Overview of nucleon form factor measurements

Focus on Generalized Parton Distribution and form factors

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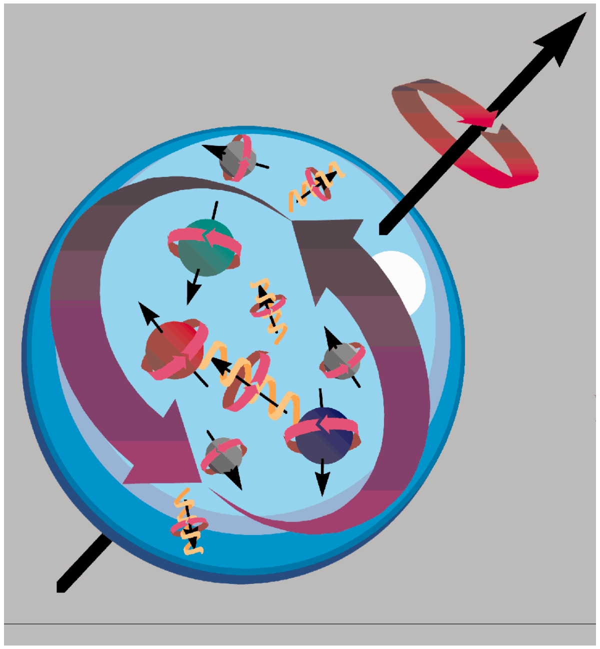
Spin content of the nucleon

$$\frac{1}{2} = \left(\frac{1}{2}\Delta\Sigma + L_q\right) + \left(\Delta G + L_g\right)$$



$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

$$2J^q = \Delta q + 2L^q$$

<u>Ji's sum rule</u>

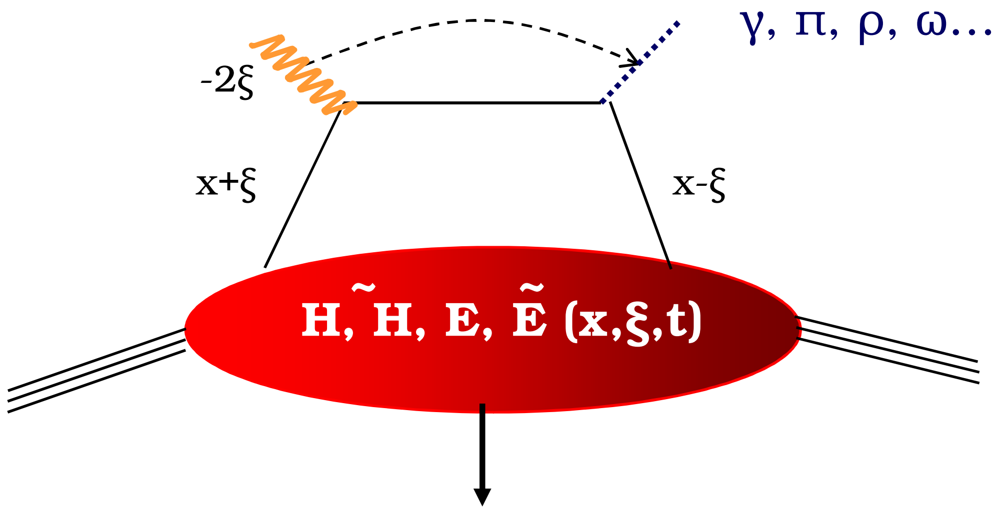
$$2J_q = \int x[H^q(x,0,0) + E^q(x,0,0)]dx$$

X. D. Ji, Phys. Rev. Lett. **78**, 610 (1997), Phys. Rev. D **55**, 7114 (1997).

Generalized Parton Distributions

$H(x, \xi, t)$ and $E(x, \xi, t)$ are general non-perturbative objects where x is the longitudinal momentum fraction
ξ is the skewness or longitudinal momentum asymmetry
and t is the four momentum transfer squared or $-Q^2$

Considerable effort presently at Jlab and in future at Jlab@12 GeV to measure through deeply virtual Compton scattering and deeply virtual meson production.



