High t form factors & Compton Scattering - quark based models

Gerald A. Miller
University of Washington

Basic Philosophy- model wave function Ψ

- Given Ψ compute form factors, densities, Compton scattering ....
- Make guess at how QCD works, improve guess, rule out simple scenarios
- Non-relativistic quark model
- 3 quarks
- 0 orbital angular momentum
- proton is round
- What can Compton scattering say?

Basic Philosophy- model wave function Ψ

- Given Ψ compute form factors, densities, Compton scattering ....
- Make guess at how QCD works, improve guess, rule out simple scenarios
- ~~Non-relativistic quark model~~
- 3 quarks
- 0 orbital angular momentum
- proton is round
- What can Compton scattering say?

Basic Philosophy- model wave function Ψ

- Given Ψ compute form factors, densities, Compton scattering ....
- Make guess at how QCD works, improve guess, rule out simple scenarios
- ~~Non-relativistic quark model~~
- ~~3 quarks~~
- 0 orbital angular momentum
- proton is round
- What can Compton scattering say?

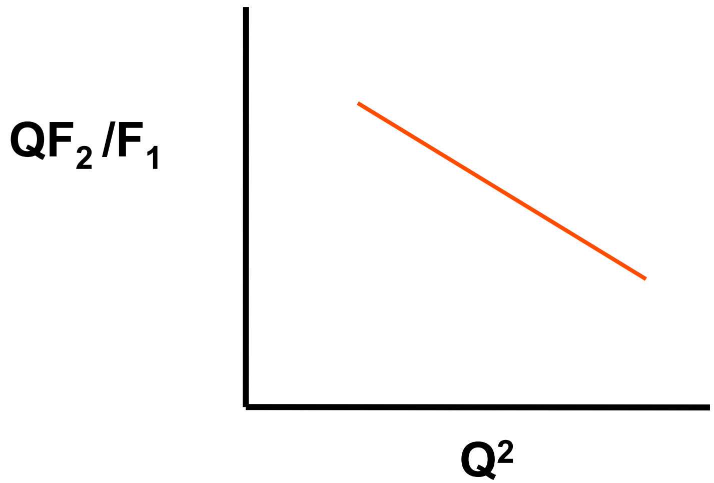
Basic Philosophy- model wave function Ψ

- Given Ψ compute form factors, densities, Compton scattering ....
- Make guess at how QCD works, improve guess, rule out simple scenarios
- ~~Non-relativistic quark model~~
- ~~3 quarks~~
- ~~0 orbital angular momentum~~
- proton is round
- What can Compton scattering say?

Basic Philosophy- model wave function Ψ

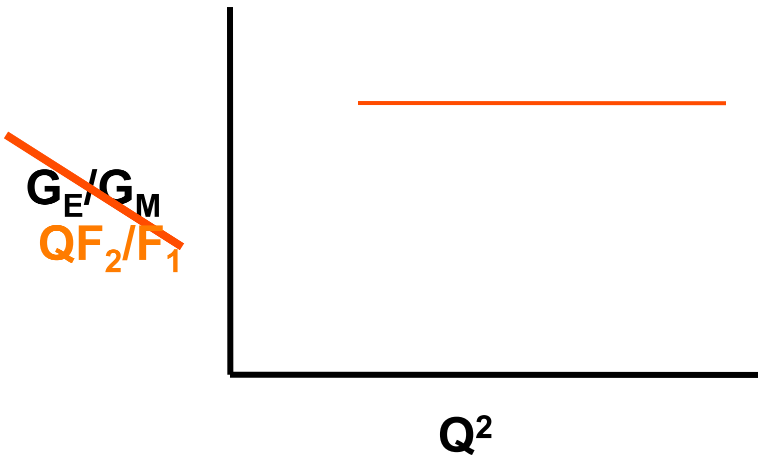
- Given Ψ compute form factors, densities, Compton scattering ....
- Make guess at how QCD works, improve guess, rule out simple scenarios
- ~~Non-relativistic quark model~~
- ~~3 quarks~~
- ~~0 orbital angular momentum~~
- ~~proton is round~~
- What can Compton scattering say?

