Outline-

1. How not to and how to analyze electromagnetic form factors- transverse density

2. Model independent proton, neutron transverse charge density
proton transverse magnetization density

3. Pion time-like data and transverse charge density

Transverse Charge Densities.
Electron-nucleon scattering

\[ j_{\mu} = \langle e' | \gamma_{\mu} | e \rangle \]
\[ J_{\mu} = \langle p' | \Gamma_{\mu} | p \rangle \]

Nucleon vertex:
\[ \Gamma_{\mu}(p', p) = \gamma_{\mu} F_1(Q^2) + \frac{i \sigma_{\mu \nu} q_{\nu}}{2M} F_2(Q^2) \]

Cross section for scattering from a point-like object
\[ \frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{Mott} \left( G_E^2 + \frac{\tau}{\epsilon} G_M^2 \right) / (1 + \tau) \]

Form factors describing nucleon shape/structure
\[ G_E(Q^2) \equiv F_1(Q^2) - \frac{Q^2}{4M^2} F_2(Q^2), \quad G_M(Q^2) \equiv F_1(Q^2) + F_2(Q^2) \]
Interpretation of Sachs - $G_E(Q^2)$ is Fourier transform of charge density

$$G_E(q^2) = \int d^3r \rho(r)e^{i\vec{q} \cdot \vec{r}} \rightarrow \int d^3r \rho(r)(1 - q^2 r^2/6 + \cdots)$$

Correct non-relativistic:
wave function invariant under Galilean transformation

Relativistic: wave function is frame dependent, initial and final states differ

interpretation of Sachs FF is wrong

Final wave function is boosted from initial

Need relativistic treatment
Interpretation of Sachs - $G_E(Q^2)$ is Fourier transform of charge density

$$G_E(q^2) = \int d^3r \rho(r) e^{iq \cdot r} \rightarrow \int d^3r \rho(r)(1 - q^2 r^2 / 6 + \cdots)$$

**WRONG**

Correct non-relativistic:
wave function invariant under Galilean transformation

Relativistic: wave function is frame dependent, initial and final states differ

interpretation of Sachs FF is wrong

Final wave function is boosted from initial

Need relativistic treatment
• Scalar meson, mass $M$ made of two scalars one neutral, $M = 2m - B$, $B > 0$

• Exact covariant calculation of form factor

\[
F(Q^2)(2P^\mu + q^\mu) = 4\frac{g^2}{16\pi^2}(2P^\mu + q^\mu) \int_0^1 dx \frac{x \text{Tanh}^{-1} \left[ \frac{\sqrt{Q^2(1-x)}}{4m^2 - x(1-x)M^2 + (1-x)^2Q^2} \right]}{\sqrt{Q^2} \sqrt{4m^2 - x(1-x)M^2 + (1-x)^2Q^2}}
\]
Toy model \( M = 2m - B, \ B > 0 \)

- Infinite momentum frame, same result
- Integrate over minus-component, same result

\[
F(Q^2) = \frac{g^2}{16\pi^2} \int d^2 \kappa \int_0^1 \frac{dx}{x(1-x)} \psi^*(x, \kappa + (1-x)q) \psi(x, \kappa)
\]

\[
\psi(x, \kappa) = g \left[ M^2 - \frac{\kappa^2 + m^2}{x(1-x)} \right]^{-1}
\]

\[
x \rightarrow \frac{m + \kappa^3}{M}, \ \psi \rightarrow \frac{g}{2m(-B - \frac{\kappa^2}{m})}
\]

- Non-relativistic limit, \( F(Q) \) IS 3Dim FT
  Valid if \( B/m \) is small
  How small must \( B \) be for non-relativistic approximation to work?
Validity of non-relativistic approximation

\[ Q^2 \leq 0.2M^2 \]

**FIG. 5:** Exact vs non-relativistic Form factors for the case \( m_1 = m_2 = m \).

We study the non-relativistic approximation, by comparing the exact model results Eq. (17) with those of the non-relativistic approximation Eq. (69). See Fig. IX A.