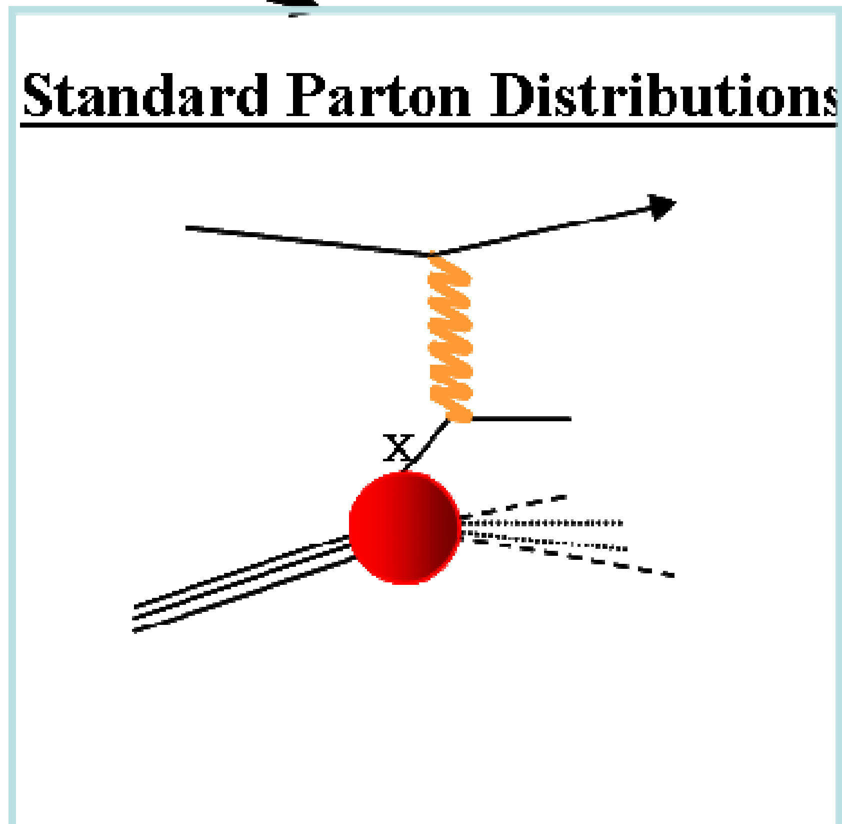
GPDs and Deep Inelastic Scattering

Unpolarized parton distribution

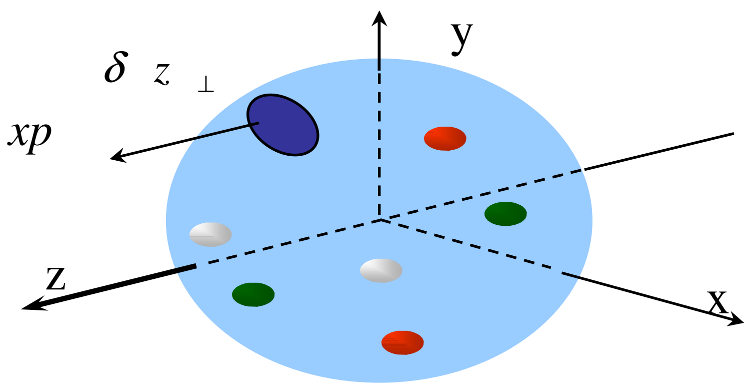
$$H(x,0,0) = q(x)$$

Polarized parton distributions

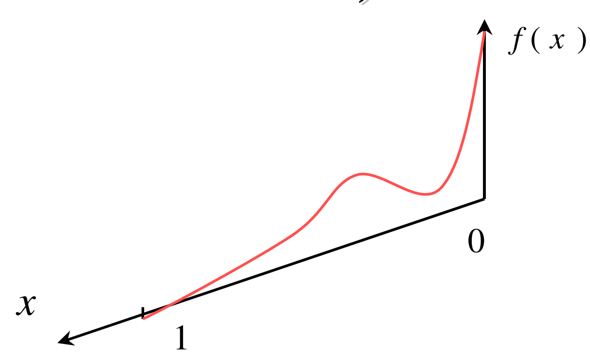
$$\tilde{H}(x,0,0) = \Delta q(x)$$



Parton Distributions



Longitudinal momentum distribution
(no information on the
transverse localisation)