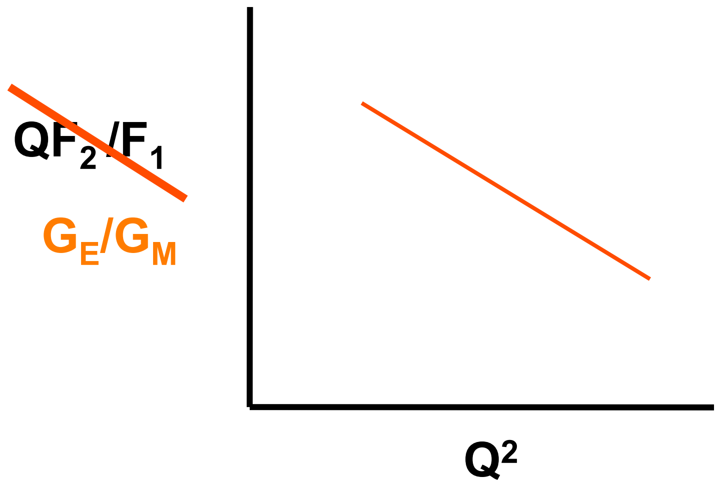
Expectations- Pre Jlab



$$\frac{G_E}{G_M} \text{ constant : non } - \text{ relativistic quark model}$$

Expectations- Pre Jlab

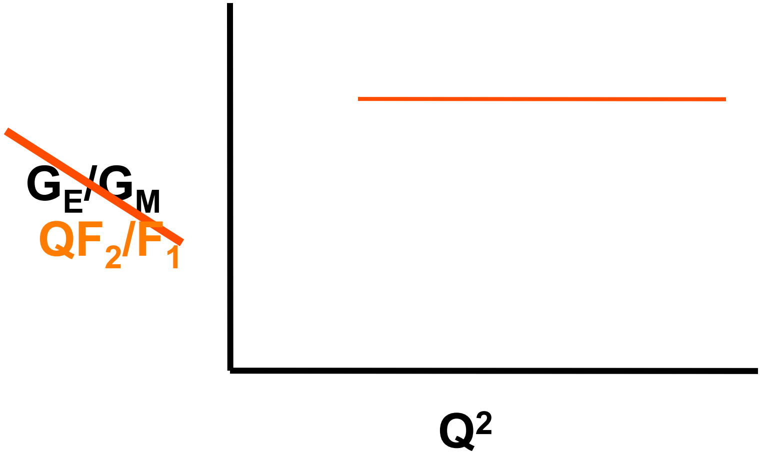


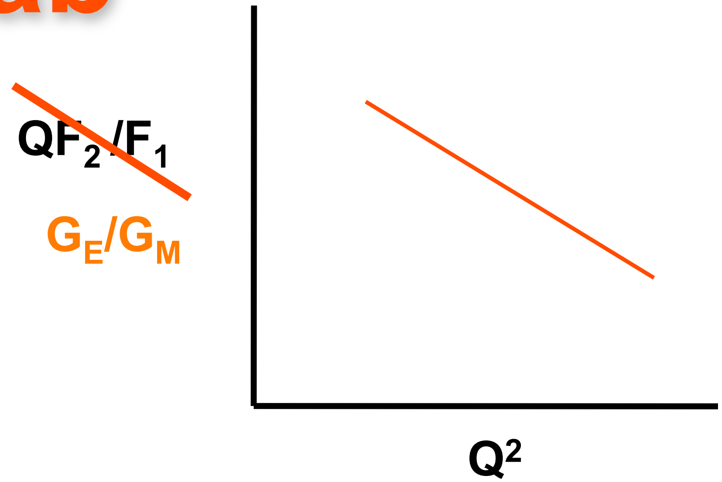


$$\frac{G_E}{G_M} \; \mathrm{constant : non - relativistic\ quark\ model}$$

Form Factor

Jlab

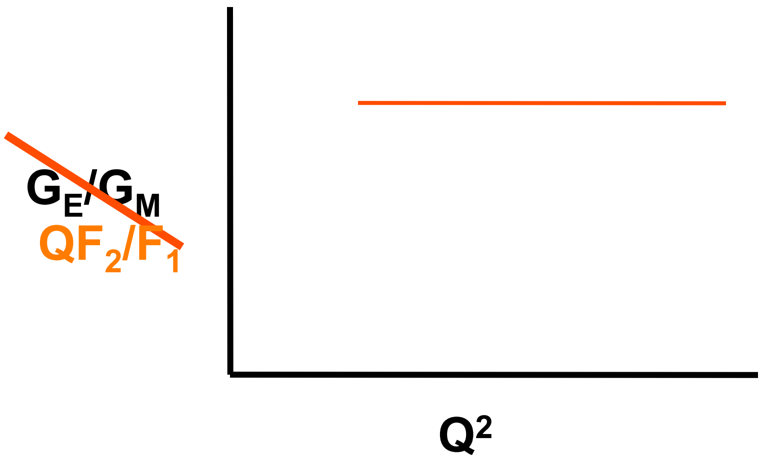


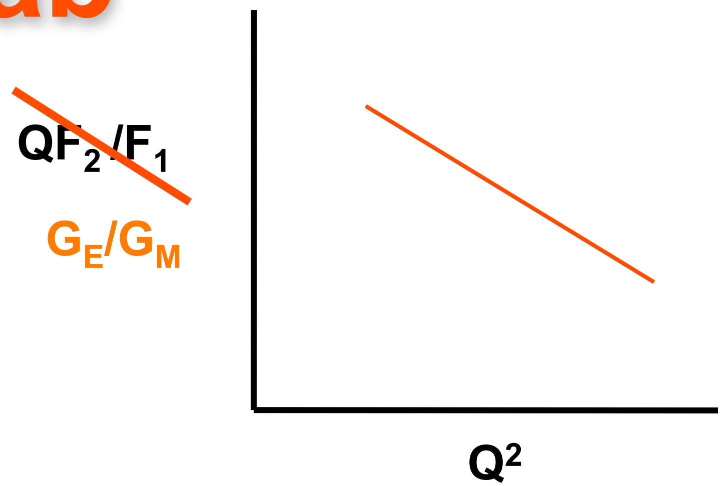


$$\frac{G_E}{G_M} \text{ constant : non} - \text{relativistic quark model}$$

Form Factor

Jlab





$$\frac{G_E}{G_M}\ \mathrm{constant : non-relativistic\ quark\ model}$$

Relativistic model needed- light front coordinates

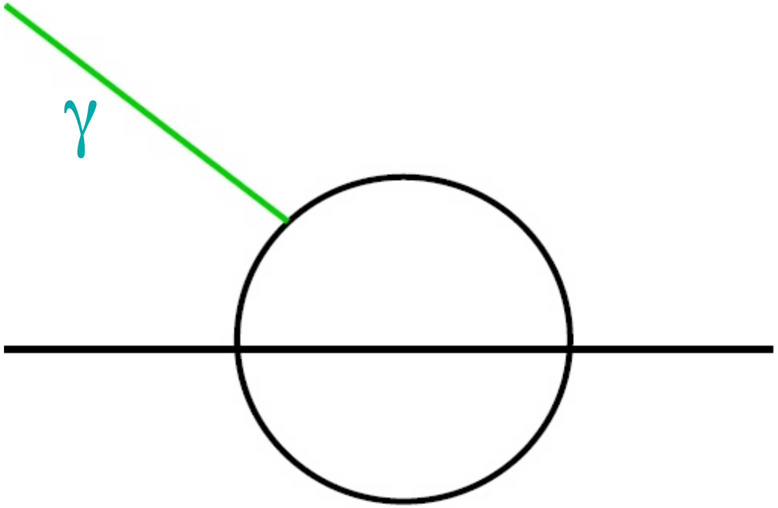
Understand phenomena-model

Model proton wave function:3 quarks

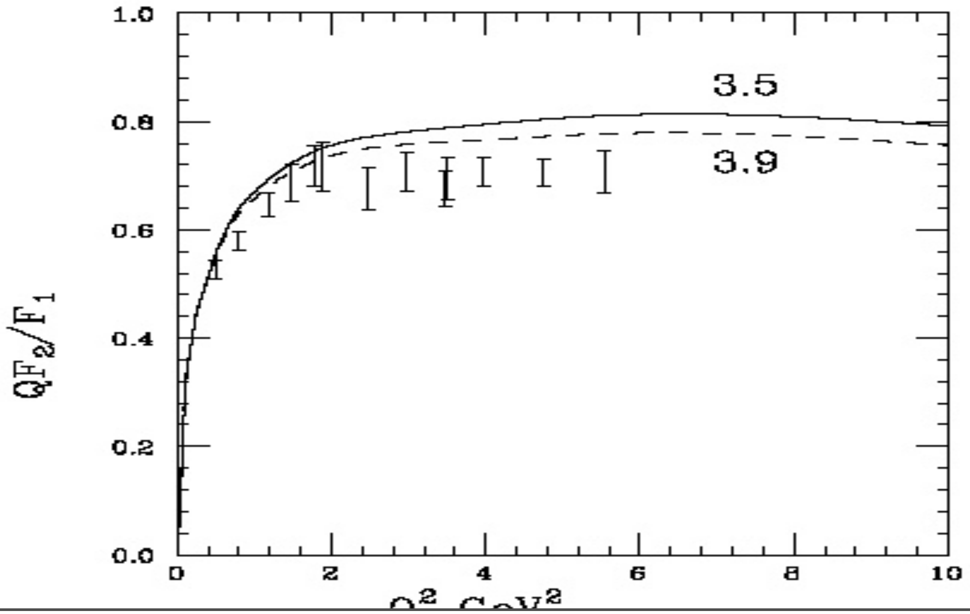
Lorentz and rotationally invariant

Light front variables

Dirac spinors-orbital angular momentum



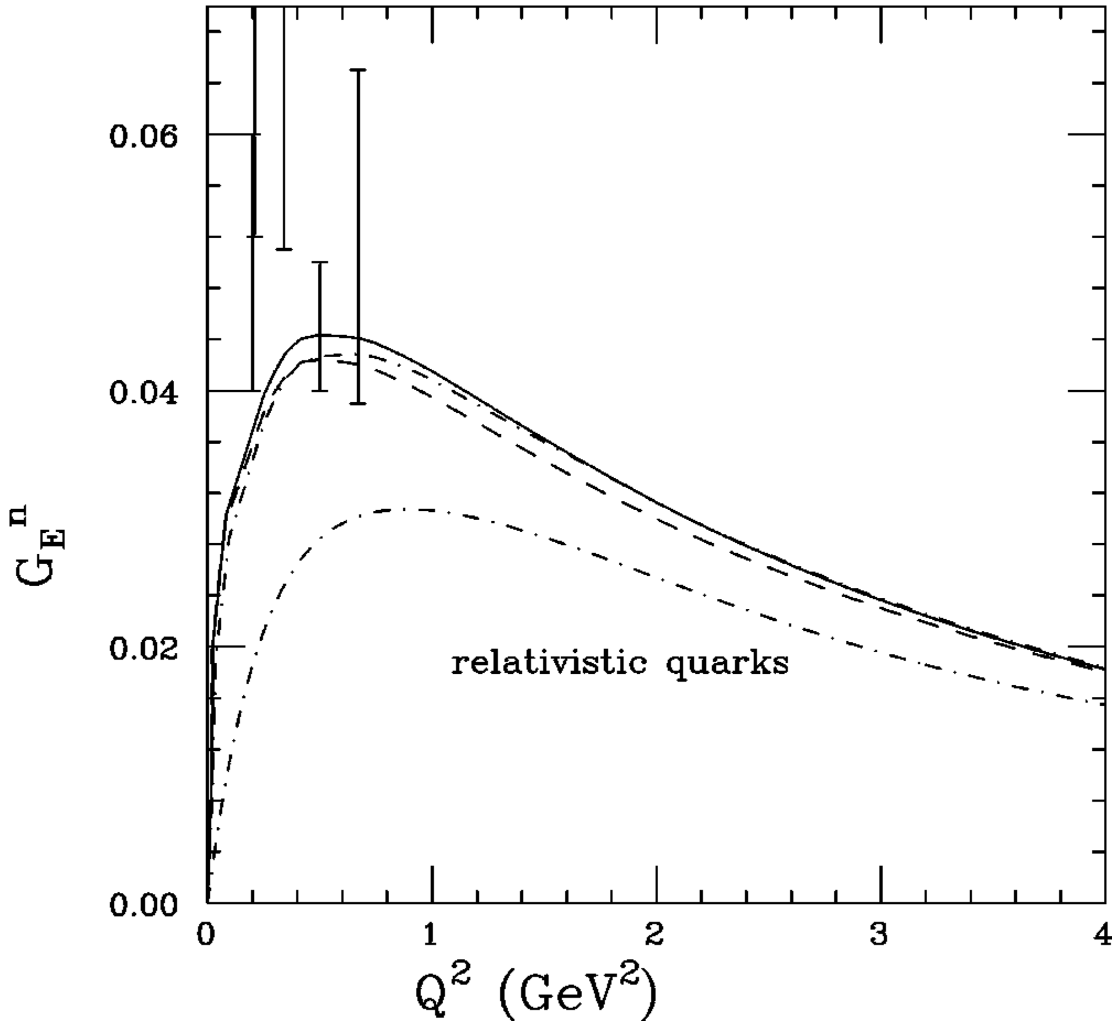
M. R. Frank, , B.K. Jennings, , G.A. Miller,. Phys.Rev.C54:920-935,1996.



Theory 1995 Data 2000

Quark spin is 75 % of proton total angular momentum

Neutron- requires pion cloud



Gerald A. Miller, Phys.Rev.C66:032201,2002

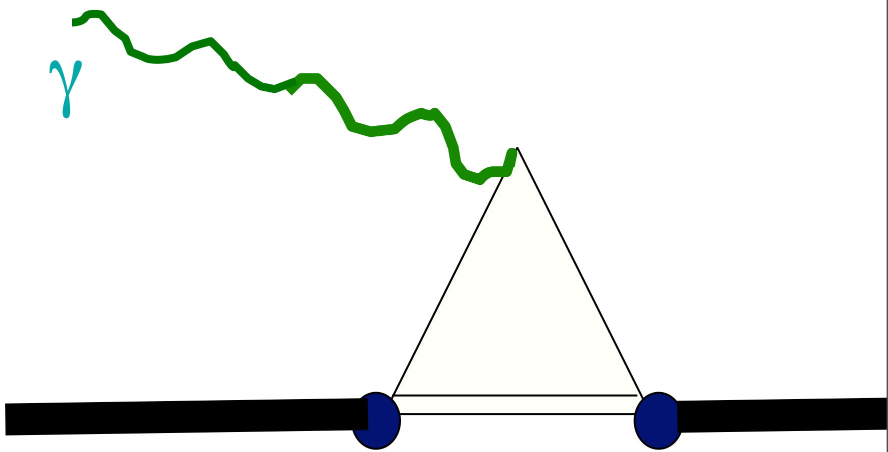
Improved model-Cloet & Miller '11 20

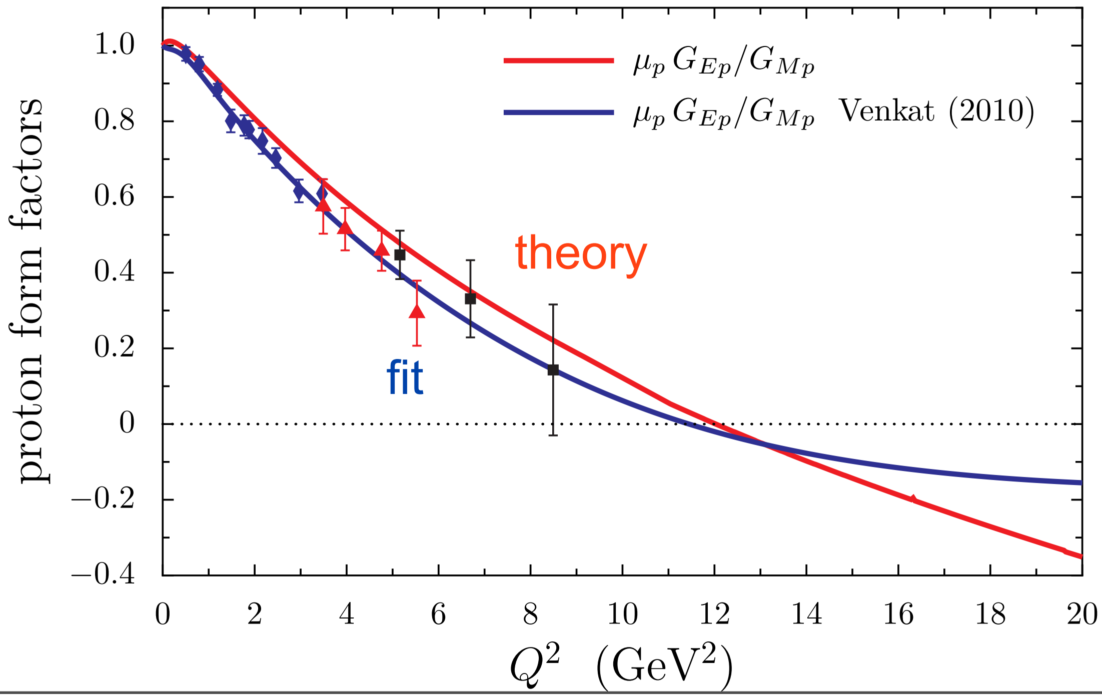
Model proton wave function: quark-diquark

Lorentz and rotationally invariant-different forms!

