#### Herman Feshbach Prize in Nuclear Physics

To recognize and encourage outstanding research in theoretical nuclear physics. The prize will consist of \$10,000 and a certificate citing the contributions made by the recipient. The prize will be presented biannually or annually-depends on your contributions.

Herman Feshbach was a dominant force in Nuclear Physics for many years. He coauthored two seminal textbooks, provided the theoretical basis for nuclear reaction theory, and originated the "Feshbach resonance" used to control the interactions between atoms in ultracold gases. He also made many administrative contributions.

The establishment of this prize depends entirely on the contributions of institutions, corporations and individuals associated with Nuclear Physics. So far, significant pledges have been made by MIT, the DNP, Elsevier, ORNL/U.Tenn, JSA/SURA, LANL, TUNL, and many individuals. But the collection of contributions has begun. Please make a contribution by going online at **http://www.aps.org/** Look for the support banner and click APS member or non-member. Another way is to send a check, made out to "The American Physical Society", with a notation indicating the purpose is the Feshbach Prize Fund, to

Darlene Logan Director of Development American Physical Society One Physics Ellipse College Park, MD 20740-3844

#### **If annual- number of experimentalists winning Bonner prize goes up by >50%**

1

If you have any questions please contact G. A. (Jerry) Miller UW, miller@uw.edu.

#### **Nucleon Electromagnetic Form Factors and Spin: is proton made of 3 quarks?**

**Gerald A. Miller, UW**

Connection between elastic form factors and OAM through models

Model wave functions, compute form factors

OAM content of Models: elastic form factors imply that quark, pion OAM is large

## What is not in the talk

- Proton radius new work
- Transverse densities slope of  $G_E$  is not the real radius
- Transverse densities from dispersion relations: PHYSICAL REVIEW D 83, 013006 (2011)

Pion transverse charge density from timelike form factor data

G. A. Miller, <sup>1</sup> M. Strikman,  $^2$  and C. Weiss<sup>3</sup>

 $\text{DINGICAL}$  Physics, University of  $\theta$ 4, 045205-(2011) PHYSICAL REVIEW C **84**, 045205 (2011)

Theory Center, Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA Realizing vector meson dominance with transverse charge densities

G. A. Miller, <sup>1</sup> M. Strikman,<sup>2</sup> and C. Weiss<sup>3</sup> **Physical physical of the imaginary integral of the imaginary integ** part of the pion form factor in the timelike region. This formulation incorporates information from eþe" <sup>1</sup>*Department of Physics, University of Washington, Seattle, Washington 98195-1560, USA* **Phys.Rev.Lett. 108 (2012) 232301**

The Electromagnetic Self-Energy Contribution to  $M_p - M_n$ and the Isovector Nucleon Magnetic Polarizability

 $\textsf{A}$  lot of other stuff  $\textsf{A}$  and respectively. And respectively,  $\textsf{A}$  and  $\textsf{$ part of the Dirac form factor in the time transverse distance region (spectral function). At a given transverse distance b the timelihood of the timel

at a distance b  $\mathcal{A}$  fm, and significantly better at larger distances. The density is found to be close to be  $\mathbf{A}$   $\mathbf{$ 

#### $\alpha$  results two-dimensional image of the fast-moving pion can be interpreted in terms of its interpreted in terms of  $\alpha$ partonic structure in Accord. We argue that the singular behavior of the charge density at the charge density a substantial presence of pointlike configurations in the pion's partonic wave function, which can be integration effective extends over energies in a range √t in a range √t in a range values. **Review of all models is absent**  $\mathbf{S}$ dels is absent of  $^{-3}$ <sup>4</sup>Department of Physics, University of Washington, Seattle, WA 98195-1560.