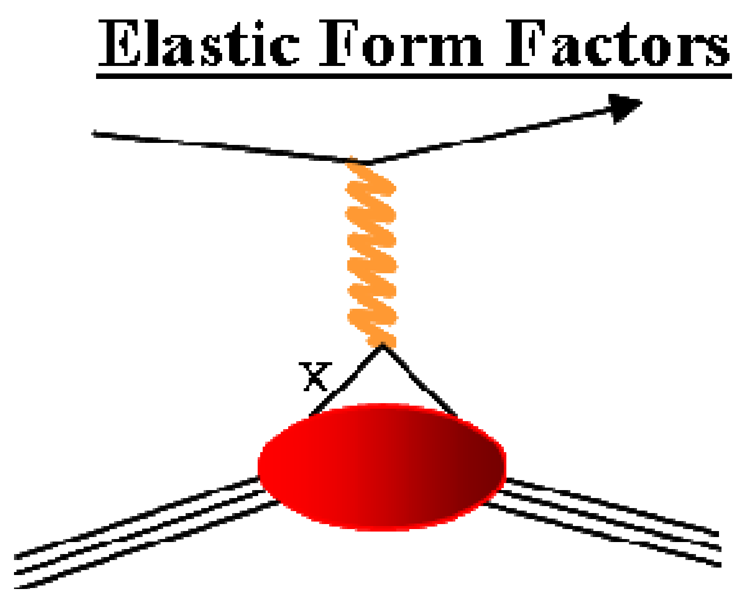
GPD and Elastic form factors

Dirac form factor

$$F_1^q(t) = \int_{-1}^{+1} dx\, H^q(x,\xi,t)$$

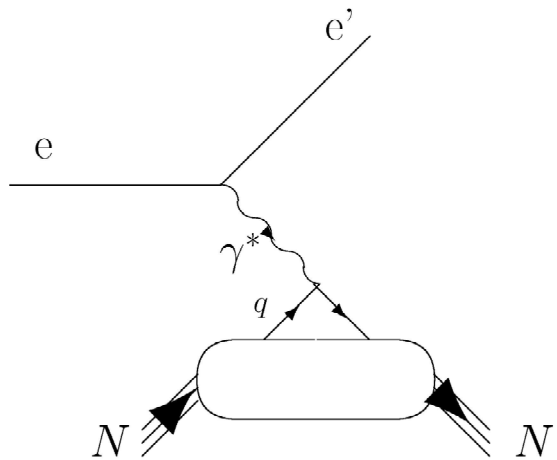
Pauli Form Factor

$$F_2^q(t) = \int_{-1}^{+1} dx\, E^q(x,\xi,t)$$



E^q is new information about the nucleon structure that can not be accessed in DIS scattering

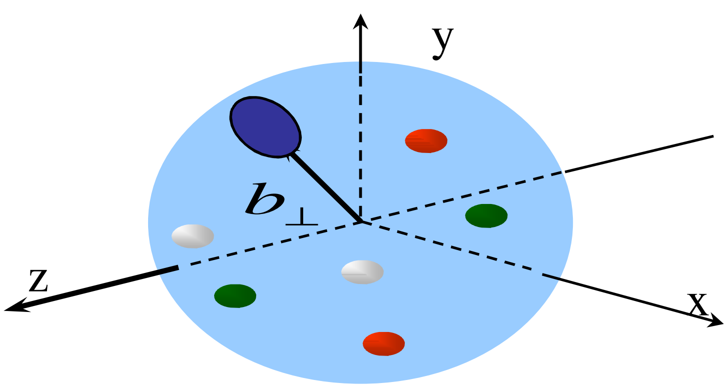
ELASTIC SCATTERING : ep ⇨ ep

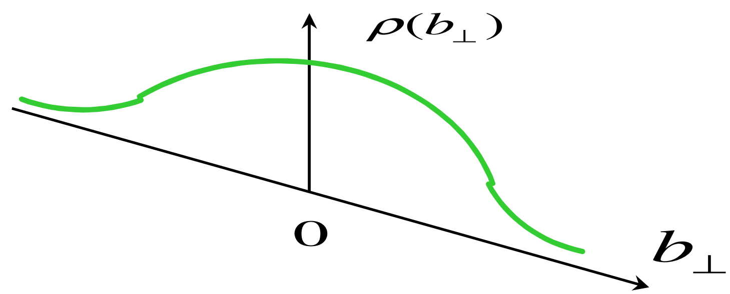


$$t = (p' - p)^2$$

$$\frac{d\sigma}{dt} \propto A\, F_1(t) + BF_2(t)$$

Transverse localisation of partons in the nucleon (independently of their longitudinal momentum)