Light front variables

Dirac spinors-orbital angular momentum

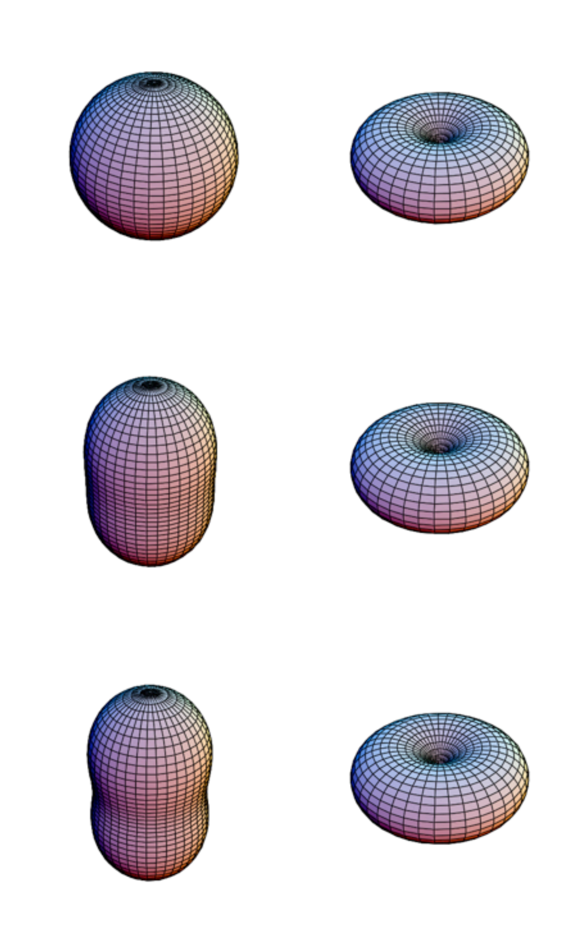




Cloet and Miller 2011

Quark spin is 35 % of proton total angular momentum

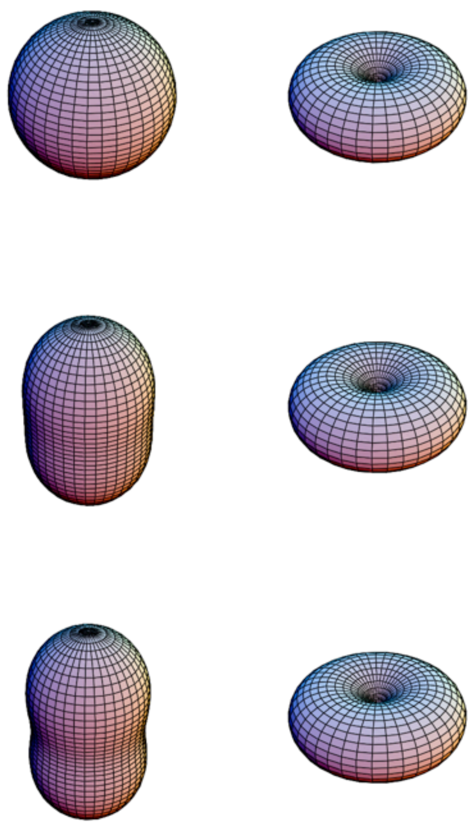
Shapes of the proton- momentum space spin-dependent-densities



three vectors n, K, S

Phys.Rev. C68 (2003) 022201

Shapes of the proton- momentum space spin-dependent-densities



three vectors n, K, S

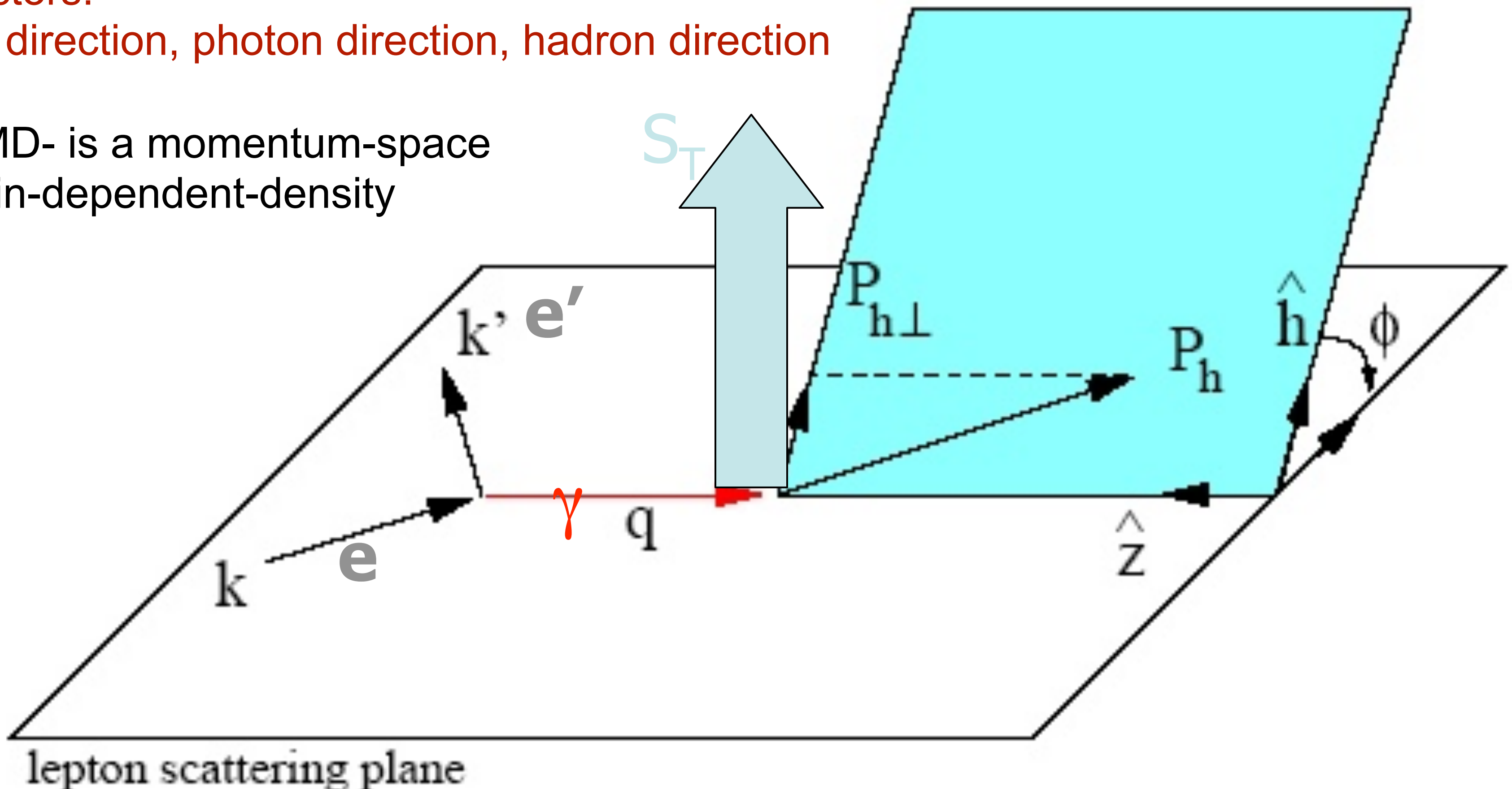
Phys.Rev. C68 (2003) 022201

MODEL , HOW TO MEASURE? How to compute fundamentally?

Measure $h_{1T}^{\perp} : e + p(\uparrow) \rightarrow e'\pi X$

3 vectors:
Spin direction, photon direction, hadron direction

TMD- is a momentum-space
spin-dependent-density



Cross section has term proportional to cos 3ϕ

Boer Mulders '98

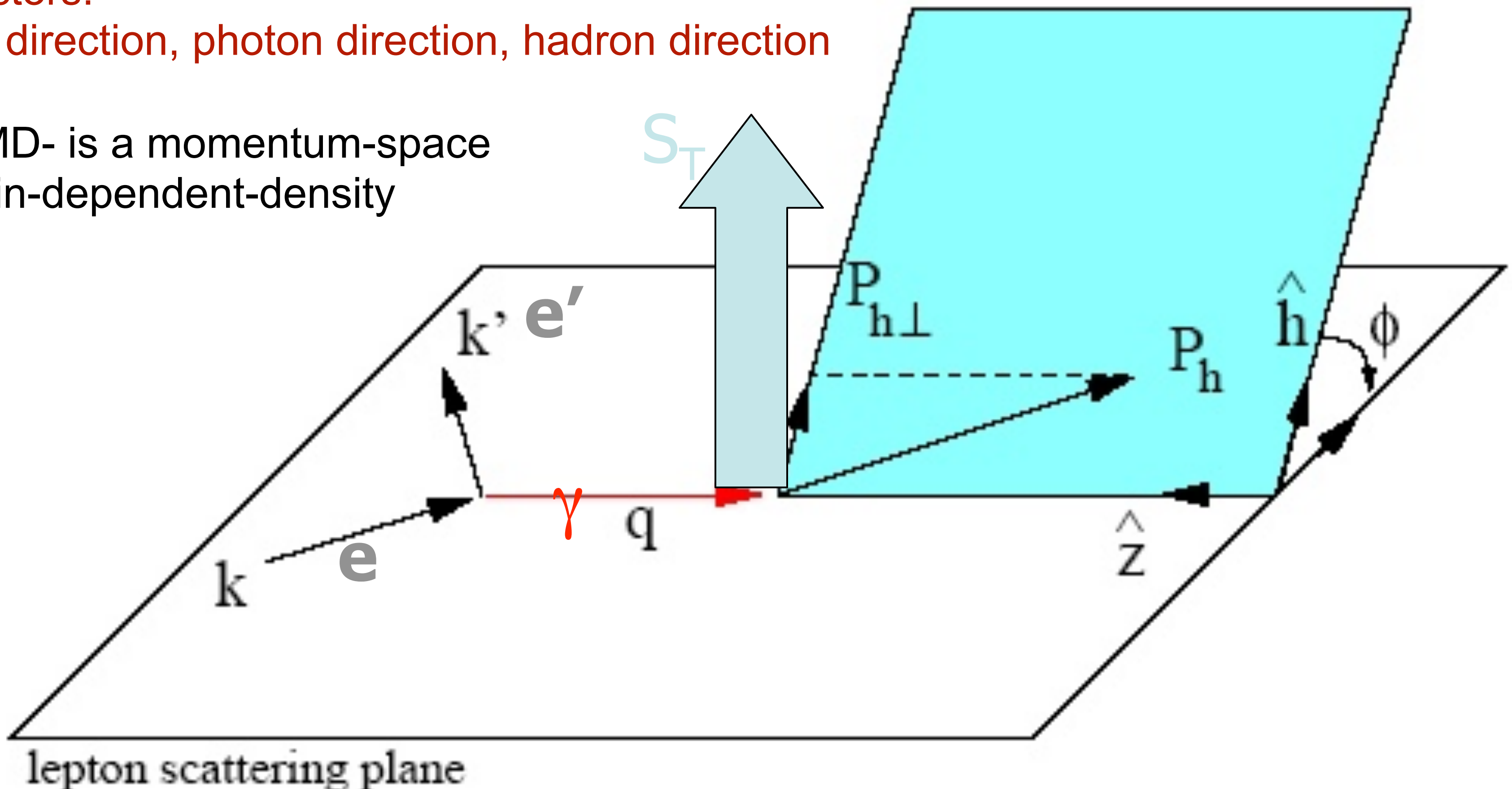
GAM Phys.Rev.C76:065209,2007

Measure $h_{1T}^{\perp} : e + p(\uparrow) \rightarrow e' \pi X$

H. Avakian, *et al.* "Transverse Polarization Effects in Hard Scattering at CLAS12 Jefferson Laboratory", LOI12-06-108, and H. Avakian private communication.