The figure shows two sets of results. In the upper panel the binding energy \( B = 0.002M \). This corresponds roughly to deuteron kinematics, in which the binding energy is of the order of a 0.004 of the deuteron mass. We see that the non-relativistic approximation is not accurate for values of \( Q^2 / M^2 \) greater than about 1. If one increases the binding energy to \( 0.1M \), one sees that the non-relativistic approximation is not accurate for any value of \( Q^2 / M^2 \).

If one approximates a nucleon by taking \( M = 1 \text{ GeV} \), then \( m = 0.55 \text{ GeV} \), which is much larger than a constituent quark mass.

We can gain some insight into the nature of the relativistic corrections to the charge radius by studying the low \( Q^2 \) limit of the form factor of Eq. (8). One finds

\[
\lim_{Q^2 \to 0} F(Q^2) = 1 - \frac{Q^2 R}{6},
\]

with

\[
M^2 R^2 = \left( \frac{1}{4} \gamma^3 + \frac{48}{\gamma} \right) \cot^{-1}(2\gamma) + \frac{2}{4\gamma^2} - \frac{24}{16} \left( \frac{2}{\gamma} + \frac{1}{2\gamma^2} \right) \cot^{-1}(2\gamma) - \frac{1}{2\gamma^2}.
\]

The non-relativistic limit corresponds to the limit of small values of \( \gamma \), which corresponds to a small value of \( B/M \).

So we expand the previous result to order \( B/M \) to find

\[
M^2 R^2 \approx \left( \frac{12288}{48\pi^4} + \frac{195}{\pi^4} \right) B^4 + 8\pi \left( \sqrt{B} \right) \left( \frac{128}{\sqrt{2}} - \frac{25}{\sqrt{2}} \pi^2 \right) \right)^{\frac{3}{4}} + 64 - \frac{5}{4\pi^2} + \frac{64}{8\pi^2} + \frac{\sqrt{2}}{\sqrt{B}} \pi^{\frac{3}{2}} + \frac{M^4 B}{8}.
\]

Only deuteron kinematics are non-rel

\[(2m-M)/M=0.002\]

\[(2m-M)/M=0.1\]
Validity of non-relativistic approximation

\[ Q^2 \leq 0.2M^2 \]

\[ \frac{(2m-M)}{M} = 0.002 \]

only deuteron kinematics are non-rel

\[ \frac{(2m-M)}{M} = 0.1 \]

Relativity needed

Exact vs non-relativistic Form factors for the case \( m_1 = m_2 = m \).
Light front, Infinite momentum frame

“Time”, \( x^+ = x^0 + x^3 \), “Evolve”, \( p^- = p^0 - p^3 \)

“Space”, \( x^- = x^0 - x^3 \), “Momentum”, \( p^+ \) (Bjorken)

Transverse position, momentum \( b, p \)

These variables are used in GPDs, TMDs, standard variables

Transverse boosts in kinematic subgroup

\[ k \rightarrow k - k^+ v \]

\[ |R, \lambda \rangle = \int d^2 p |p, \lambda \rangle \]

space-like \( q^\mu, q^+ = 0 \),

momentum transfer in transverse direction

then density is 2 Dimensional Fourier Transform
Model independent transverse charge density

\[ J^+(x^-, b) = \sum_q e_q q_+^\dagger(x^-, b) q_+(x^-, b) \]

\[ \rho_\infty(x^-, b) = \langle p^+, \mathbf{R} = 0, \lambda | \sum_q e_q q_+^\dagger(x^-, b) q_+(x^-, b) | p^+, \mathbf{R} = 0, \lambda \rangle \]

\[ F_1 = \langle p^+, p', \lambda | J^+(0) | p^+, p, \lambda \rangle \]

\[ \rho(b) \equiv \int dx^- \rho_\infty(x^-, b) = \int \frac{Q dQ}{2\pi} F_1(Q^2) J_0(Qb) \]