GPDs and form factors

Define the nucleon F_1 and F_2 in terms of sum of quark form factor weighted by charge

$$F_i(t) = \sum_q e_q F_i^q(t)$$

Relate F_1 and F_2 to valence quark GPDs through sum rules

$$F_1^q(t) = \int_{-1}^{+1} dx\, H^q(x,\xi,t) \qquad F_2^q(t) = \int_{-1}^{+1} dx\, E^q(x,\xi,t)$$

Choose $\xi = 0$ and define nonforward parton densities

$$\begin{aligned} \mathcal{H}^q(x,t) &= H^q(x,0,t) + H^q(-x,0,t) \\ \mathcal{E}^q(x,t) &= E^q(x,0,t) + E^q(-x,0,t) \end{aligned}$$

M. Guidal, M. V. Polyakov, A. V. Radyushkin, M. Vanderhaeghen Phys.Rev.D72:054013,2005

Non Forward parton densities

In the t = 0 limit
the nonforward parton densities equal the valence quark parton densities

$$\mathcal{H}^u(x, t=0) = u_v(x) \qquad \mathcal{H}^d(x, t=0) = d_v(x)$$

The t=0 limit of $\mathcal{E}^q(x, 0)$ does not have a partonic distribution.

$\mathcal{E}^q(x, t)$ has new information about the structure of the nucleon

$$\kappa_q \equiv \int_0^1 dx\, \mathcal{E}^q(x) \qquad \begin{aligned} \kappa_u &= 2\,\kappa_p + \kappa_n \approx +1.673 \\ \kappa_d &= \kappa_p + 2\,\kappa_n \approx -2.033 \end{aligned}$$

Ansatz for the non forward parton distribution

What x and t dependent form should be chosen for H and E?

Formulate H in terms of the valence quark dependence and term that mixes the x and t dependence

$$\mathcal{H}_G^q(x,t) = q_v(x)\, e^{(1-x)t/4x\lambda^2}$$

λ^2 characterizes the average transverse momentum of the quarks in the nucleon

Fit was done to proton F_1 giving $\lambda^2 = 0.7$ GeV^2 or average transverse momentum of 300 MeV

Main problem with Gaussian form is that it is divergent in predicting the proton rms radius. This limits in usefulness below $Q^2 = 1$ GeV^2

Regge Ansatz for the non forward parton distribution

$$\mathcal{H}^q_{R1}(x,t) = q_v(x) x^{-\alpha_1^{'} t}$$

$$F_1^u(t) = \int_0^1 dx\, u_v(x)\, e^{-\alpha_1^{'} t \ln x} \qquad F_1^d(t) = \int_0^1 dx\, d_v(x)\, e^{-\alpha_1^{'} t \ln x}$$

$$F_1^p(t) = e_u\, F_1^u(t) + e_d\, F_1^d(t) \qquad F_1^n(t) = e_u\, F_1^d(t) + e_d\, F_1^u(t)$$

RMS radius for proton and neutron

$$r^2_{1,p} = -6\,\alpha_1^{'} \int_0^1 dx \left\{ e_u\, u_v(x) + e_d\, d_v(x) \right\} \ln x$$

$$r^2_{1,n} = -6\,\alpha_1^{'} \int_0^1 dx \left\{ e_u\, d_v(x) + e_d\, u_v(x) \right\} \ln x$$

$$\mathcal{E}^q_{R1}(x,t) = \mathcal{E}^q(x)\, x^{-\alpha_2^{'} t}$$

$$\mathcal{E}^u(x) = \frac{\kappa_u}{2} u_v(x) \qquad \mathcal{E}^d(x) = \kappa_d d_v(x)$$