3 vectors:
Spin direction, photon direction, hadron direction

TMD- is a momentum-space spin-dependent-density



Cross section has term proportional to cos 3ϕ

Boer Mulders '98

GAM Phys.Rev.C76:065209,2007

Generalized Coordinate Space Densities

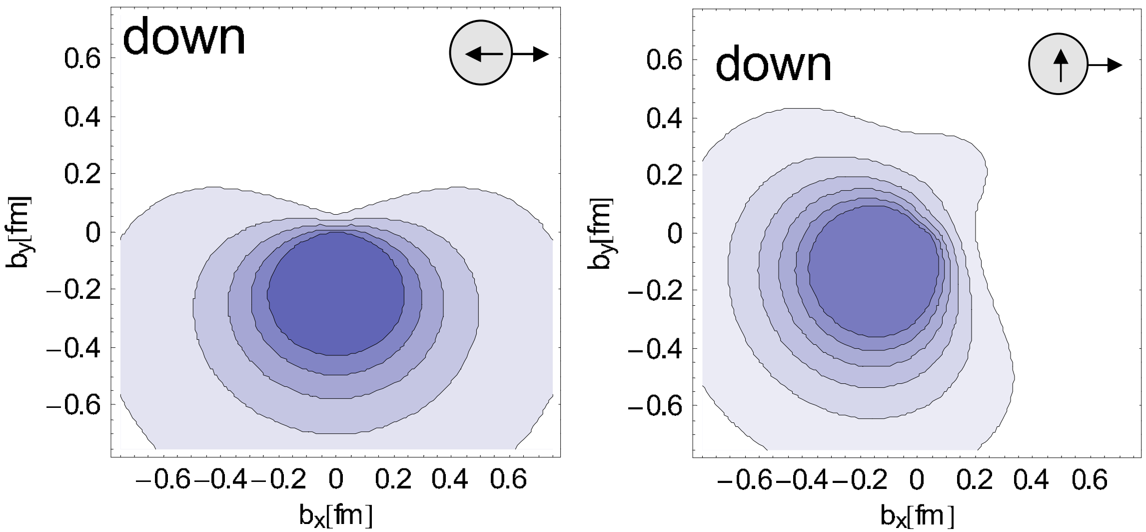
$$\rho^\Gamma(\mathbf{b}) = \sum_q e_q \int dx^- q_+(x^-, \mathbf{b}) \gamma^+ \Gamma q_+(x^-, \mathbf{b})$$

$$\Gamma = \frac{1}{2}(1 + \mathbf{n} \cdot \boldsymbol{\gamma}\, \gamma_5) \text{ gives spin} - \text{dependent density}$$

PRL **98,** 222001 (2007) PHYSICAL REVIEW LETTERS week ending 1 JUNE 2007

Transverse Spin Structure of the Nucleon from Lattice-QCD Simulations

M. Göckeler,[1] Ph. Hägler,[2,*] R. Horsley,[3] Y. Nakamura,[4] D. Pleiter,[4] P. E. L. Rakow,[5] A. Schäfer,[1] G. Schierholz,[6,4] H. Stüben,[7] and J. M. Zanotti[3]



spin-dependent density
-depends on direction
of **b**: proton is not round

Compton scattering

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **69**, 052201(R) (2004)

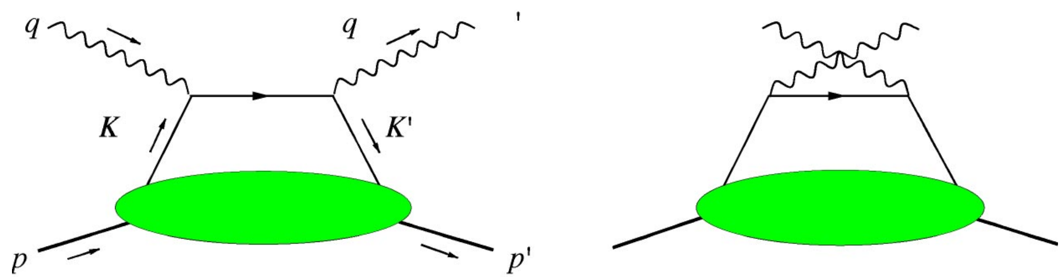
Handling the handbag diagram in Compton scattering on the proton

Gerald A. Miller

Department of Physics, University of Washington, Seattle, Washington 98195-1560, USA

(Received 1 March 2004; published 25 May 2004)

Poincaré invariance, gauge invariance, conservation of parity, and time reversal invariance are respected in an impulse approximation evaluation of the handbag diagram. Proton wave functions, previously constrained by comparison with measured form factors, that incorporate the influence of quark transverse and orbital angular momentum (and the corresponding violation of proton helicity conservation) are used. Computed cross sections are found to be in reasonably good agreement with early measurements. The helicity correlation between the incident photon and outgoing proton, K_{LL}, is both large and positive at back angles. For photon laboratory energies of $\leqslant 6$ GeV, we find that $K_{LL} \neq A_{LL}$, and $D_{LL} \neq 1$.



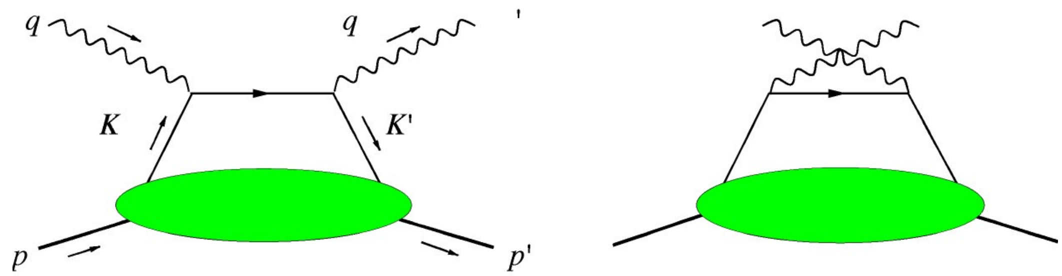
Wave function supplies amplitudes for on-mass shell quarks, CC respected

Technical aspects

- Transverse momentum of quarks included
- Photon momenta are transverse, no boosts
- No energy transfer
- $$\mathcal{M}_{S',S}(\boldsymbol{\epsilon}', \boldsymbol{\epsilon}) = \rho \otimes \mathcal{O}$$

$$\rho_{S',s';S,s}(\eta, K'_\perp, K_\perp) = \int d\xi \; d^2k_\perp \Psi^\dagger_{S',s'}(\xi, k_\perp, \eta, K'_\perp)\Psi_{S,s}(\xi, k_\perp, \eta, K_\perp)$$

$$\mathcal{O} =$$



$$K'_\perp = k_\perp + (1-\eta)(q'_\perp - q_\perp)$$

Technical II

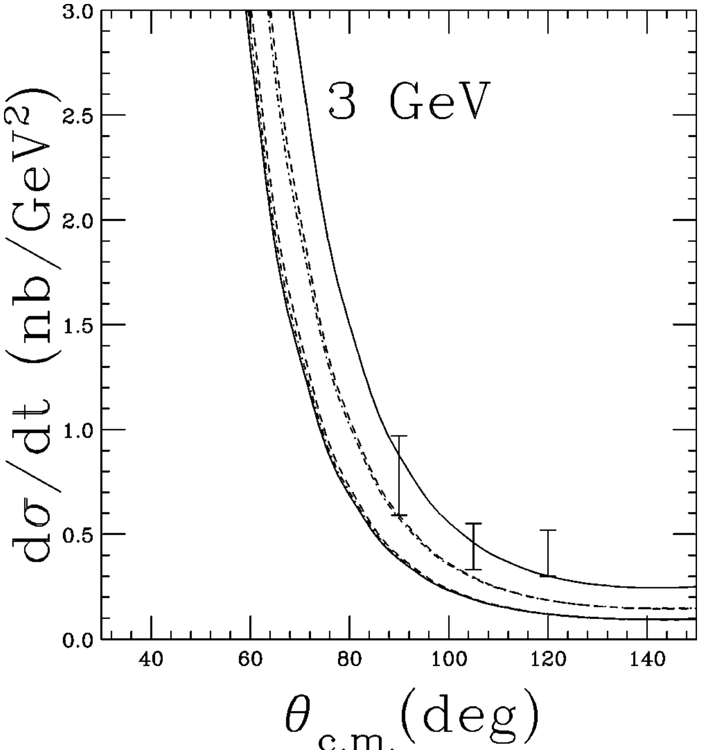
- S',S, ε , ε', 16 amplitudes
- 6 independent, challenge to calc'n
- transform to helicity basis,
- λ nucleon helicity, μ photon helicity

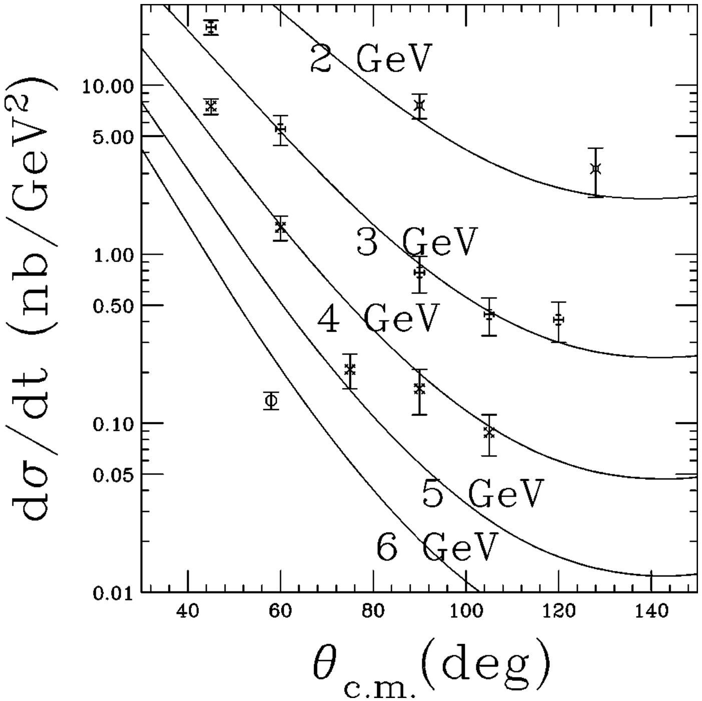
$$\frac{d\sigma}{dt} = \frac{1}{64\pi(s-m^2)^2}\Sigma_{\mu,\mu',\lambda,\lambda'}|\Phi_{\mu',\lambda',\mu\lambda}|^2.$$

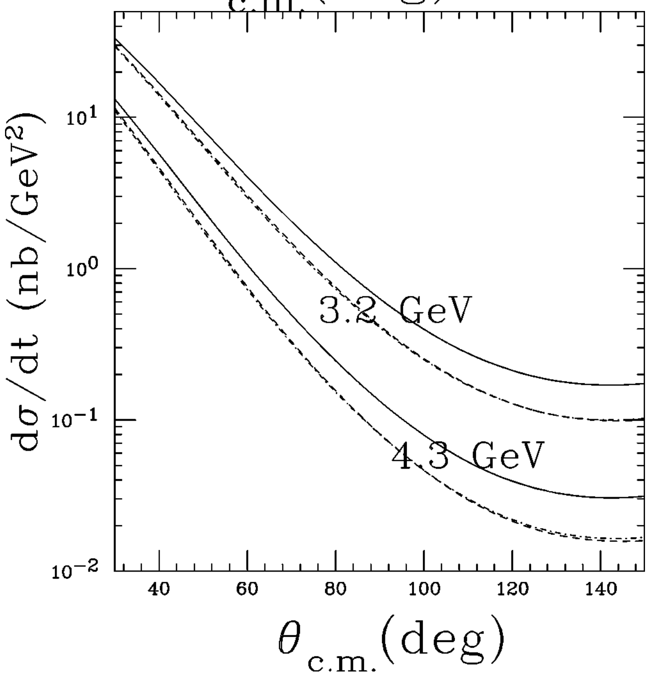
$$A_{LL}\frac{d\sigma}{dt} = \frac{1}{2}\left[\frac{d\sigma(\mu=+,\lambda=+)}{dt} - \frac{d\sigma(\mu=+,\lambda=-)}{dt}\right].$$

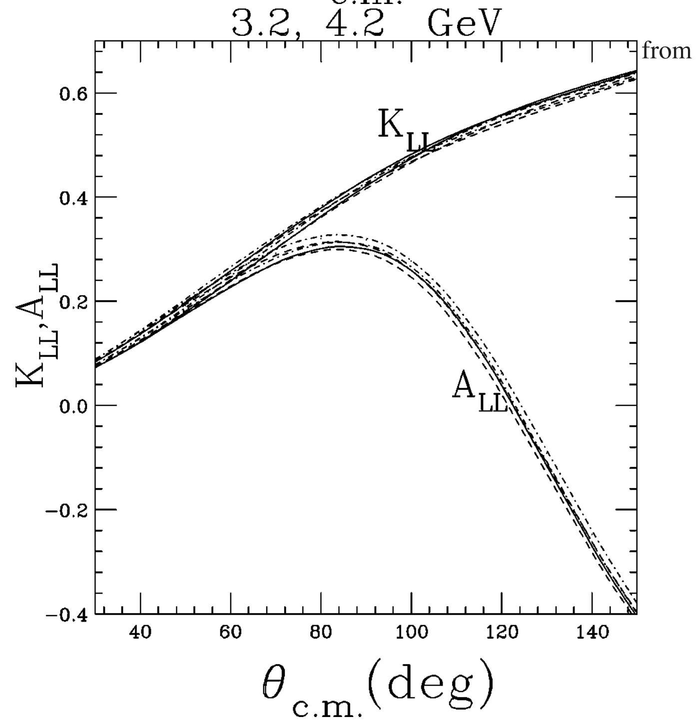
$$A_{LL} \neq K_{LL}$$

$$K_{LL}\frac{d\sigma}{dt} = \frac{d\sigma(\mu=+,\lambda'=+)}{dt} - \frac{d\sigma(\mu=+,\lambda'=-)}{dt},$$

