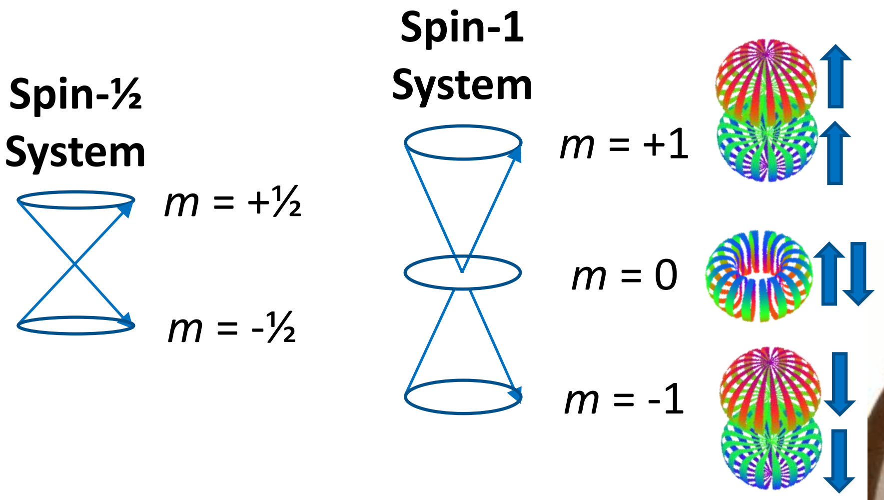
* Sum of valence quark spin ≠ nucleon spin

The Tensor Polarized Future of Nucleon Structure



Tensor Structure Functions

For tensor polarization, need spin-1 particles



Spin-½ System

m = +½

m = -½

Spin-1 System

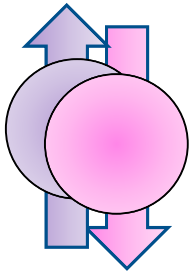
m = +1

m = 0

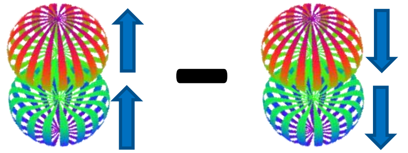
m = -1

Protons and neutrons are spin-½ particles, but a system of two gives a ½ + ½ = spin-1 system

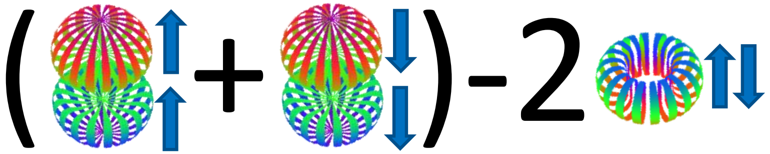
We can tensor polarize deuterons, which are made up of one neutron and one proton

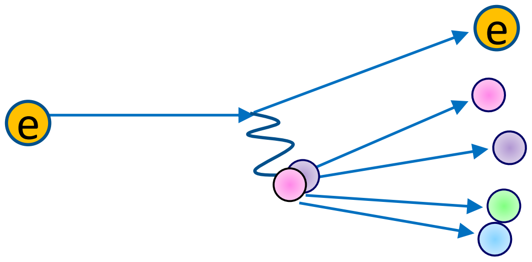


Vector $P_z = p_+ - p_-$



Tensor $P_{zz} = (p_+ + p_-) - 2p_0$





Tensor Structure Functions

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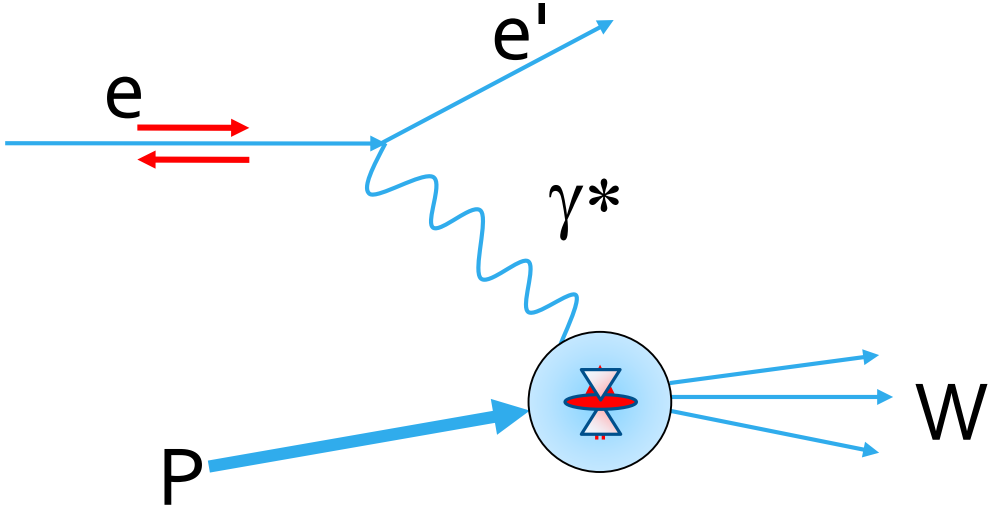
$$\sigma = \sigma_{\text{Mott}}\left[\frac{2}{Mc^2}F_1(x,Q^2)\tan^2\frac{\theta}{2} + \frac{1}{\nu}F_2\,(x,Q^2)\right]$$



$$W_{\mu\nu} = -\alpha F_1 + \beta F_2$$

Scattering on Unpolarized Targets

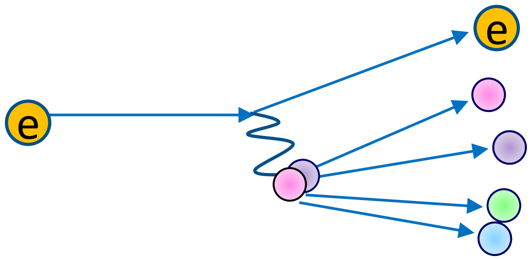
$$+i\gamma g_1 + i\delta g_2$$

Scattering on Vector Polarized Targets (spin up or down)

$$-\varepsilon b_1 + \zeta b_2 + \eta b_3 + \kappa b_4$$

Scattering on Tensor-Polarized Targets (spin 0)

Tensor Structure Functions



b_1 → Leading twist

$$b_1(x) = \frac{q^0(x) - q^1(x)}{2}$$

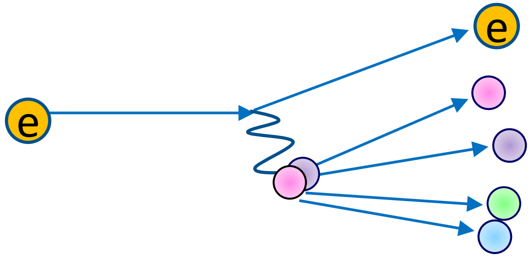
q^0: Probability to scatter from a **quark** (any flavor) carrying momentum fraction *x* while the *deuteron* is in state m=0

q^1: Probability to scatter from a **quark** (any flavor) carrying momentum fraction *x* while the *deuteron* is in state |m|=1