2^{nd} Regge Ansatz for the non forward parton distribution

$$\mathcal{H}^q_{R2}(x,t) = q_v(x) x^{-\alpha_1'(1-x)t}$$

$$\mathcal{E}^q(x,t) = \mathcal{E}^q(x) x^{-\alpha_2'(1-x)t}$$

Experimental find that F_2 falls off faster than F_1

$$\mathcal{E}^u(x) = \frac{\kappa_u}{N_u}(1-x)^{\eta_u} u_v(x) \qquad \mathcal{E}^d(x) = \frac{\kappa_d}{N_d}(1-x)^{\eta_d} d_v(x)$$

$$N_u = \int_0^1 dx\,(1-x)^{\eta_u}\,u_v(x) \qquad N_d = \int_0^1 dx\,(1-x)^{\eta_d}\,d_v(x)$$

$$F_2^u(t) = \int_0^1 dx\,\frac{\kappa_u}{N_u}\,(1-x)^{\eta_u}\,u_v(x)\,x^{-\alpha_2'(1-x)\,t}$$

$$F_2^d(t) = \int_0^1 dx\,\frac{\kappa_d}{N_d}\,(1-x)^{\eta_d}\,d_v(x) x^{-\alpha_2'(1-x)\,t}$$

Fit parameters $\eta_u, \eta_d, \alpha_1'$ and α_2'

Use MSRT valence parton distributions

$$\mathcal{H}^q_{R2}(x,t) = q_v(x) x^{-\alpha_1^{'}(1-x)t}$$

$$u_v \;=\; 0.262\, x^{-0.69} (1-x)^{3.50} \left(1 + 3.83\, x^{0.5} + 37.65\, x\right)$$

$$d_v \;=\; 0.061\, x^{-0.65} (1-x)^{4.03} \left(1 + 49.05\, x^{0.5} + 8.65\, x\right)$$

A. D. Martin, R. G. Roberts, W. J. Stirling and R. S. Thorne, Phys. Lett. B **531**, 216 (2002)

Proton and neutron RMS radius

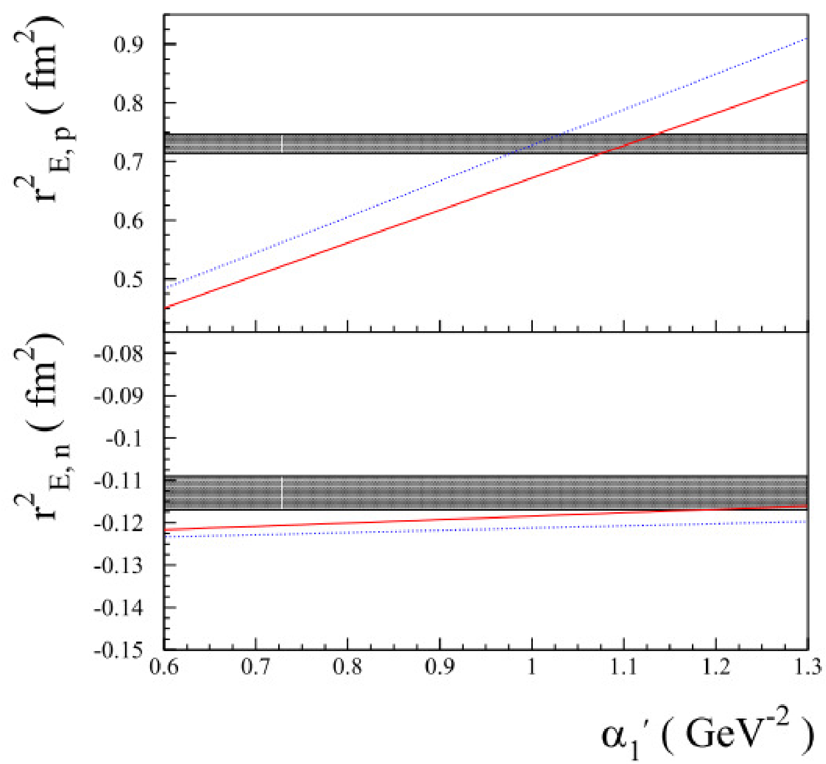
In the 2nd Regge type model

$$r_{1,p}^2 = -6\,\alpha_1' \int_0^1 dx \left\{ e_u\, u_v(x) + e_d\, d_v(x) \right\} (1-x) \ln x$$

$$r_{1,n}^2 = -6\,\alpha_1' \int_0^1 dx \left\{ e_u\, d_v(x) + e_d\, u_v(x) \right\} (1-x) \ln x$$