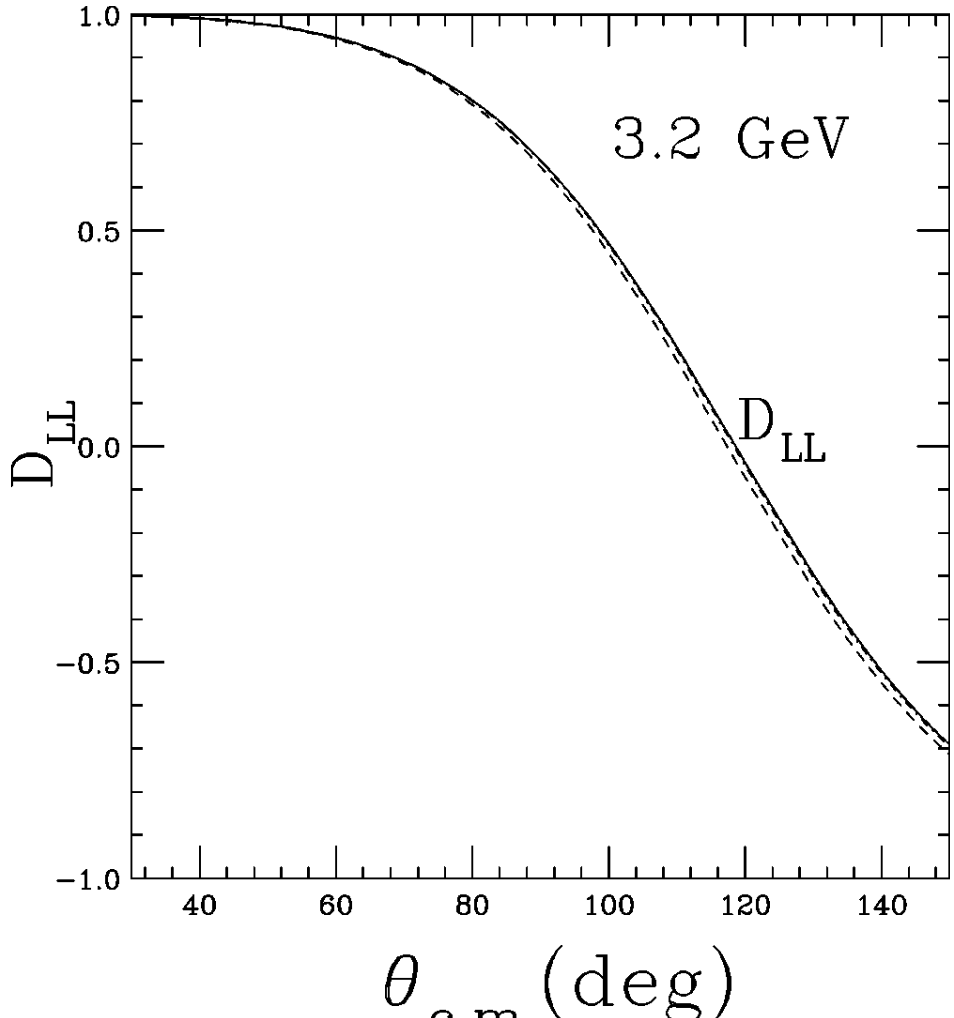

3 GeV
dσ/dt (nb/GeV²)
θ_c.m.(deg)


2 GeV
3 GeV
4 GeV
5 GeV
6 GeV
dσ/dt (nb/GeV²)
θ_c.m.(deg)


3.2 GeV
4.3 GeV
dσ/dt (nb/GeV²)
θ_c.m.(deg)


3.2, 4.2 GeV
from
K_LL
A_LL
K_LL, A_LL
θ_c.m.(deg)

13



$$D_{LL}\frac{d\sigma}{dt} = \frac{d\sigma(\mu=+,\mu'=+)}{dt} - \frac{d\sigma(\mu=+,\mu'=-)}{dt}$$

Let us summarize. Poincaré invariance, gauge invariance, conservation of parity, and time reversal invariance are respected in our impulse approximation evaluation of the handbag diagrams. Proton wave functions, previously constrained by comparison with measured form factors, that incorporate the influence of quark orbital angular momentum (and the corresponding violation of proton helicity conservation) are used. Computed cross sections are in reasonably good agreement with early measurements. The value of K_{LL} is large and positive for scattering at large angles. In contrast with earlier work, we find that $K_{LL} \neq A_{LL}$, and $D_{LL} \neq 1$ at large scattering angles.

Summary

- Form factors, GPDs, TMDs, understood from unified light-front formulation, GPD-coordinate space density,TMD momentum space density
- Potential of Compton scattering unrealized-more data needed
- 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

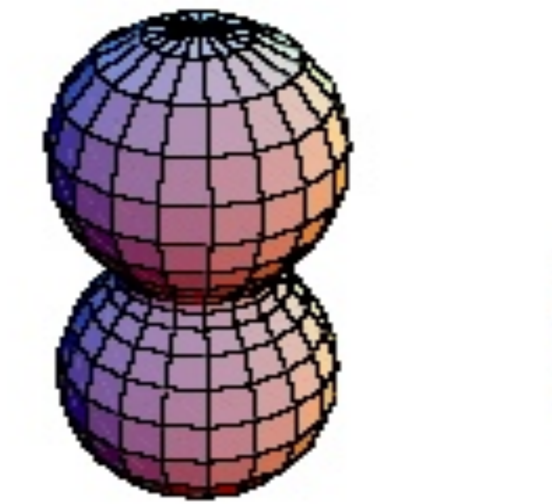
- Form factors, GPDs, TMDs, understood from unified light-front formulation, GPD-coordinate space density,TMD momentum space density
- Potential of Compton scattering unrealized-more data needed
- Proton is not round- lattice QCD spin-dependent-density is not zero
- Experiment can whether or not proton is round by measuring $h_{1T}^{\perp}$

The Proton

Spares follow

Summary of SDD

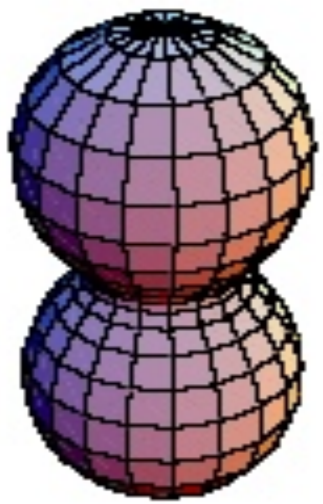
- **SDD are closely related to TMD's**
- **If $h_{1T}^{?}$ is not 0, proton is not round. Experiment can show proton ain't round.**



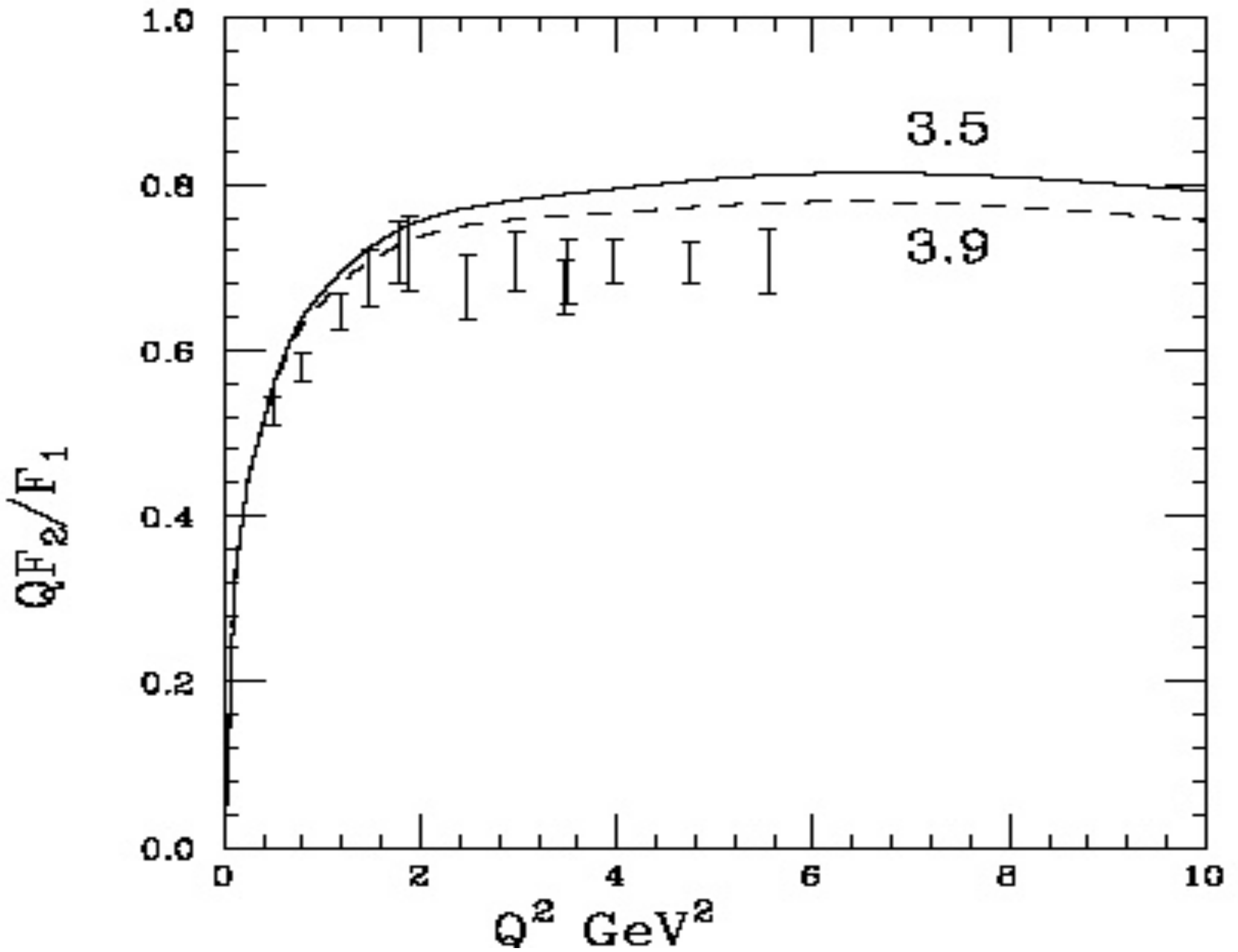
Summary of SDD

- **SDD are closely related to TMD's**
- **If $h_{1T}^{?}$ is not 0, proton is not round. Experiment can show proton ain't round.**

The Proton



Ratio of Pauli to Dirac Form Factors 1995 theory, data 2000



How to study the proton?

How to study the proton?

- EXPERIMENTS

How to study the proton?

- EXPERIMENTS
- Theory –numerical simulations lattice

How to study the proton?

- EXPERIMENTS
- Theory –numerical simulations lattice
  masses + … low Q^2

How to study the proton?