Density is \( u - \bar{u}, \ d - \bar{d} \)

Soper '77
Impact parameter dependent GPD Burkardt

Probability that quark at b from CTM has long momentum fraction x: \( \rho(x, b) \)

\[
\rho(b) = \int dx \rho(x, b)
\]

Transverse density is integral over longitudinal position or momenta

Example of Parseval’s theorem

\[
\mathbb{R} = 0 = \sum_{i}^{N} x_i b_i
\]

Quark of x=1, must have b=0

x=1 is rare
What is charge density at the center of the neutron?

- Neutron has no charge, but charge density need not vanish.
- Is central density positive or negative?

Fermi: n fluctuates to $p\pi^-$  
$p$ at center, pion floats to edge

One gluon exchange favors dud

Real question- how does form factor relate to charge density?
Transverse charge densities from parameterizations (Alberico)

Figure 4

Nucleon $\rho(b)$. (a) Proton transverse charge density. (b) Neutron transverse charge density. These densities are obtained by using the parameterization of Reference 91.

by a nonzero value of $Q^2$, no matter how small, because the momentum difference between the initial and final states appears via the use of derivatives of momentum-conserving delta functions in the moments computed in Reference 85. Any attempt to analytically incorporate relativistic corrections in a $p^2/m_q^2$ type of expansion would be doomed by the presence of the quark mass to be model dependent. This feature is explained more thoroughly in References 6 and 86.

We exploit Equation 31 by using measured form factors to determine $\rho(b)$. Recent parameterizations (87–91) of $G_E$ and $G_M$ are very useful, so we use Equation 43 to obtain $F_1$ in terms of $G_E$, $G_M$. Then $\rho(b)$ can be expressed as a simple integral of known functions,

$$\rho(b) = \int_0^\infty dQ Q^2 \pi J_0(Qb) G_E(Q^2) + \tau G_M(Q^2).$$

where $\tau = Q^2/4M^2$ and $J_0$ is a cylindrical Bessel function.

A straightforward application of Equation 44 to the proton using the parameterizations of Reference 91 yields the results shown in Figure 4a. The curves obtained by using the two different parameterizations overlap. Furthermore, there seems to be negligible sensitivity to form factors at very high values of $Q^2$ that are currently unmeasured. The density is peaked at low values of $b$ but contains has a long positive tail, suggesting a long-ranged, positively charged pion cloud.

The neutron results are shown in Figure 4b. The curves obtained by using the two different parameterizations seem to overlap. Surprisingly, the central neutron charge density is negative. The values of the integral of Equation 44 are somewhat sensitive to the regime $8 < Q^2 < 16 \text{ GeV}^2$.

Negative central density - GAM PRL '07
Neutron

Figure 5

Neutron $F_1$ and $b\rho(b)$. (a) $F_1(Q^2)$. (b) $b\rho(b)$. The solid light brown curves are obtained using fit 1 of Reference 91, and the dashed green curves are obtained by using fit 2 of the same reference.

That $\rho(b = 0) < 0$ was confirmed in References 80 and 92–94. The negative central density deserves further explanation. See Figure 5a, which shows $F_1$ for the neutron from two parameterizations of Reference 91. In both cases, $F_1$ is negative (because of the dominance of the $G_M$ term of Equation 44) for all values of $Q^2$. This feature, along with taking $b = 0$ so that $J_0(Qb) = 1$ in Equation 44, immediately leads to the central negative result.