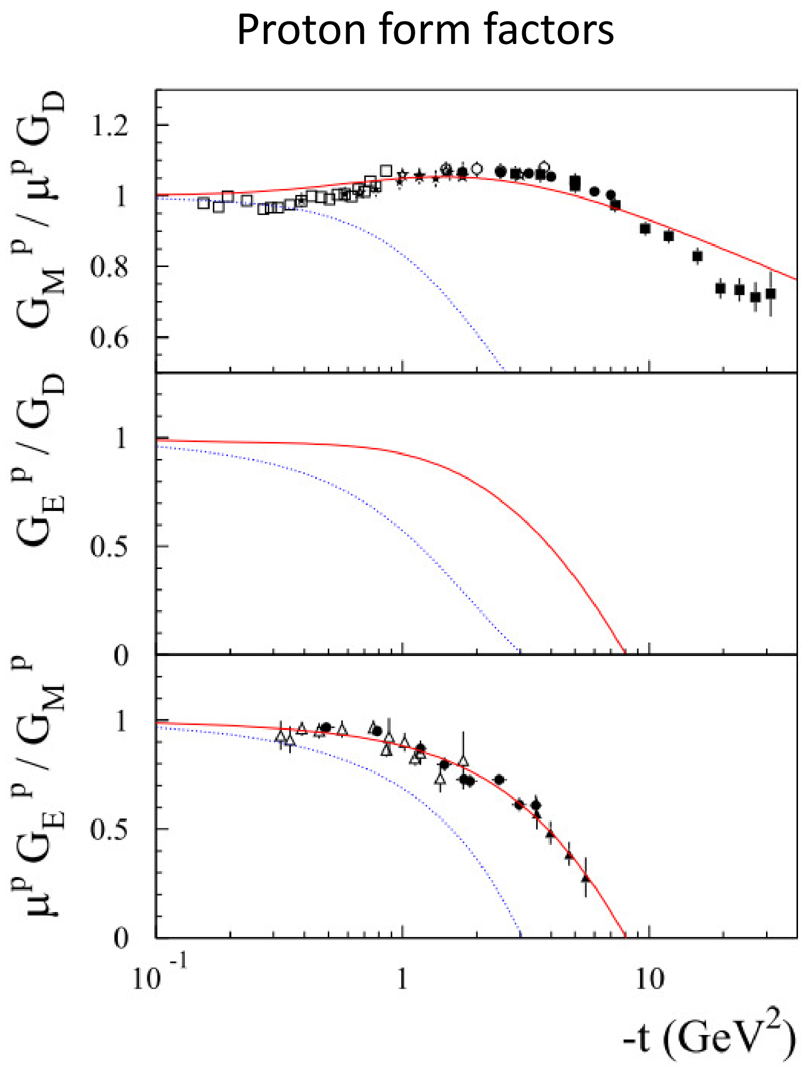
$$r_{E,p}^2 = r_{1,p}^2 + \frac{3}{2} \frac{\kappa_p}{M_N^2}$$