- EXPERIMENTS
- Theory –numerical simulations lattice
  masses + … low Q^2
  eventually exact

How to study the proton?

- EXPERIMENTS
- Theory –numerical simulations lattice

  masses + … low Q^2

  eventually exact
- Phenomenology- symmetries, dynamical guesses, high Q^2

How to study the proton?

- EXPERIMENTS
- Theory –numerical simulations lattice
  masses + … low Q^2
  eventually exact
- Phenomenology- symmetries, dynamical guesses, high Q^2
- Model independent techniques

How to study the proton?

- EXPERIMENTS
- Theory –numerical simulations lattice
  masses + … low Q^2
  eventually exact
- Phenomenology- symmetries, dynamical guesses, high Q^2
- Model independent techniques

How to study the proton?

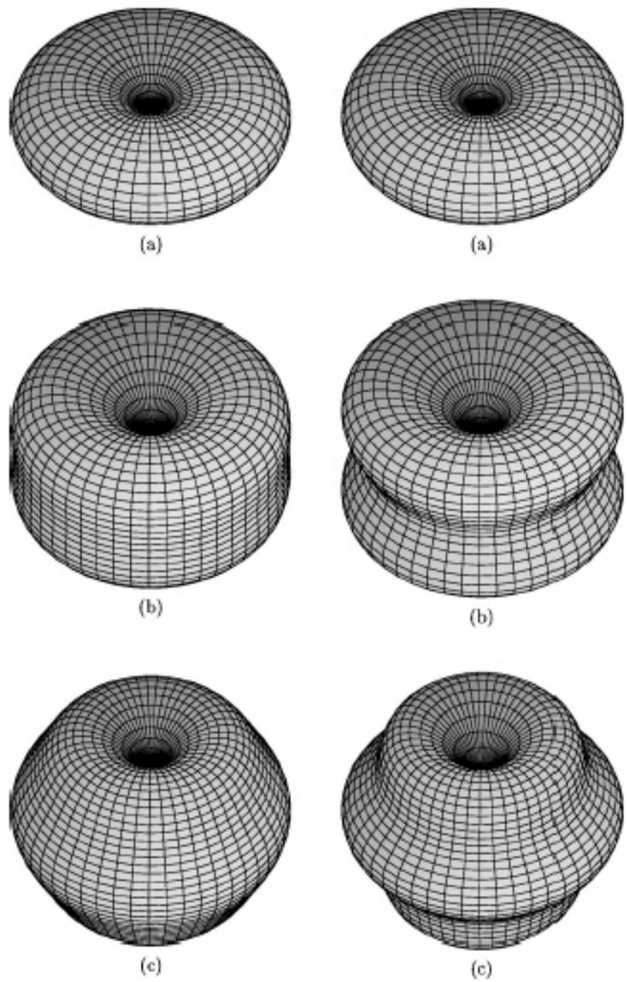
- EXPERIMENTS
- Theory –numerical simulations lattice
  masses + … low Q^2
  eventually exact
- Phenomenology- symmetries, dynamical guesses, high Q^2
- Model independent techniques

what the lattice will find

Spin density operator: $\delta(\mathbf{r}-\mathbf{r}_p)\ \sigma \cdot \mathbf{n}($

Canted ferromagnetic structure of UNiGe high magnetic fields

PRB65, 144429



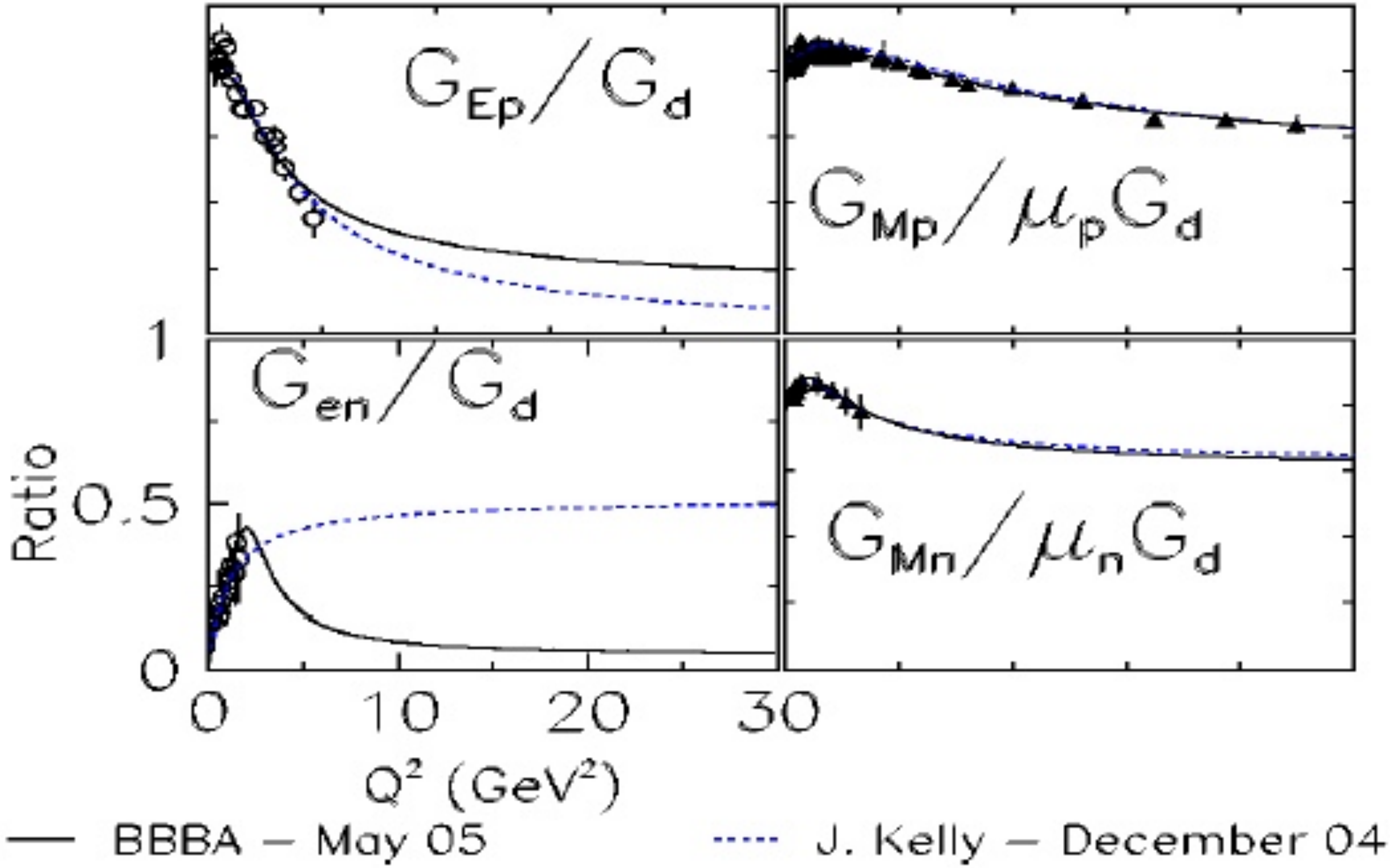
- **Neutron magnetic scattering**

- **Neutron, B, crystal**

A New Parameterization of the Nucleon Elastic Form Factors

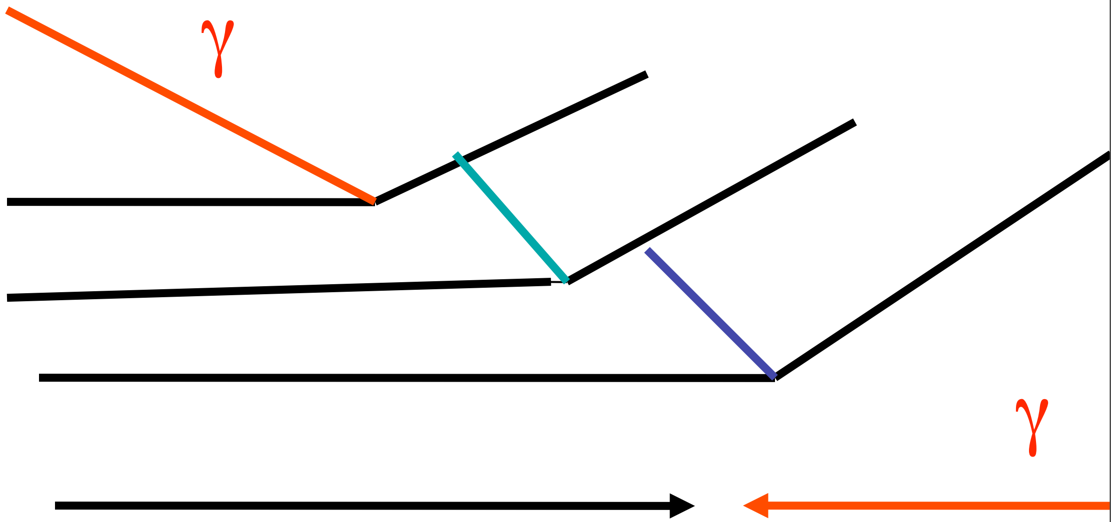
R. Bradford,[a] A. Bodek,[a] H. Budd,[a] and J. Arrington[b]