The long-range structure of the charge density is captured by displaying the quantity $b\rho(b)$ in Figure 5b. At very large distances from the center, $b\rho(b) < 0$, which suggests the existence of the long-ranged pion cloud. Thus, the neutron transverse charge density displays an unusual behavior, in which the positive charge density in the middle region is sandwiched by negative charge densities at the inner and outer reaches of the neutron. A simple model in which the neutron fluctuates into a proton and a $\pi^-$ parameterized to reproduce the negative-definite nature of the neutron's $F_1(95)$ reproduces the negative transverse central density. In this case, the negative nature arises from pions that penetrate to the center. The change from the nominal positive value obtained from $G_E$ can be understood as originating in the boost to the IMF (86).

One can gain information about the individual $u$ and $d$ quark densities by invoking charge symmetry [invariance under a rotation by $\pi$ about the $z$ (charge) axis in isospin space (96–99)] and by neglecting the effects of $s\bar{s}$ pairs (100). Model-independent information about nucleon structure is thereby obtained and shows, surprisingly, that the central density of the neutron is negative.
Neutron interpretation

- Impact parameter gpd Burkardt $\rho(x, b)$
- Drell-Yan-West relation between high x DIS and high $Q^2$ elastic scattering
- High x related to low b, not uncertainty principle
  \[ \lim_{x \to 1} \nu W_2(x) = (1 - x)^{2n-1} \leftrightarrow \lim_{Q^2 \to \infty} F_1(Q^2) \sim \frac{1}{Q^{2n}}, n = 2 \]
- d quarks dominate DIS from neutron at high x
- d quarks dominate at neutron center, or $\pi$

Density is $u - \bar{u}$, $d - \bar{d}$
$\pi^- \text{ is } \bar{u}d$

decreases $u$ contribution
enhances $d$ contribution
Neutron interpretation $\rho(x,b)$

Using other people’s models

$d$ or $\pi^-$ dominates at high $x$, low $b$
Transverse Nucleon anomalous magnetization density

\[ \vec{\mu} \cdot \vec{B} = \langle X | \int d^3r \frac{1}{2} (\vec{r} \times \vec{j}) \cdot \vec{B} | X \rangle \]

\[ \frac{1}{2} \vec{r} \times \vec{j} \] is magnetization density (OAM) 

\( \vec{B} \) in \( x \)-direction, \( \vec{J} \) in \( z \)-direction

Magnetization density

\[ \rho_M(b) = \frac{\sin^2 \phi}{2M} b \int \frac{Q^2 dQ}{2\pi} F_2(Q^2) J_1(Qb) \]
Figure 7: Upper panel: \( \tilde{\rho}_M(b, \pi/2) \) as a function of \( b \). Lower panel: Density plot of \( \tilde{\rho}_M(b) \). The horizontal axis is the direction of the applied magnetic field. The largest (smallest) values of \( \tilde{\rho}_M \) are denoted by the brightest (darkest) areas. This figure is obtained using a dipole parametrization for \( F_2 \) of the proton.
How well are these known now?

- Analyze effect of experimental errors and errors due to finite range of $Q^2$

Proton transverse charge density

$$\rho(b) = \frac{1}{\pi R^2} \sum_{n=1}^{\infty} J_1(X_n)^{-2} F(Q_n^2) J_0(X_n \frac{b}{R}),$$

$$Q_n \equiv \frac{X_n}{R}.$$

Venkat, Arrington, Miller, Zhan new analysis-

Proton anomalous magnetization density

\[ \rho_{m}^{FRA} = \frac{1}{\pi R^2} \sum_{n=1}^{\infty} J_2^{-2}(X_{1,n}) b Q_{1,n} F_2(Q_{1,n}^2) J_1(Q_{1,n} b), \quad Q_{1,n} = \frac{X_{1,n}}{R_2} \]
Determination of $F_\pi$ via Pion Electroproduction

At low $Q^2 < 0.3$ GeV$^2$, the $\pi^+$ form factor can be measured exactly using high energy $\pi^+$ scattering from atomic electrons.