3

### History -Definitions

$$
\overline{u}(p',\lambda')\Gamma^{\mu}u(p,\lambda) = \overline{u}(p',\lambda')[\gamma^{\mu}F_1(Q^2) + \frac{i\sigma^{\mu\nu}(p'-p)_{\nu}}{2M}F_2(Q^2)]u(p,\lambda)
$$
  
\n
$$
G_E \equiv F_1 - \frac{Q^2}{4M}F_2, \ G_M = F_1 + F_2
$$

 $F_1$  is light-front helicity non-flip,  $F_2$  is light-front helicity flip

old pQCD:

$$
\frac{QF_2(Q^2)}{2M_NF_1} \sim \frac{m_{\text{quark}}}{Q} \to \frac{G_E}{G_M} = \text{ const}
$$

Same as non-relativistic





#### JLab 2000,2002



### Relativistic Wave function

Frank, Jennings, Miller PR C54, 920 (1996) Relativistic model for color transparency

- 3 quark anti-symmetric
- **Light front variables** • relative variables, frame independent
- eigenstate of spin operator- rotational invariant
- reduces to non-relativistic if  $m\to\infty$

 $\Psi = \Phi(M_0^2)u(p_1)u(p_2)u(p_3=K)\psi(s_i,t_i)$  Terentev, Coester spatial dist DIRAC SPINORS spin-ispin color amp Schlumpf Mom space wf  $\Phi(M_0) = N/(M_0^2 + \beta^2)^\gamma$  $\beta = 0.607$ GeV  $\gamma = 3.5$   $m = 0.267$  GeV

### **Impulse Approximation**



## 1995 Frank, Jennings, Miller



### Ratio of Pauli to Dirac Form Factors 1995



## Relativistic Explanation

 $J^+$  acts on third quark, other two have 0 spin

$$
u(K,s) = \left(\begin{array}{c} (E(K) + m)|s\rangle \\ \boldsymbol{\sigma} \cdot \mathbf{K}|s\rangle \end{array}\right)
$$

 $\langle \sigma_y | s \rangle$ : quark spin  $\neq$  proton ang mom

lower components  $\equiv L_z \neq 0$ 

$$
\bar{u}(K',s')\gamma^+u(K,s)\sim \langle s'|K^++i\sigma_yQ|s\rangle\text{ Large }Q
$$

spin non-flip  $F_1(Q^2) = \int \cdots Q \Phi \Phi$ , flip  $QF_2 = \int \cdots Q \Phi \Phi$ 

$$
\frac{QF_2}{F_1} \sim Constant
$$

Miller, Frank **Phys.Rev. C65 (2002) 065205**

## Relativistic Explanation

 $J^+$  acts on third quark, other two have 0 spin

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**Large OAM associated with relativistic effects**

 $\langle \sigma_y | s \rangle$ : quark spin  $\neq$  proton ang mom

lower components  $\equiv L_z \neq 0$ 

 $\bar{u}(K',s')\gamma^+u(K,s)\sim \langle s'|K^++i\sigma_yQ|s\rangle$  Large Q

spin non-flip  $F_1(Q^2) = \int \cdots Q \Phi \Phi$ , flip  $QF_2 = \int \cdots Q \Phi \Phi$ 

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Miller, Frank **Phys.Rev. C65 (2002) 065205**

# $s_{\mu}\Delta q = \langle N, s|\bar{q}\gamma_{\mu}\gamma_5 q|N, s\rangle$  $\Sigma = \Delta u + \Delta d + \Delta s$ Spin content - OAM

**75 % of proton angular momentum carried by quark spin**

Textbook relativistic effect that reduces calculated axial vector coupling constant below NRQM value 5/3



Relativistic treatment needed Feynman graphs,  $\int dk^{-}$ 

Light front cloudy bag model LFCBM 2002

**Miller Phys.Rev. C66 (2002) 032201**

- $\gamma N$  form factors from model (our model)
- rel.  $\pi N$  form factor  $\Lambda_{\pi N}$
- Model parameters:  $m, \beta, \gamma, \Lambda_{\pi N}$

Consistent with leading non-analytic terms in chiral expansion

## Neutron Electric Form Factor



#### **LFCBM 2002- much better data now**

### Ratio of Pauli to Dirac Form



### Two More Form Factors Needed



## OAM content of light front cloudy bag model

 $\Sigma \rightarrow (Z - \frac{1}{3})$ 3  $P_{N\pi}$  + 5 3  $P_{\Delta\pi}$ ) $\Sigma$ Schreiber*,* Thomas PLB215*,* 141(88)  $LFCBM : P_{N\pi} \approx .25, P_{\Delta \pi} = 0$  $\sum \rightarrow$ 2 3  $\sum \sim$ 2 3 3 4 = 1 2