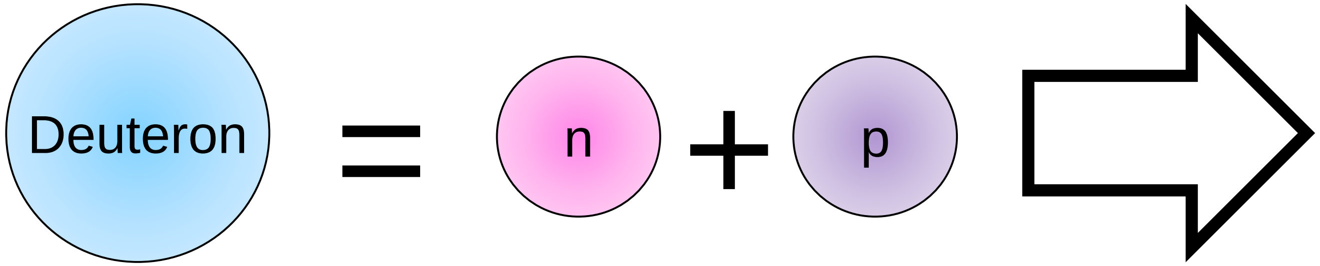
DIS, so measuring quark structure but requires the nucleus to be in a certain state!

Looks at nuclear effects at the resolution of quarks!

Tensor Structure Functions



If there are no nuclear effects, then b_1 vanishes.

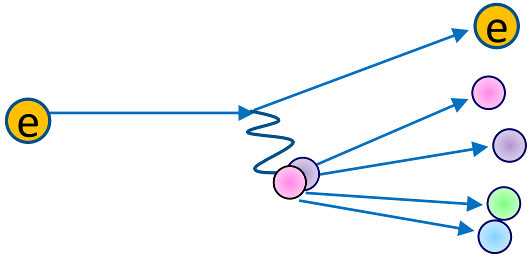


$$b_1 = 0$$

Even with D-state admixture, b_1 is expected to be tiny

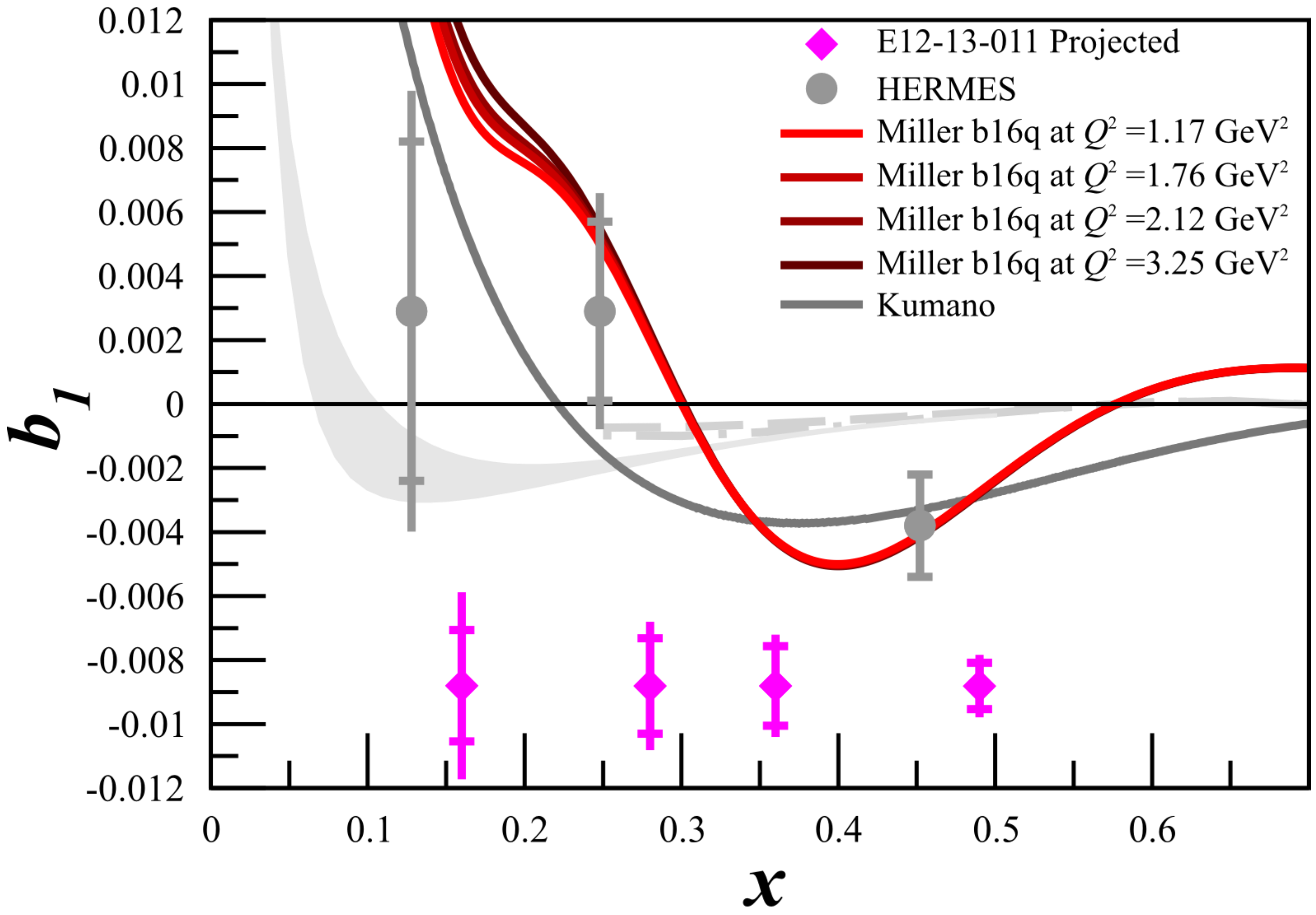
Khan & Hoodbhoy, PRC 44 ,1219 (1991) (Relativistic convolution model with binding)
$b_1 \approx O(10^{-4})$

Umnikov, PLB 391, 177 (1997) (Relativistic convolution with Bethe-Salpeter formalism)
$b_1 \approx O(10^{-3})$

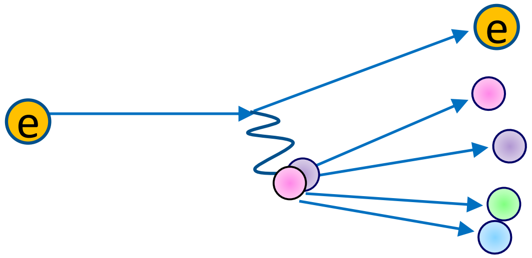


Tensor Structure Functions

All conventional **models predict small or vanishing values of b_1** in contrast with the HERMES data