$\Rightarrow$ 300 GeV pions at CERN SPS. [Amendolia et al., NP B277(1986)168]

$\Rightarrow$ Provides an accurate measure of the $\pi^+$ charge radius.

$$r_\pi = 0.657 \pm 0.012 \text{ fm}$$

To access higher $Q^2$, one must employ the $p(e,e'\pi^+)n$ reaction.

- $t$-channel process dominates $\sigma_L$ at small $-t$.
- In the Born term model:

\[
\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t - m_{\pi}^2)} g_{\pi NN}^2(t) F_\pi^2(Q^2, t)
\]
Pion Transverse Charge Density

\[ F_\pi(Q^2) = \frac{1}{(1 + R^2Q^2/6)}, \]

Dashed- monopole fit, solid rel. cqm Huang

\[ \rho_\pi(b) = \frac{3K_0(\frac{\sqrt{6}b}{R})}{\pi R^2} \]

Singular - varies as \( \log(b) \)

Small \( b \), \( \log(\log(b)) \) in pQCD

Large argument

\[ K_0(x) \sim \frac{e^{-x}}{x} \]

Fractional Difference

FIG. 1: (Color online)

\[ F_\pi(Q^2) \]

FIG. 2: (Color online)

\[ \rho(b)(GeV^2) \]

\[ b(\frac{1}{GeV}) \]

\[ b(\frac{1}{GeV}) \]

\[ b(\frac{1}{GeV}) \]
Pionic Transverse Density From Time-like and Space-Like Probes

Gerald A. Miller\textsuperscript{1}, Mark Strikman\textsuperscript{2}, Christian Weiss\textsuperscript{3}

\[
\rho(b) = \frac{1}{(2\pi)} \int_0^\infty dQ Q J_0(Qb) F_\pi(Q^2)
\]

\[
F_\pi(t) = \frac{1}{\pi} \int_0^\infty \frac{dt' ImF_\pi(t')}{t' - t + i\epsilon}.
\]

\[
K_0(x) \sim \frac{e^{-x}}{x} \rho(b) = \frac{1}{2\pi} \int_{4m_\pi^2}^{\infty} dt K_0(\sqrt{tb}) \frac{ImF_\pi(t)}{\pi}.
\]

Dispersion relation

Low \( t \) dominates except for very small values of \( b \)

Model needed: C. Bruch et al E. J. Phys.C39, 41
\( \rho_\pi(b) \) is known for \( b > 0.1 \text{ fm} \)
Summary

- Much data exist, Jlab12 will improve data set
- Charge density is not a 3 dimensional Fourier transform of $G_E$
- Interpret form factor as determining transverse charge and magnetization densities
- Nucleon transverse densities known now to high precision
- Pion transverse density known fairly well
Spares follow
Proton

Results finalized, accepted for publication in PRL

50% increase in $Q^2$

New data favor a slowing rate of decrease of $R$


$\mu \frac{G^p_{PE}}{G^p_M}$ $G^p_M$ known $Q^2 \leq 31 GeV^2$
Generalized transverse densities-

\[ \mathcal{O}_q^\Gamma (px, b) = \int \frac{dx^- e^{ipxx^-}}{4\pi} q_+^\dagger (0, b) \Gamma q_+ (x^-, b) \]

\[ \rho^\Gamma (b) = \int dx \sum_q e_q \langle p^+, R = 0, \lambda | \mathcal{O}_q^\Gamma (p^+ x, b) | p^+, R = 0, \lambda \rangle \]

\[ \int dx \text{ sets } x^- = 0, \text{ get } q_+^\dagger (0, b) \Gamma q_+ (0, b) \quad \text{Density!} \]

\[ \Gamma = \frac{1}{2} (1 + n \cdot \gamma \gamma^5) \] gives spin-dependent density

Local operators calculable on lattice M. Göckeler et al PRL98,222001 \[ \tilde{A}_{T10}'' \sim \text{sdd} \quad \text{spin-dependent density} \]

Schierholtz, 2009 -this quantity is not zero, proton is not round
Observing shape of proton