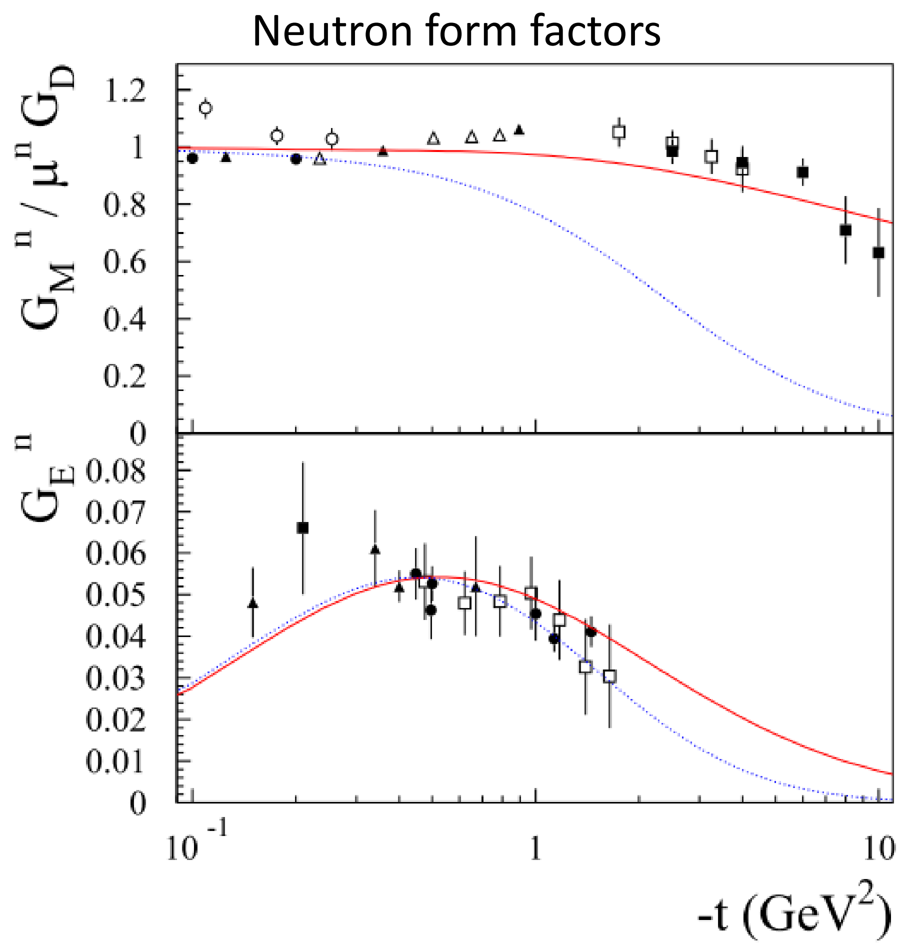
$$r_{E,n}^2 = r_{1,n}^2 + \frac{3}{2} \frac{\kappa_n}{M_N^2}$$



In plot
Blue line is 1st Regge type model
Red line is 2nd Regge type model

Fit to the nucleon form factors





R1 (blue line) using R2 fit

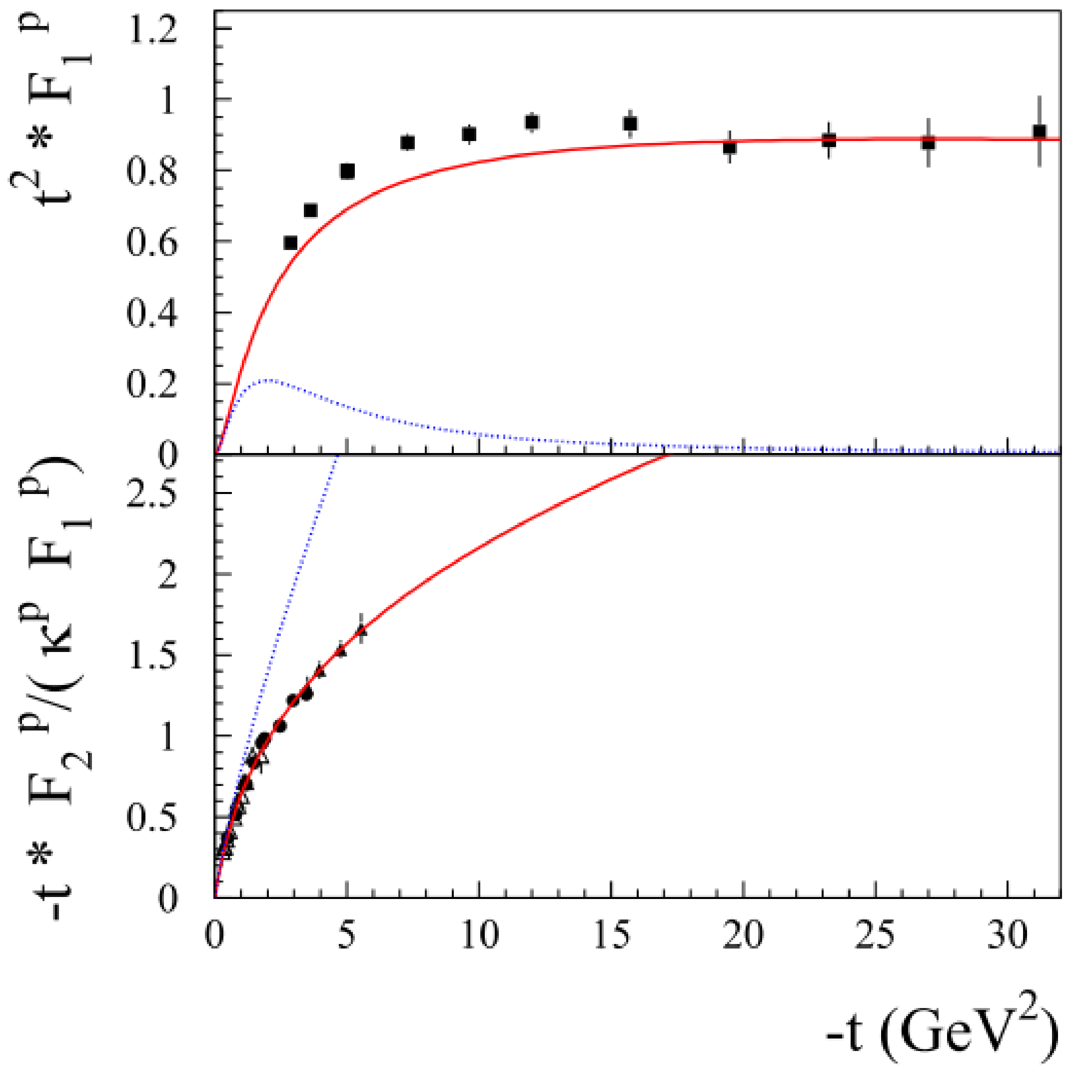
$\alpha'_1 = 1.098 \;\; \alpha'_2 = 1.158$