Any measurement of a $b_1<0$ indicates exotic physics



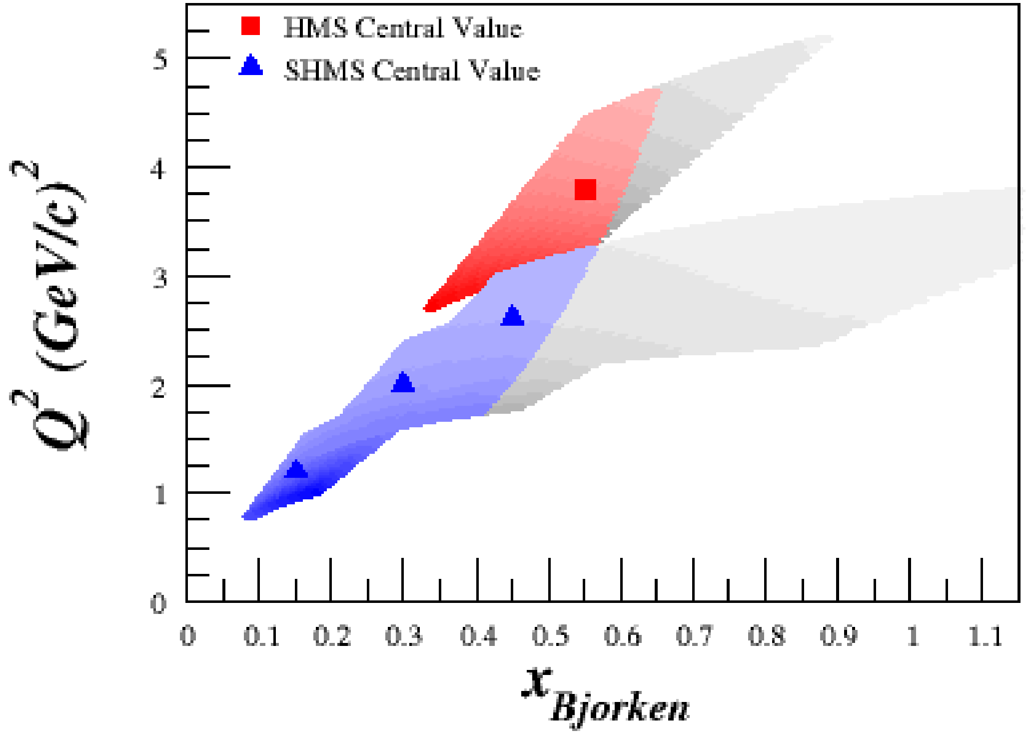
Tensor Structure Functions

Measured by ratio method

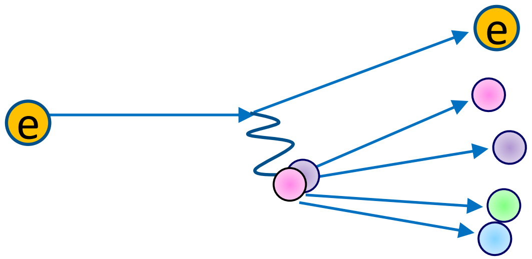
$$\frac{N_{Pol}}{N_u} - 1 = f\frac{1}{2}A_{zz}P_{zz}$$

$$A_{zz} = \frac{2}{f \cdot P_{zz}}\left(\frac{N_{Pol}}{N_u} - 1\right)$$

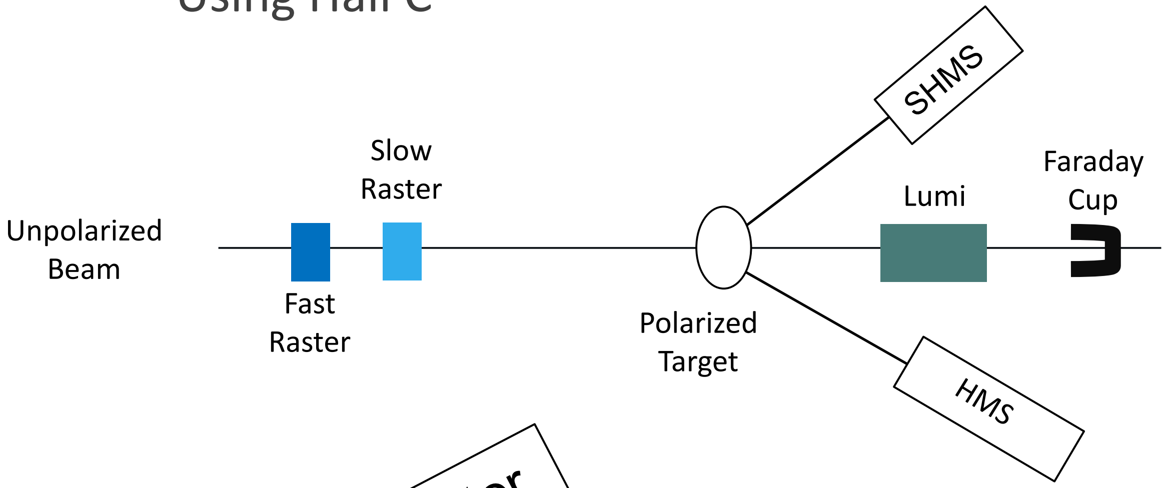
$$b_1 = -\frac{3F_1}{f \cdot P_{zz}}\left(\frac{N_{Pol}}{N_u} - 1\right)$$