16 Can now include ∆ Alberg, Miller PRL **108 (2012) 172001**

# 2011 Update model

- In LFCBM  $G_F/G_M$  falls too fast with  $Q^2$
- New data -slower fall, flavor decomposition not good Cates et al **Phys.Rev.Lett. 106 (2011) 252003**
- get smaller quark spin?
- Many invariant forms of nucleon wave function
- Cloet & Miller **arXiv:1204.4422**quark di-quark model:
- uses other invariant wave functions

(Brodsky, Hiller, Karmanov, Hwang PRD 2001) 17

#### Cloet Miller 2011-12  $C$ *loet Miller*  $\frac{1}{2}$ ϕ*a* <sup>1</sup> + *M* ω*/* ω *· p* ϕ*a* 2 , *u*(*p,* λ)*,* (5)

where the first term represents the first term represents the first term represents the  $\sim$ 

ω *· p*

where *<sup>M</sup>* is the nucleon mass and *<sup>Q</sup>*<sup>2</sup> = <sup>−</sup>*q*<sup>2</sup>, where *<sup>q</sup>*

is the 4-momentum transfer. We choose to work in the

Drell-Yan-West frame, where the light-front momentum

the Dirac and Pauli from factors are identified with the

helicity-conserving and helicity-flip matrix elements of

 $t_{\rm eff}$ 

decompositions of the relevant 4-vectors are

so that *<sup>q</sup>*<sup>2</sup> = <sup>−</sup>2 *<sup>p</sup> · <sup>q</sup>* = <sup>−</sup>*q*<sup>2</sup>

$$
\Phi_{\lambda_q \lambda_D}^{\lambda_N}(k, p) = \bar{u}(k, \lambda_q) \left[ \varphi_1^s + \frac{M}{p^+} \gamma^+ \varphi_2^s \right] u_N(p, \lambda_N)
$$

$$
+ \bar{u}(k, \lambda_q) \, \varepsilon_{\nu}^*(q, \lambda_D) \gamma^{\nu} \gamma_5 \left[ \varphi_1^a + \frac{M}{p^+} \gamma^+ \varphi_2^a \right] u_N(p, \lambda_N)
$$

**Axial vector diquark** with the dimensional vector of the dimensional vector of the dimensional vector of the dimension of the dimension

$$
\begin{aligned} |p\rangle &= \frac{1}{\sqrt{2}} |u \, S_0 \rangle + \frac{1}{\sqrt{6}} |u \, T_0 \rangle - \frac{1}{\sqrt{3}} |d \, T_1 \rangle, \\ \varphi_1 &= \frac{1}{(M_0^2 + \beta^2)^\gamma}, \qquad \varphi_2 = c \, \frac{(M_0 - M)}{2 \, M} \varphi_1. \end{aligned}
$$

#### **Plus pion cloud- 9 parameters**



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$$

#### **Plus pion cloud- 9 parameters**



#### **Cloet &Miller '11-'12**  $\blacksquare$ *F*1*<sup>p</sup>* = *ZN*<sup>π</sup> *F*(0) <sup>1</sup>*<sup>p</sup>* + <sup>2</sup> *<sup>F</sup>*(0) <sup>1</sup>*<sup>p</sup>* <sup>+</sup> *<sup>F</sup>*(0)  $\overline{\phantom{a}}$ &<sup>1</sup> <sup>2</sup> *<sup>F</sup>*(0) <sup>2</sup>*<sup>p</sup>* <sup>+</sup> *<sup>F</sup>*(0) 2*n*

| Model proton wave function: quarknetic current. The first diagram represents the photon of  $\mathbb{R}^n$ cleon is introduced via a single pion loop around our bare coupling to the bare nucleon, multiplied by *ZN*π, which

Lorentz and rotationally invariant- $Z_{N\pi} \times \longrightarrow p$  + *µ q*  $p \rightarrow p'$ *µ q*  $+$ *p p' µ q*

&<sup>1</sup>

'

*F*(*N*)*,*ten

'

*F*(*N*)*,*vec

<sup>1</sup>*<sup>N</sup> ,* (45)

<sup>1</sup>*<sup>N</sup>* <sup>+</sup> *<sup>F</sup>*(π)

Light front variables with a pion in the air, the photon coupling is given by  $\mathbf{r}$ 

different forms!