hep-ex/0602017



How proton holds together-high Q^2

- **pQCD**

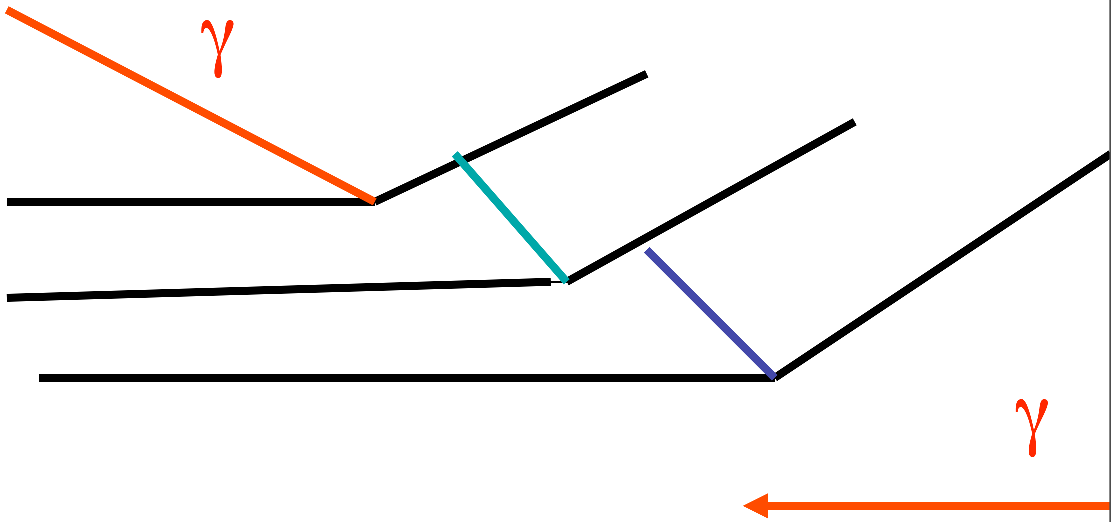


Feynman

Non perturbative
∞ gluon exch

How proton holds together-high Q^2

- **pQCD**

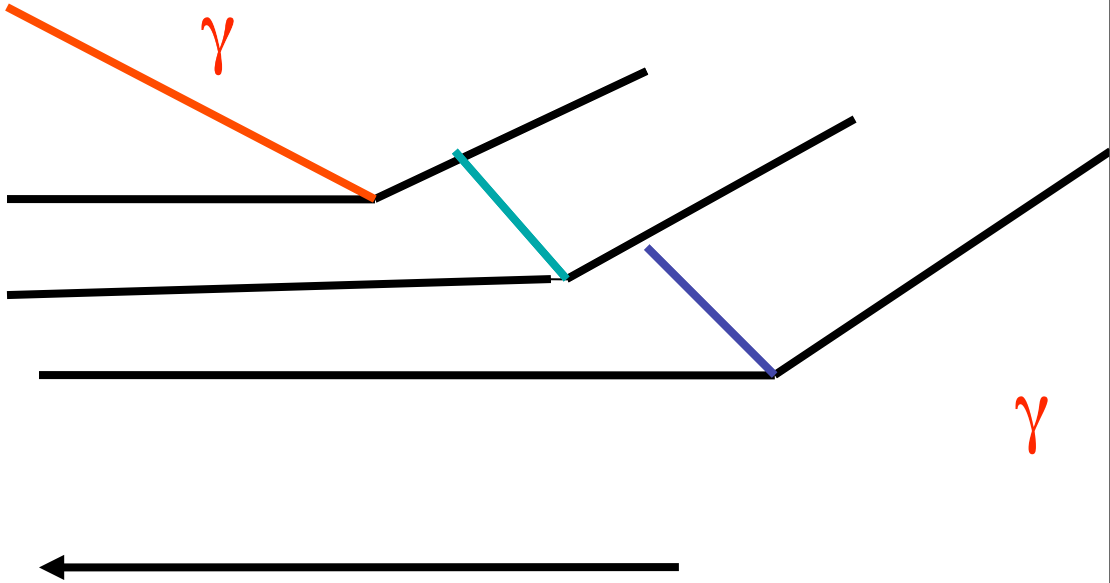


Feynman

Non perturbative
∞ gluon exch

How proton holds together-high Q^2

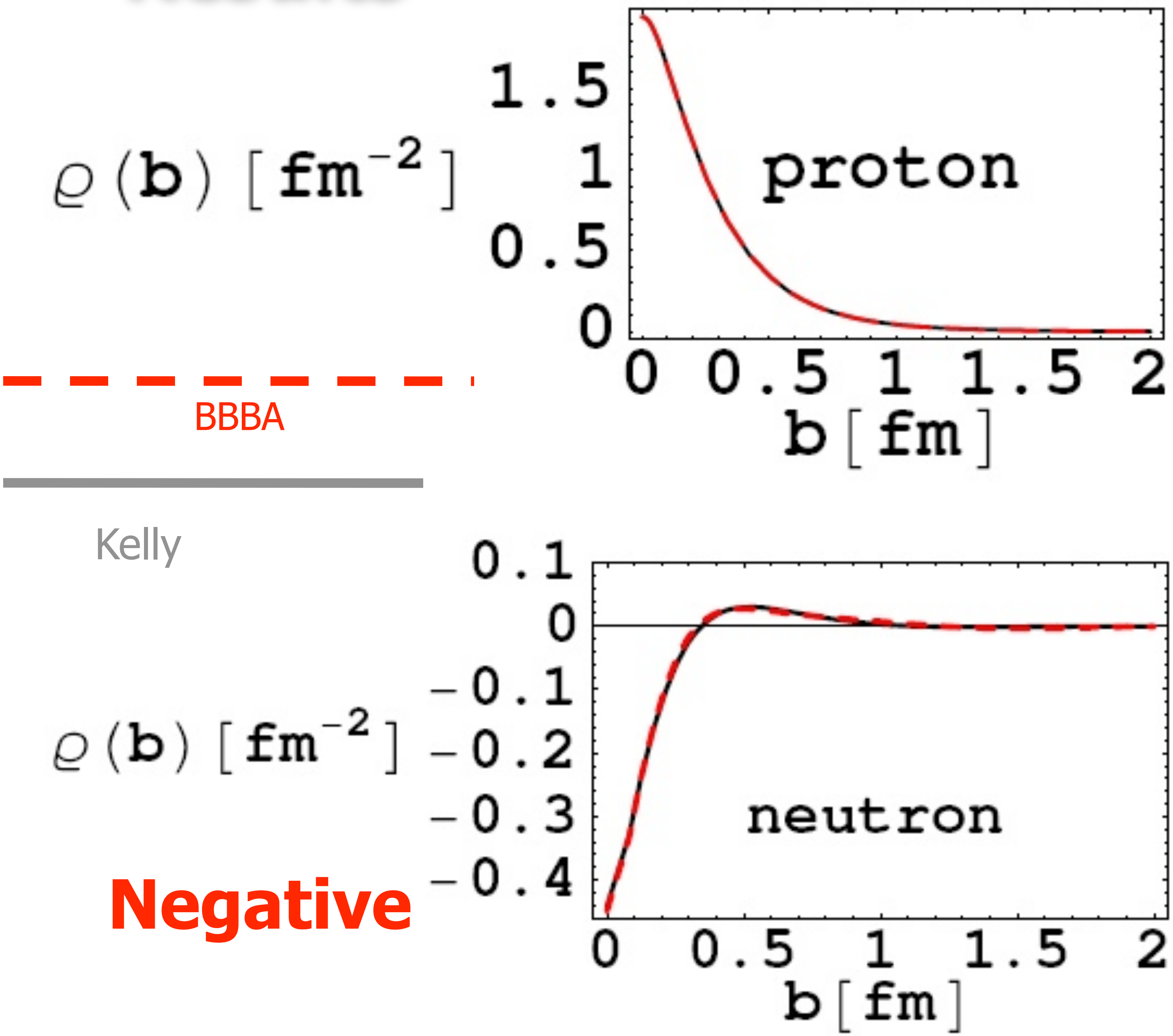
- **pQCD**



Feynman

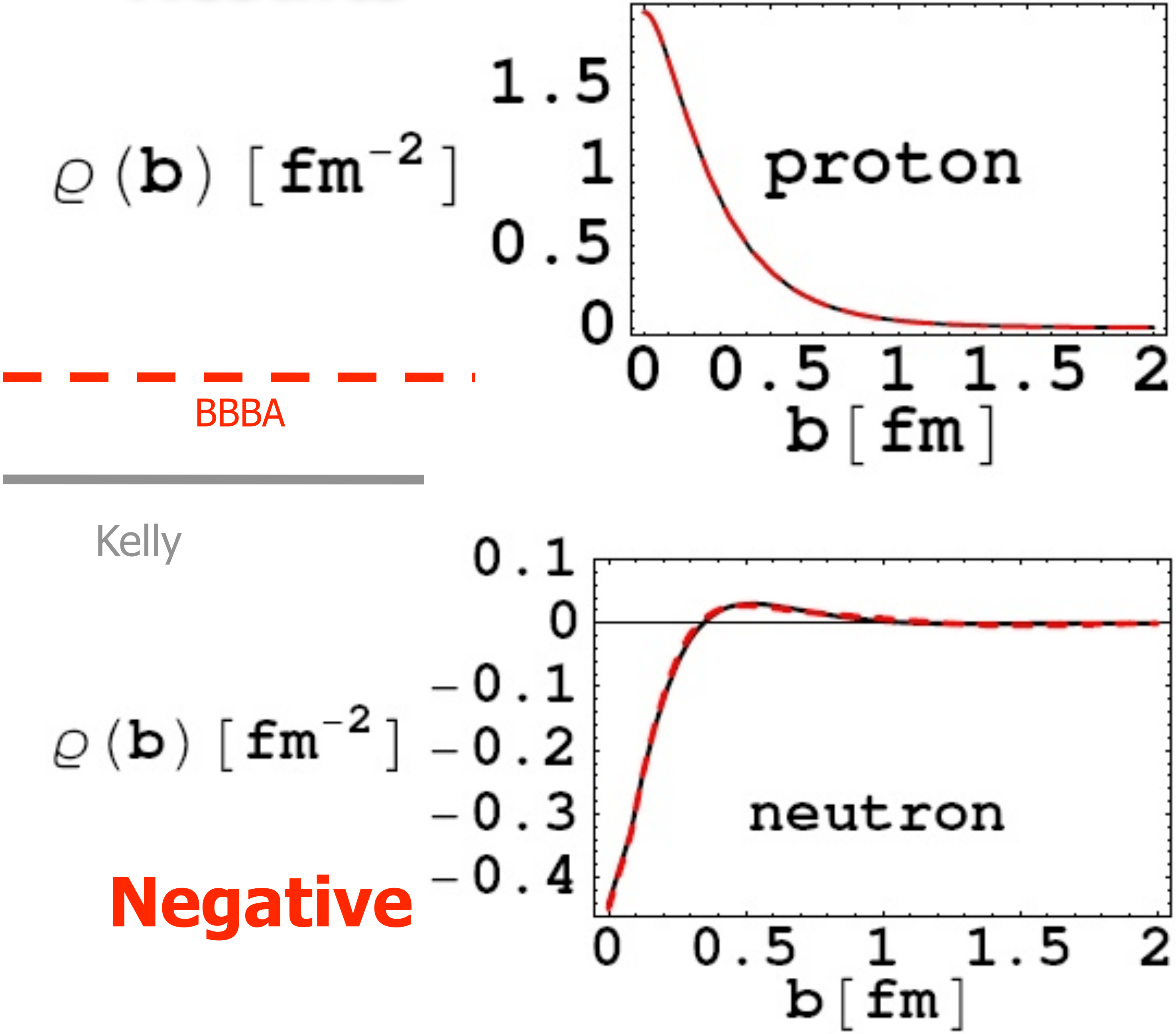
Non perturbative
∞ gluon exch

Results

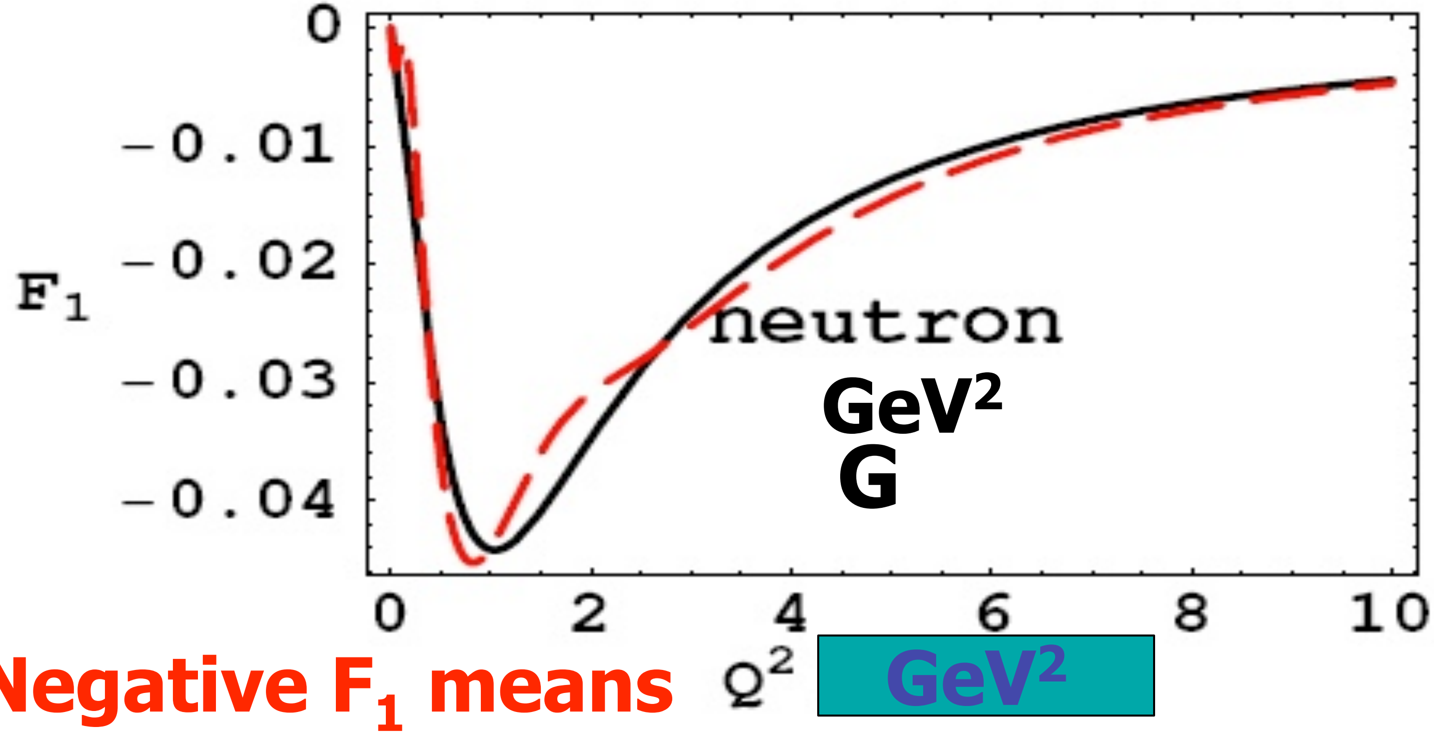


Negative

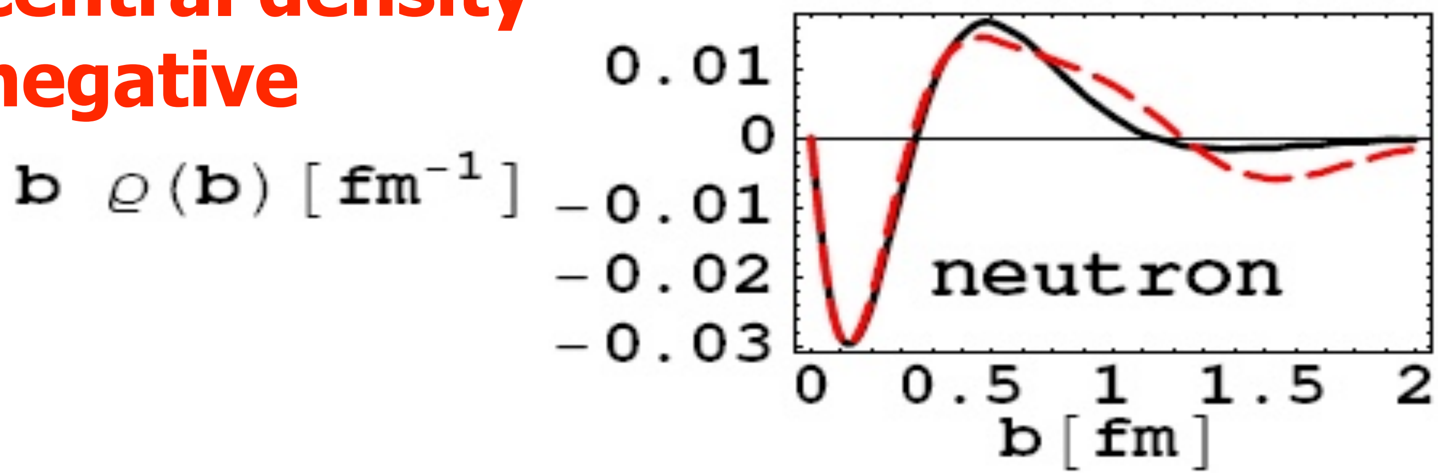
Results



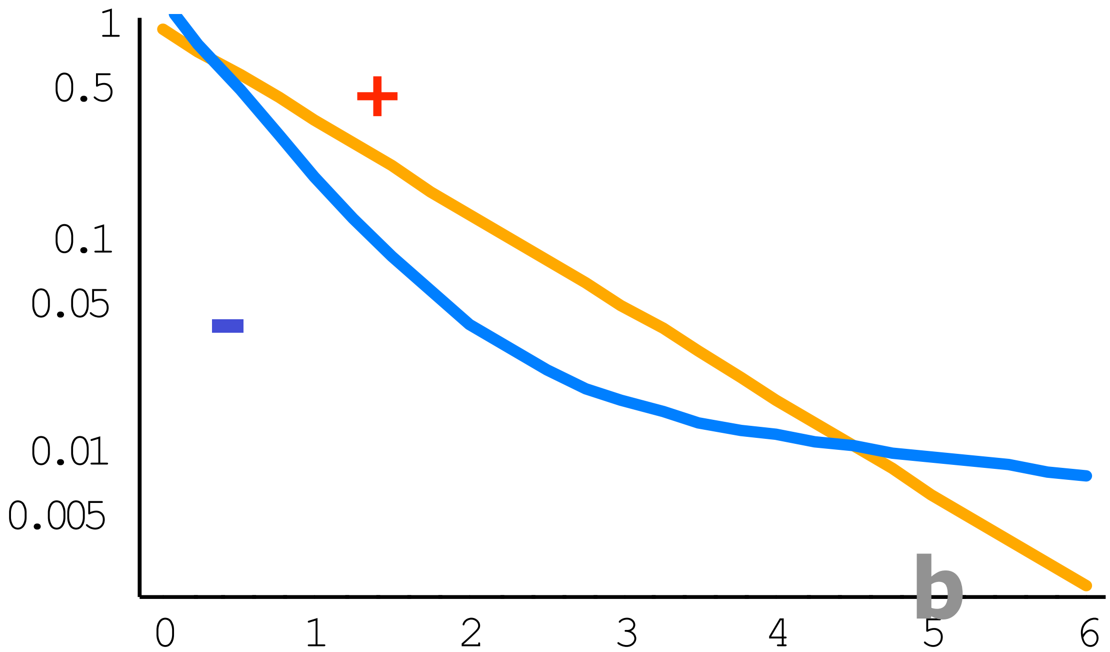
Negative

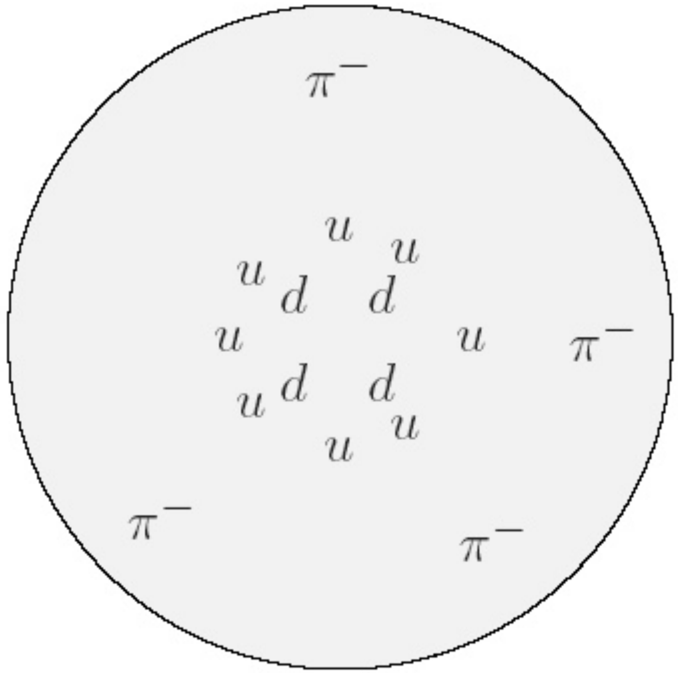


Negative F_1 means central density negative



Neutron Interpretation





? π^- at short distance ?

Central quark density reduced

by orbital ang. momentum OAM?

Summary of density

- Model independent information on charge density

$$\rho(b) \equiv \sum_q e_q \int dx\, q(x,\mathrm{b}) = \int d^2q F_1(Q^2 = \mathrm{q}^2) e^{i\,\mathrm{q}\cdot\mathrm{b}}.$$

- Central charge density of neutron is negative

- Pion cloud at large b

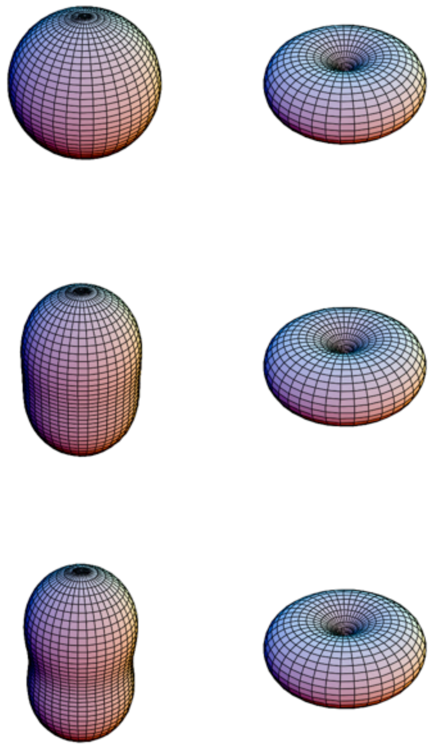
Field theoretic SDD