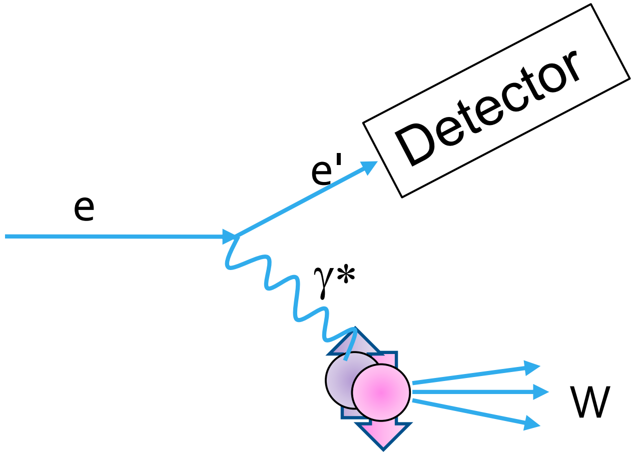


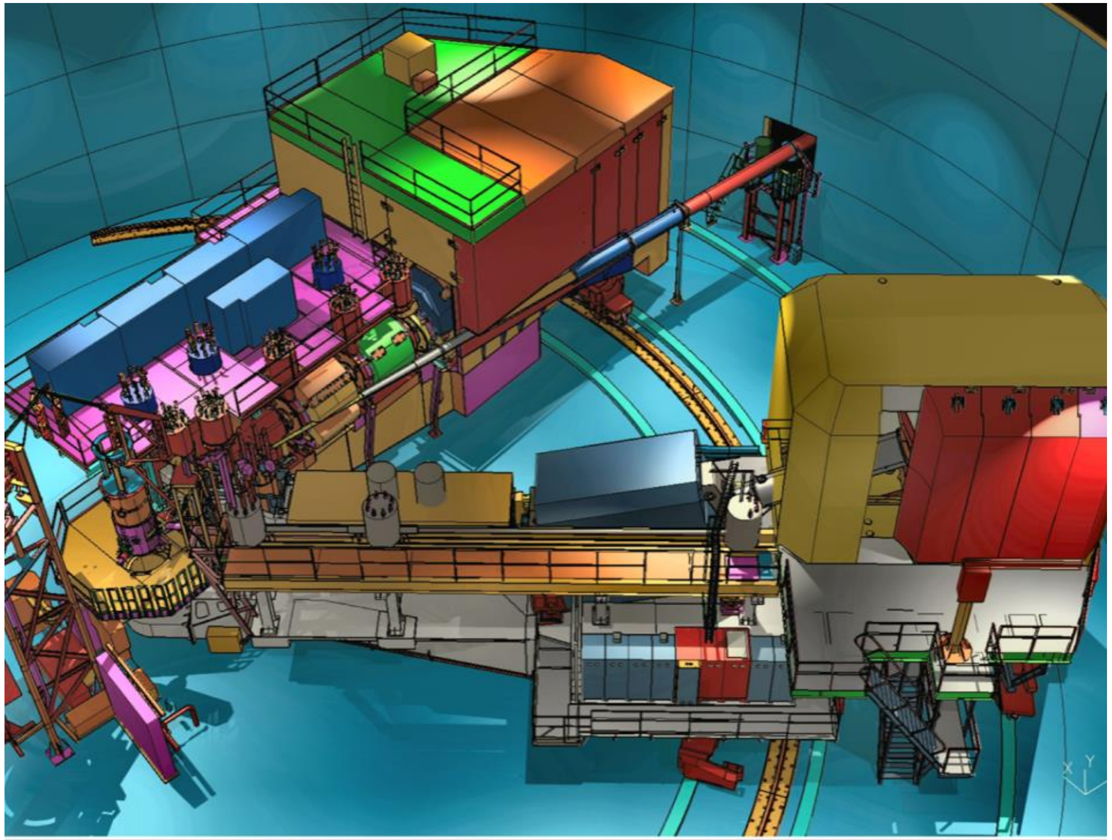
Tensor Structure Functions

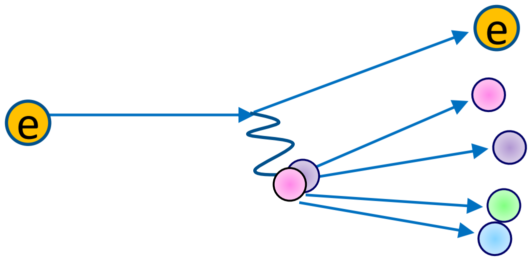


Using Hall C



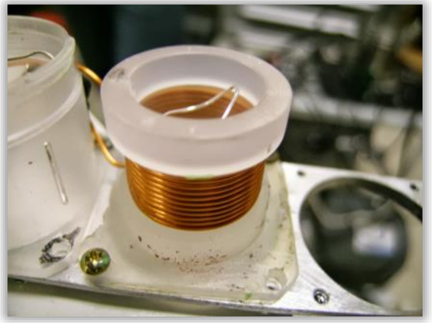


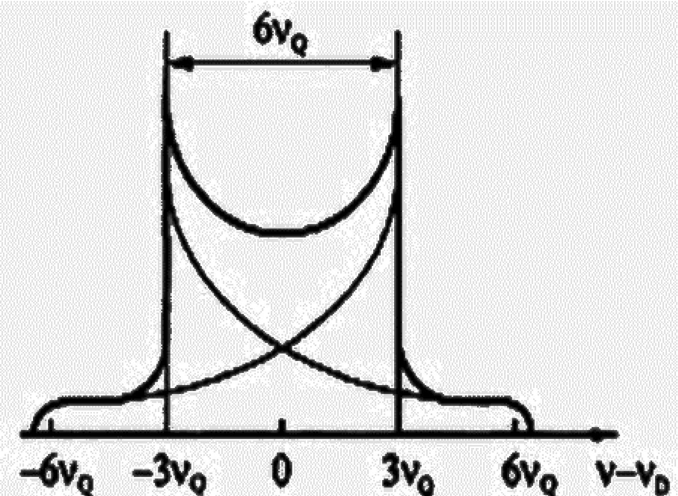


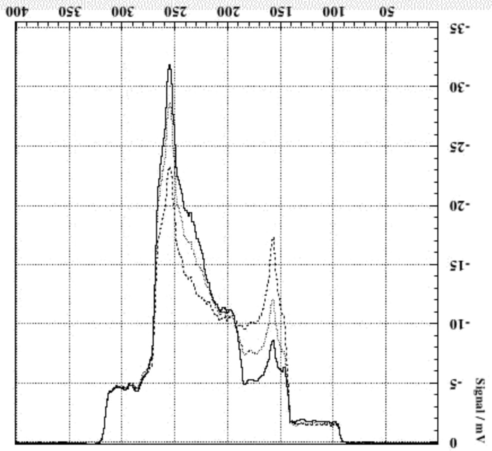


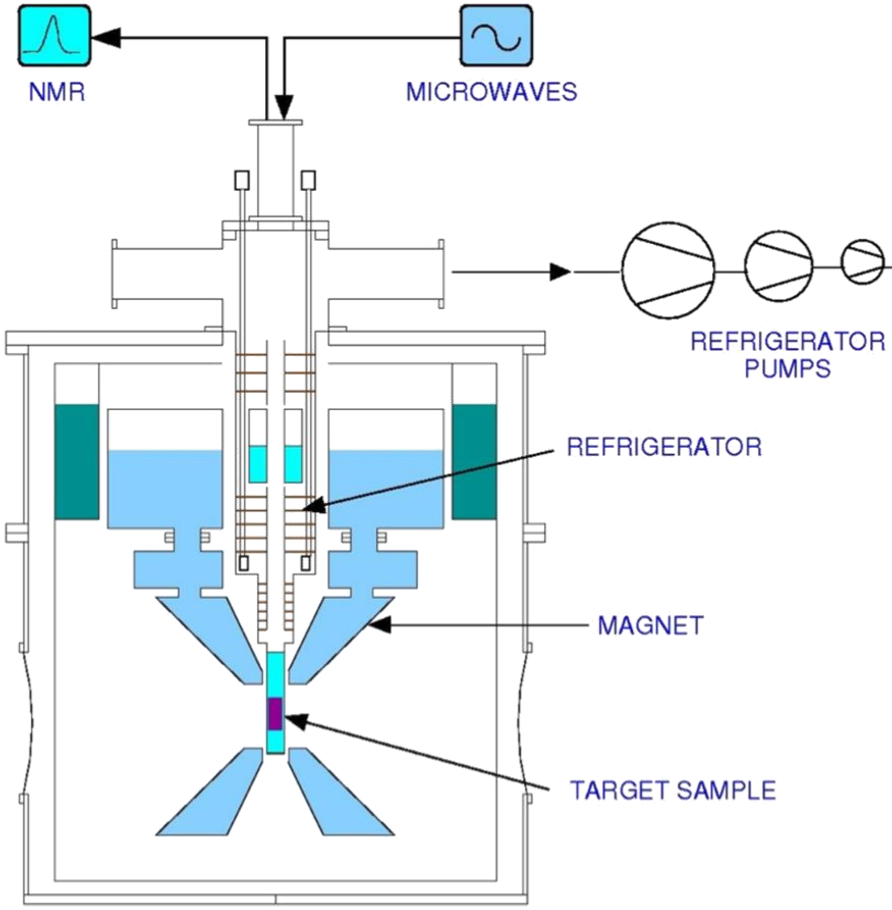
Tensor Structure Functions

- Dynamic Nuclear Polarization of ND_3
- $P_{zz} \sim 30\%$
- 5 Tesla at 1 K