- Transverse coordinate space density is a GPD, observe on lattice
- Transverse momentum space density is a TMD, can be observed in

\[ e, \uparrow p \rightarrow e' \pi \ X \]
\[
\langle \mathbf{r}_p | \psi_{1,1/2s} \rangle = R(r_p) \mathbf{\sigma} \cdot \hat{\mathbf{r}}_p | s \rangle
\]

\[
\rho(r) = \langle \psi_{1,1/2s} | \delta(\mathbf{r} - \mathbf{r}_p) | \psi_{1,1/2s} \rangle = R^2(r)
\]

probability proton at \( r \) & spin direction \( \mathbf{n} \):

\[
\rho(r, \mathbf{n}) = \langle \psi_{1,1/2s} | \delta(\mathbf{r} - \mathbf{r}_p)^{(1+\mathbf{\sigma} \cdot \mathbf{n})/2} | \psi_{1,1/2s} \rangle
\]

\[
= \frac{R^2(r)}{2} \langle s | \mathbf{\sigma} \cdot \hat{\mathbf{r}} (1 + \mathbf{\sigma} \cdot \mathbf{n}) \mathbf{\sigma} \cdot \hat{\mathbf{r}} | s \rangle
\]

\( \mathbf{n} \parallel \hat{s} : \quad \rho(r, \mathbf{n} = \hat{s}) = R^2(r) \cos^2 \theta \)

\( \mathbf{n} \parallel -\hat{s} : \quad \rho(r, \mathbf{n} = -\hat{s}) = R^2(r) \sin^2 \theta \)

non-spherical shape depends on spin direction
Summary

• Much data exist, Jlab12 will improve data set
• Interpret form factor as determining transverse charge and magnetization densities
• Nucleon transverse densities known now to high precision,

• Pion known fairly well

•
Relativistic formalism-kinematic subgroup of Poincare

- Lorentz transformation – transverse velocity \( v \)

\[
k^+ \rightarrow k^+, \quad k \rightarrow k - k^+v
\]

\( k^- \) such that \( k^2 \) not changed

**Just like non-relativistic with \( k^+ \) as mass, take momentum transfer in perp direction, then density is 2 Dimensional Fourier Transform, also**

\[
q^+ = q^0 + q^3 = 0, \quad -q^2 = Q^2 = q^2
\]
Transverse charge densities

\[ \rho(b) \, [ \text{fm}^{-2} ] \]

Proton

\[ \rho(b) \, [ \text{fm}^{-2} ] \]

Neutron

Negative
Negative $F_1$ means central density negative
Return of the cloudy bag model

- In a model nucleon: bare nucleon + pion cloud - parameters adjusted to give negative definite $F_1$, pion at center causes negative central transverse charge density

- Boosting the matrix element of $J^0$ to the infinite momentum frame changes $G_E$ to $F_1$

Rinehimer and Miller
PRC80,015201, 025206
Spin dependent densities-transverse-Lattice QCDSF, Zanotti, Schierholz…

This is not zero!
Transverse Momentum Distributions - momentum space density

In a state of fixed momentum

$\Phi^\Gamma_q(x, \mathbf{K})$ give probability of quark of given 3-momentum

$h_{1T}^\perp$ gives momentum-space spin-dependent density

measurable experimentally

hard to calculate on lattice because - gauge link
Relation or not between GPD and TMD

GPD:

\[
\langle P', S' \mid \int \frac{dx^-}{4\pi} \bar{q}(-\frac{x^-}{2}, 0) \gamma^+ q(\frac{x^-}{2}, 0) e^{ixp^+x^-} \mid P, S \rangle_{x^+} = 0
\]

\[
= \frac{1}{2p^+} \bar{u}(P', S') \left( \gamma^+ H_q(\xi, t) + i \frac{\sigma^{+\nu} \Delta^\nu}{2M} E_q(x, \xi, t) \right) u(P, S)
\]