 $\frac{1}{2}$  and only forms.

γ*<sup>µ</sup> F*(0)

 $|$  *Dirac spinors-orbital angular* momentum <mark>S-</mark>OI *<u></u><br><i>F*(a) angu <sup>1</sup>*<sup>n</sup>* (*Q*<sup>2</sup>) + *<sup>i</sup>*σ*<sup>µ</sup>*<sup>ν</sup>*q*<sup>ν</sup>

> Pion cloud of Light Front Cloudy Bag Model -GAM PRC **66 (2002) 032201** Could be improved according to Alberg Miller **Phys.Rev.Lett. 108 (2012) 172001**





#### Flavor separation: Cates, de Jager, Riordan, Wojtsekhowski PRL 106,252003 1.4  $Q^4 f_1^{\ u}$ 1.2  $\mathbf 1$  $Q^4F_1(Q^2)$  $0.8$  $0.6$  $2.5 \times Q^{4}f_{1}^{d}$  $0.4$  $0.2$  $\overline{2}$  $\mathbf{1}$  $\overline{4}$ 5  $Q^2$  (GeV<sup>2</sup>) 22



#### Quark-Diquark model -spin content  $\overline{\phantom{a}}$ nucleon, and netic current. The first diagram represents the photon <sup>2</sup> *<sup>F</sup>*(0) <sup>2</sup>*<sup>p</sup>* <sup>+</sup> *<sup>F</sup>*(0) 2*n* ' <sup>1</sup>*<sup>N</sup>* <sup>+</sup> *<sup>F</sup>*(π)

<sup>2</sup> *<sup>F</sup>*(0)

<sup>1</sup>*<sup>p</sup>* <sup>+</sup> *<sup>F</sup>*(0)

1*n*

*F*(*N*)*,*ten

'

1*N*

*µ*

<sup>1</sup>*<sup>p</sup>* +

 $\overline{a}$ 



24 No gluons, so effects of quark orbital angular momentum **Changes to naive quark model are modest, not revolutionary**

 $T_{\rm eff}$  component of our model for the nu-

#### Understanding Parameters and spin content



- Lighter quark mass 191 vs 267 MeV Table I. Model parameters: *m* constituent quark mass, *M<sup>s</sup>* scalar diquark mass, *M<sup>a</sup>* axial vector diquark mass, quark–scalar- $\Box$  Eightor quarty muod-Tor vo Eq. (54). All mass-dimensioned parameters are in GeV. The first column  $\Box$
- Relativistic effects are larger than in earlier models, therefore more OAM gives the fit expressed in the fit expressed in Eq. (58) and the fit expressed in Eq. (58) and neutron and neu  $\blacksquare$  . Re
	- **Axial vector di-quark has enhanced** components with quark spin opposing proton spin, signature of OAM  $\Omega$ 0*.*5 1*.*0 1*.*5 2*.*0 2*.*5  $G_{Ep}$   $\longrightarrow$   $G_{Mp}$  $\Omega$ 0*.*2 *µp* 0*.*6 0*.*8 1*.*0 *G*  $E_p(\widetilde{\boldsymbol{\mathcal{G}}}^2)/\widetilde{\boldsymbol{\mathcal{G}}}$ *M* **pas empanced** model result empirical – Venkat

 $0 \qquad \qquad 2 \qquad \qquad 4 \qquad \qquad 6 \qquad \qquad 8$  $Q^2$  (GeV<sup>2</sup>)

result and the dashed curve is the phenomenological fit of

Ref. [15]. The data are from Refs. [16–20].

0 0*.*5 1*.*0 1*.*5 2*.*0  $Q^2$  (GeV<sup>2</sup>)

 $\mathbb{P}^1(\mathbb{R}^d)$  . (Color online) Solid lines are the model results for model results for model results for the proton Sachs form factors and the dashed lines are the

empirical results from Kelly given in Ref. [14].

proton Sachs form factors

## Integrands for spin content



### Quark distribution q(x)-non evolved



### Summary

- Relativistic light front quark model with pion cloud can reproduce nucleon form factors
- Flavor separation works and is testable in the future
- Model quark spin is 36.5 % of total angular momentum, quark OAM is important
- (Relativistic) quark model alive and well, proton is made mainly of three quarks