- 3cm Target Length
- $p_f \sim 0.65$
- $f_{dil} \sim 0.27$

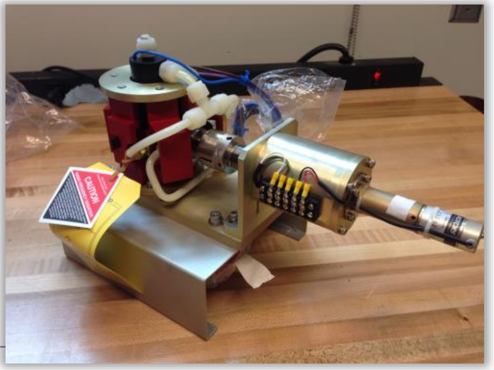




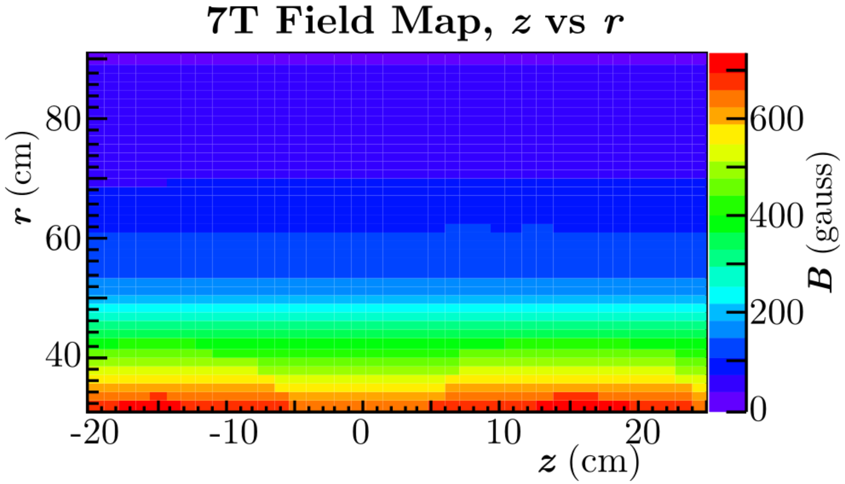


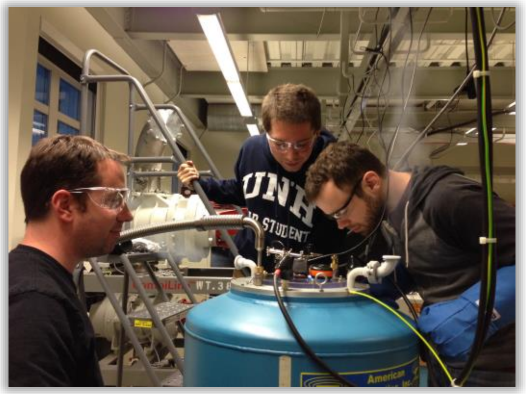


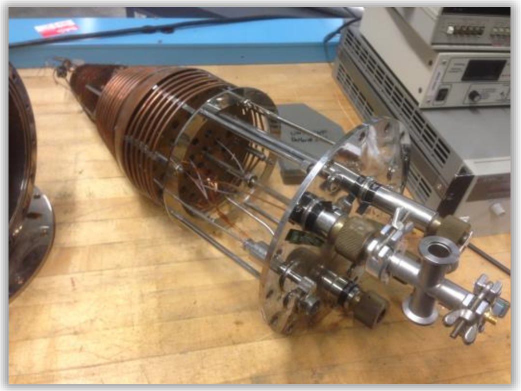
Tensor Structure Functions

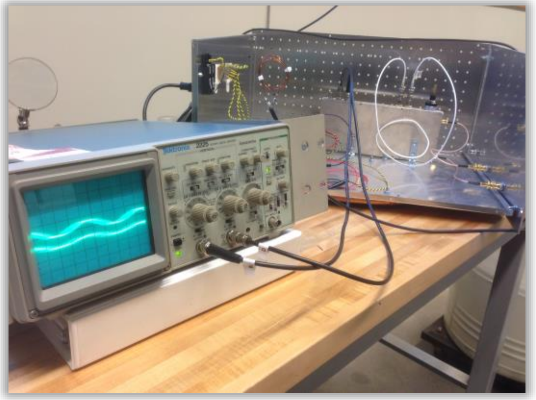


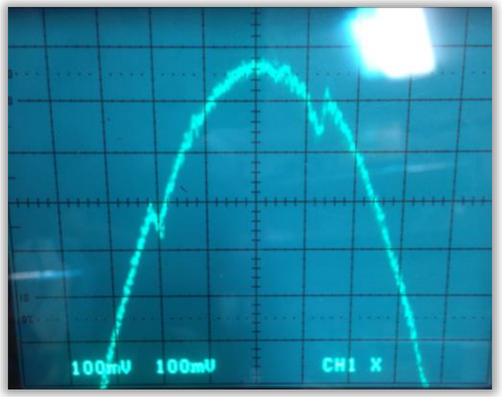
- UNH Target Lab is ramping up, first cool-down in January, successfully reached 7T