R2 fit (red line)

$\eta_u = 1.52 \;\; \eta_d = 0.31$

$\alpha'_1 = 1.098 \;\; \alpha'_2 = 1.158$

Large Q^2 behavior of the form factors



Find Q4F1 = constant

But calculation not assuming Two hard gluon exchange as in pQCD

Rather an overlap of soft wavefunctions

Total quark angular momentum

$$2J^q = \Delta q + 2L^q$$

$$2J^q = \int_{-1}^{1} dx\, x\, \{H^q(x,0,0) + E^q(x,0,0)\}$$

$$M_2^q \equiv \int_{-1}^{1} dx\, x\, H^q(x,0,0) = \int_0^1 dx\, x\, [\, q_v(x) + 2\,\bar{q}(x)\,]$$

$$\begin{aligned} 2\,J^u &= M_2^u + \frac{\kappa^u}{N_u} \int_0^1 dx\, x\, (1-x)^{\eta_u}\, u_v(x) \\ 2\,J^d &= M_2^d + \frac{\kappa^d}{N_d} \int_0^1 dx\, x\, (1-x)^{\eta_d}\, d_v(x) \\ 2\,J^s &= M_2^s \end{aligned}$$

Sea quark Eq is unknown. Need hard exclusive process like deeply virtual compton scattering

Quark contribution to nucleon angular momentum

$$2J^q = \Delta q + 2L^q$$

	M_2^q (MRST2002)	$2\,J^q$ (R2 model)	$2\,J^q$ (lattice [59])
u	0.40	0.63	0.734 ± 0.135
d	0.22	-0.06	-0.085 ± 0.088
s	0.03	0.03	
$u+d+s$	0.65	0.60	0.65 ± 0.16

$$\Delta d_v \simeq -0.25 \qquad 2L^d \simeq 0.2$$

$$\Delta u_v \simeq 0.6$$

[59] M. Gockeler, R. Horsley, D. Pleiter, P. E. L. Rakow, A. Schafer, G. Schierholz and W. Schroers [QCDSF Collaboration], Phys. Rev. Lett. **92**, 042002 (2004) [arXiv:hep-ph/0304249].

Summary

- This is first glimpse into the structure of GPDs
- Form factor sensitive to E, a new information on the nucleon structure.
- What is the sea contribution to *E ?*
  - ➢ need hard exclusive process to access the sea contribution to GPDs

Drell-Yan-West relation

If the parton density behaves as $(1-x)^\nu$ then
the large Q^2 behavior of the form factor behaves as $t^{\frac{-(\nu+1)}{2}}$