TMD:

\[
\Phi^\Gamma_{q}(x = \frac{k^+}{P^+}, k) = \langle P, S \mid \int \frac{d\zeta^- d^2\zeta}{2(2\pi)^3} e^{ik\cdot\zeta} \bar{q}(0) \Gamma q(\zeta) \mid P, S \rangle_{\zeta^+ = 0}
\]

GPD: nucleons have different momenta, but FT local in coordinate space if integrate over x

TMD: nucleons have same momenta, operator is local in momentum space
Both can be obtained Wigner distribution operator

$$W^\Gamma_q (\zeta^-, \zeta, k^+, \mathbf{k})$$

$$= \frac{1}{4\pi} \int d\eta^- d^2\eta e^{i\mathbf{k} \cdot \eta} \eta^- (\zeta^- - \frac{\eta^-}{2}, \zeta - \frac{\eta^-}{2}) \Gamma_q (\zeta^- + \frac{\eta^-}{2}, \zeta + \frac{\eta^-}{2})$$

$$H_q (x, \xi, t) = \langle P', S' | \int \frac{d^2\mathbf{k}}{(2\pi)^2} W^\gamma_q (\zeta^- = 0, \zeta = 0, k^+, \mathbf{k}) | P, S \rangle$$

$$\Phi^\Gamma_q (x, \mathbf{k}) = \langle P, S | \int \frac{d\zeta^-}{(2\pi)^2} W^\Gamma_q (\zeta^-, \zeta, k^+, \mathbf{k}) | P, S \rangle$$
Summary

- Form factors, GPDs, TMDs, understood from unified light-front formulation
- Neutron central transverse density is negative-consistent with Cloudy Bag Model
- Proton is not round- lattice QCD spin-dependent-density is not zero
- Experiment can whether or not proton is round by measuring $h_{1T}^{\perp}$
Summary

• Form factors, GPDs, TMDs, understood from unified light-front formulation
• Neutron central transverse density is negative-consistent with Cloudy Bag Model
• Proton is not round- lattice QCD spin-dependent-density is not zero
• Experiment can whether or not proton is round by measuring $h_{1T}$

The Proton
Cloudy bag model of the nucleon

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(Received 28 January 1981)

A previously derived model in which a baryon is treated as a three-quark bag that is surrounded by a cloud of pions is used to compute the static properties of the nucleon. The only free parameter of the model is the bag radius which is fixed by a fit to pion-nucleon scattering in the (3,3)-resonance region to be about 0.8 fm. With the model so determined the computed values of the root-mean-square radii and magnetic moments of the neutron and proton, and $g_A$, are all in very good agreement with the experimental values. In addition, about one-third of the $\Delta$-nucleon mass splitting is found to come from pionic effects, so that our extracted value of $\alpha_s$ is smaller than that of the MIT bag model.

Many successful predictions

One feature- pion penetrates to the bag interior
What is charge density at the center of the neutron?

- Neutron has no charge, but charge density need not vanish
- Is central density positive or negative?

Fermi: \( n \) fluctuates to \( p\pi^- \)  

\( p \) at center, pion floats to edge

One gluon exchange favors  \( dud \)

Real question- how does form factor relate to charge density?
interpretation of FF as quark density

overlap of wave function Fock components with different number of constituents

NO probability/charge density interpretation

Absent in a Drell-Yan Frame

$q^+ = q^0 + q^3 = 0$

From Marc Vanderhaeghen
Electric Form Factor of the Neutron up to $Q^2=3.4$ GeV$^2$ using the Reaction $\text{He}^3(e,e'n)pp$.

S. Riordan et al. Aug 2010. e-Print: 1008.1738
Overview of results for $G_M^n$

A systematic difference of several % between results from JLab and MAMI in $Q^2$-range 0.4 - 1.0 GeV$^2$

Reminder that at least two independent experiments are always needed

High-quality data set now available up to ~4.5 GeV$^2$