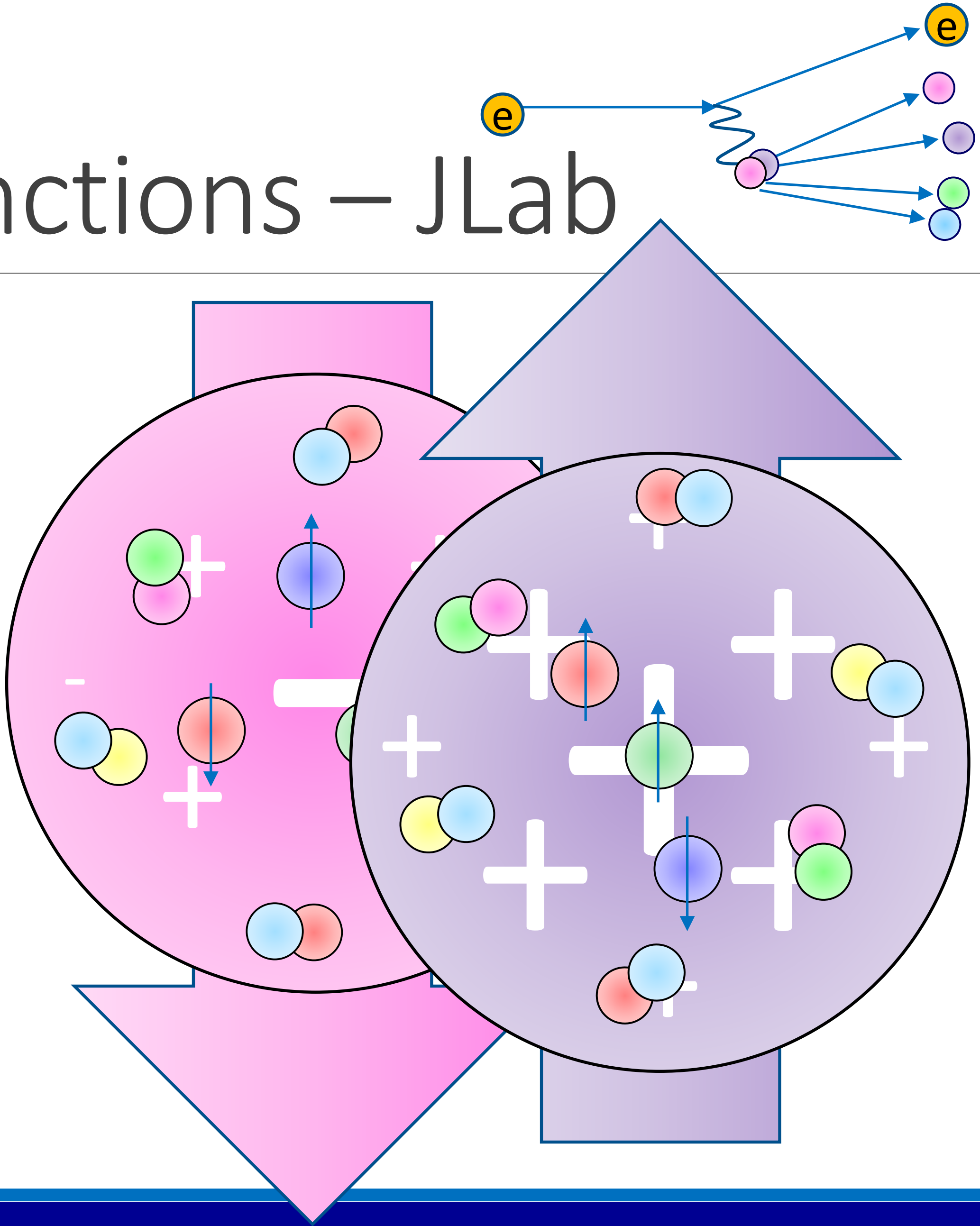








Tensor Structure Functions – JLab

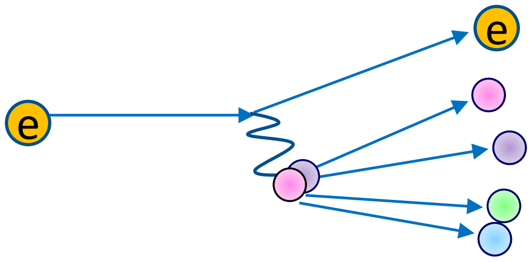


Measuring b_1 will give insight into

- Exotic effects in tensor-polarized systems
- OAM and spin crisis
- Pionic effects
- Polarization of the quark sea
- Hidden color from 6-quark configuration

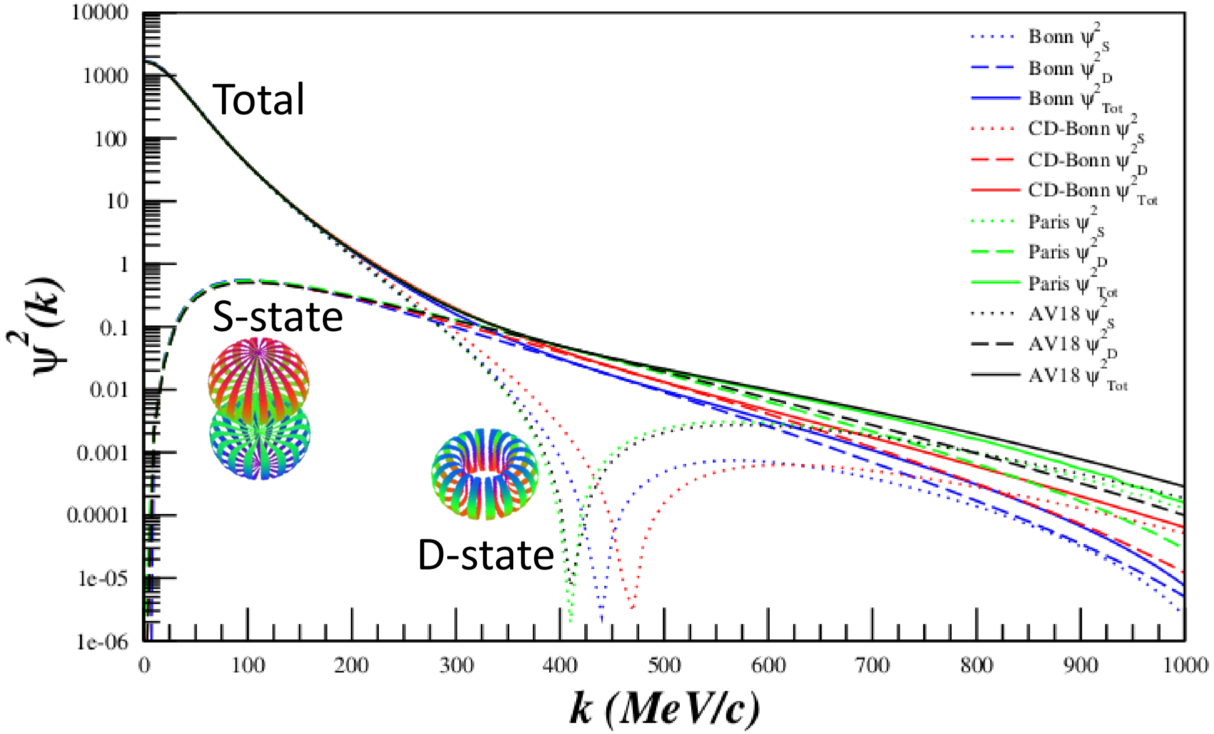
Approved JLab Experiment E12-13-011
Spokespersons: K. Slifer, E. Long, D. Keller, P. Solvignon, J.P. Chen, O.R. Aramayo, N. Kalantarians