$$\widehat{\rho}_{\mathrm{REL}}(\mathbf{K},\mathbf{n}) = \int \frac{d^3\xi}{(2\pi)^3} e^{-i\mathbf{K}\cdot\boldsymbol{\xi}}\, \bar{\psi}(0)\gamma^0(1+\boldsymbol{\gamma}\cdot\mathbf{n}\gamma_5)\mathcal{L}(0,\xi;\ \mathrm{path})\psi(\boldsymbol{\xi})\Big|_{t=\xi^0=0}$$

- **Probability to have momentum K, and spin direction n**

Matrix elements depend on three vectors

n, K, S



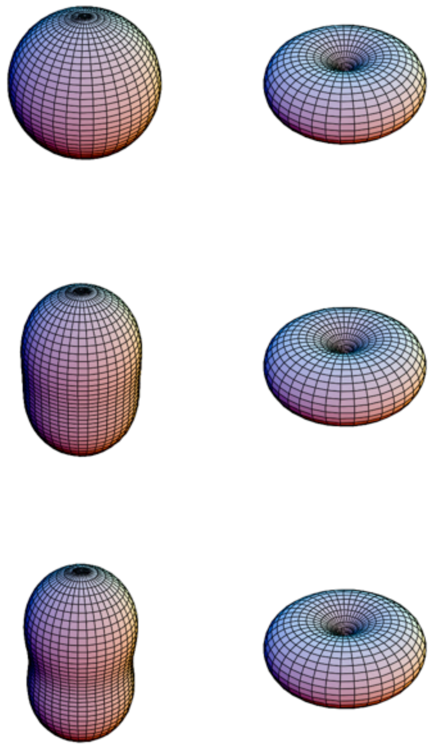
Field theoretic SDD

$$\hat{\rho}_{\rm REL}(\mathbf{K},\mathbf{n}) = \int \frac{d^3\xi}{(2\pi)^3} e^{-i\mathbf{K}\cdot\boldsymbol{\xi}}\ \bar{\psi}(0)\gamma^0(1+\boldsymbol{\gamma}\cdot\mathbf{n}\gamma_5)\mathcal{L}(0,\xi;\ \text{path})\psi(\boldsymbol{\xi})\Big|_{t=\xi^0=0}$$

- **Probability to have momentum K, and spin direction n**

Matrix elements depend on three vectors

n, K, S



Equal time correlation function

Relate SDD to TMD

- **SDD depend on K_x, K_y , K_z & equal time correlation function**
- **TMD depend on x, K_x , K_y & $\xi^+=0=t+z$ correlation function**
- **Integrate SDD over K_z --> t=0,z=0**
- **Integrate TMD over x ! $\xi^§=0$, t=0,z=0**

Result :non-spherical nature of proton related to h_{1T}?