Quasi-Elastic Tensor Structure



Repeat same experiment, only look at A_{zz} in the quasi-elastic region

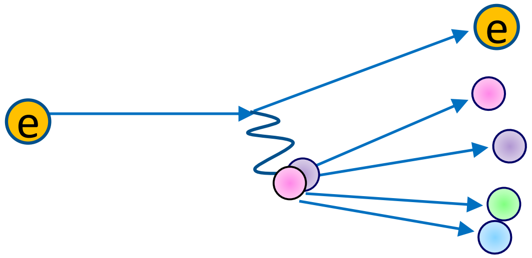
Can give insight to short range deuteron structure



$$A_{zz} = \frac{2}{f \cdot P_{zz}}\left(\frac{N_{Pol}}{N_u} - 1\right)$$

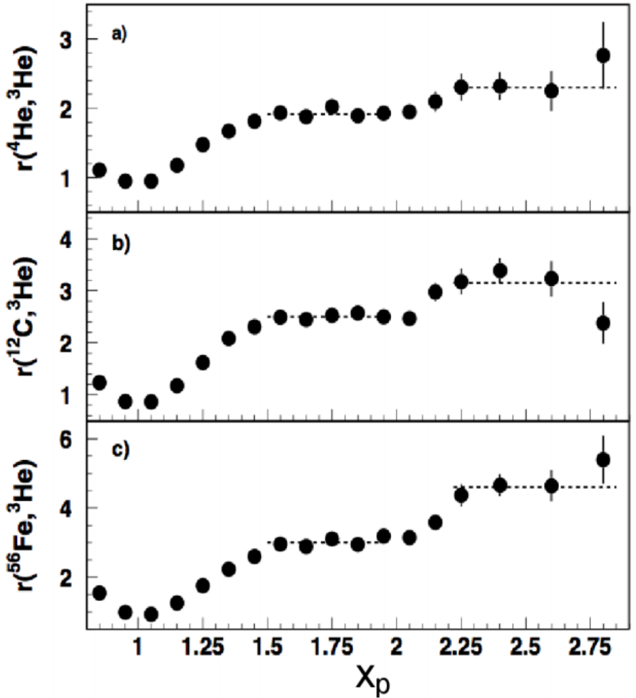
$$A_{zz} \propto \frac{\frac{1}{2}D^2 - SD}{S^2 + D^2}$$

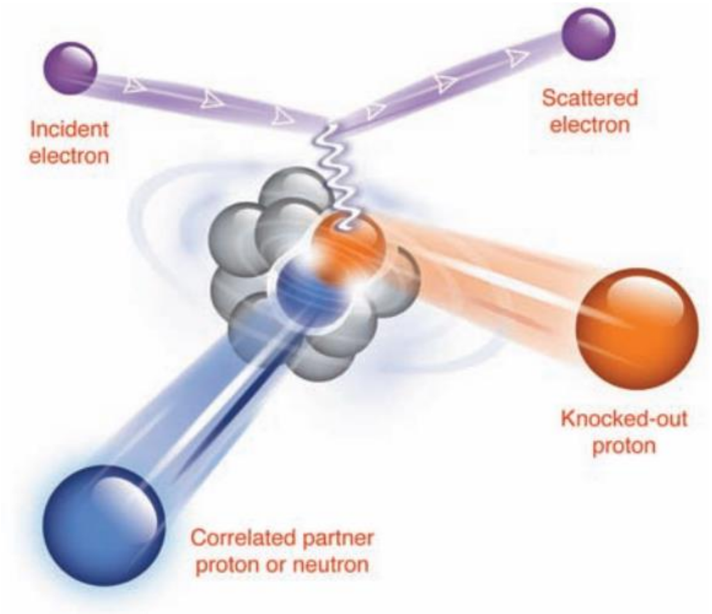
Quasi-Elastic Tensor Structure

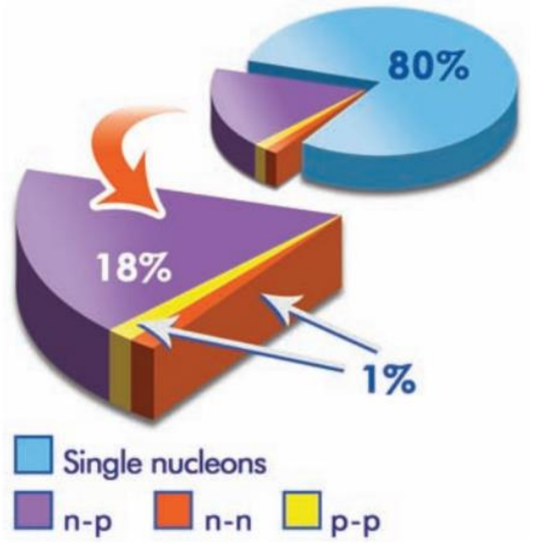


Repeat same experiment, only look at A_{zz} in the quasi-elastic region

Can give insight to short range correlations



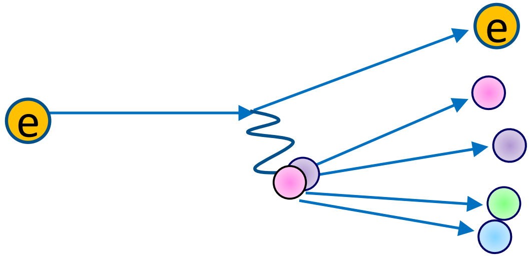


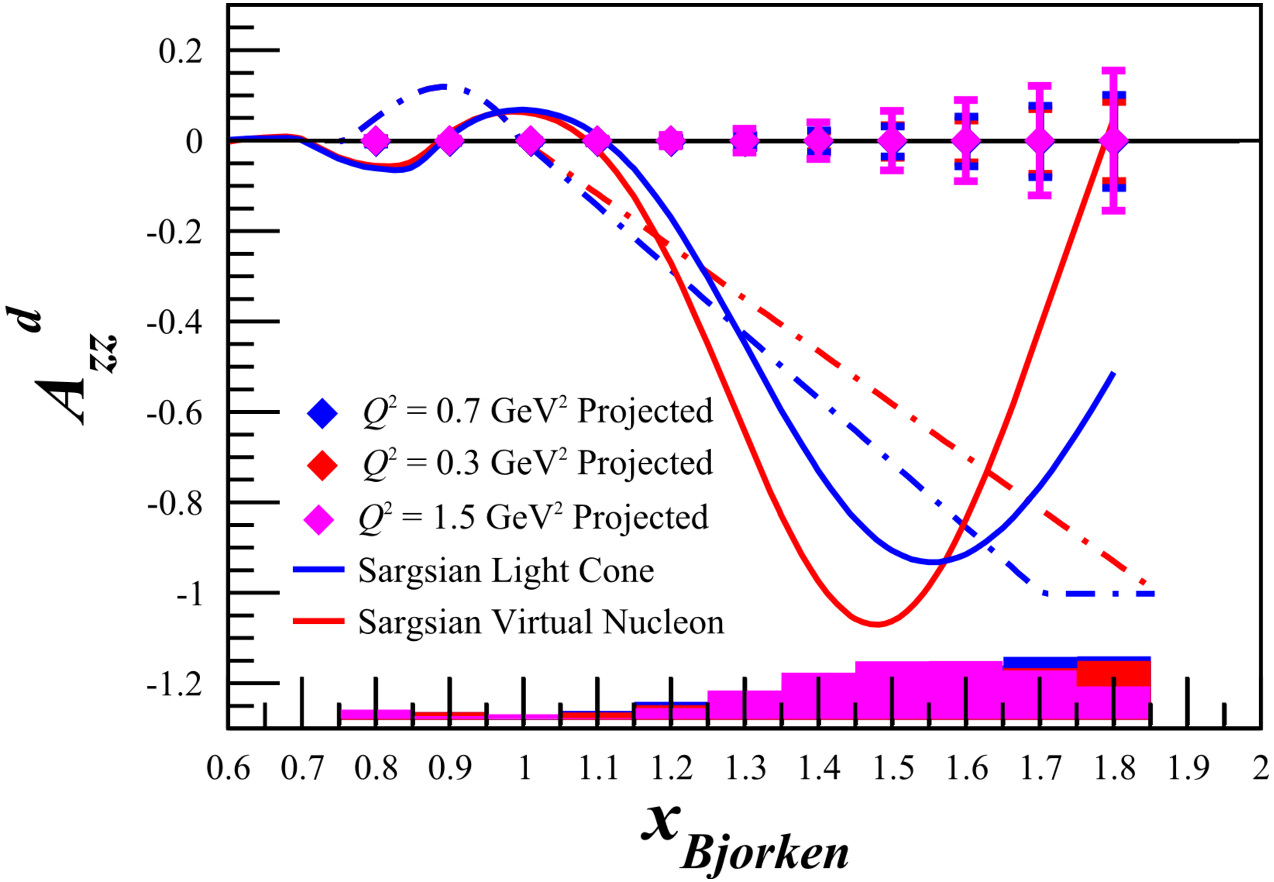


K. S. Egiyan et al., Phys. Rev. Lett. **96**, 082501 (2006)

R. Subedi et al., Science **320**, 1476 (2008)

Quasi-Elastic Tensor Structure





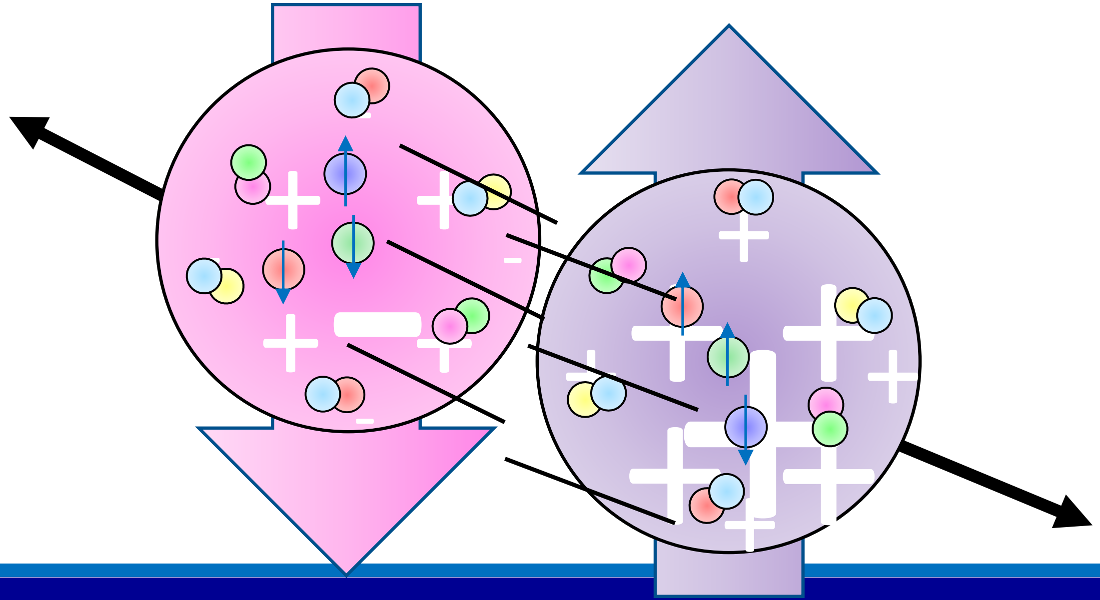
SRCs & pn dominance[1]

Differentiate light cone and VN models[2]

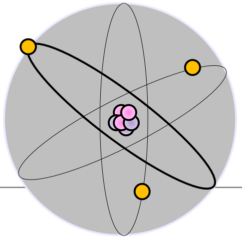
Better understanding of S/D[3]

Final state interaction models[4]

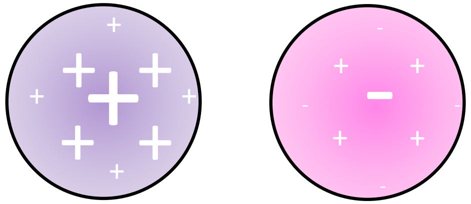
JLab LOI12-14-002 Encouraged for full proposal



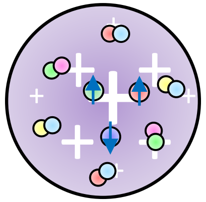
Summary



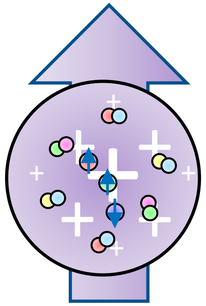
- The Structure of Matter



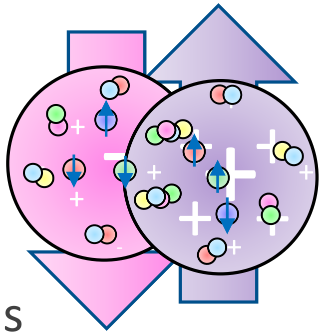
- Electromagnetic Form Factors



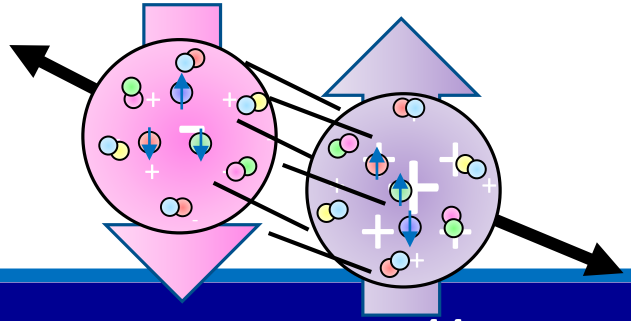
- Unpolarized Structure Functions



- Polarized Structure Functions



- Tensor Polarized Structure Functions



- Quasi-Elastic Tensor Structure/Short Range Correlations

Thank you