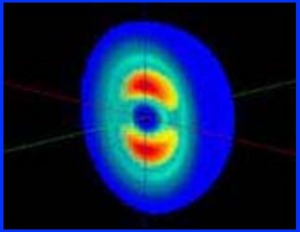
The DEUTERON Electromagnetic Structure



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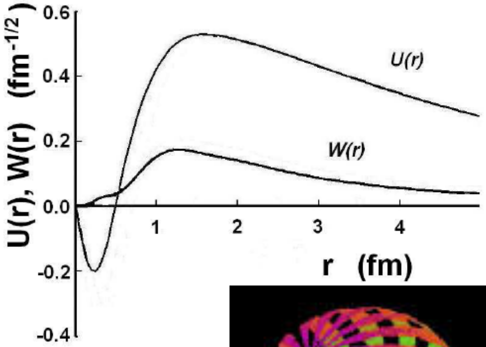
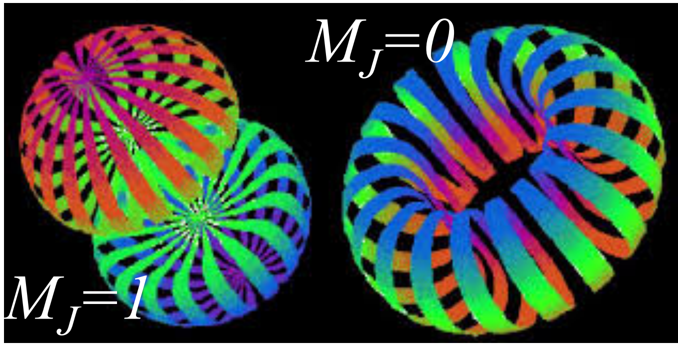
The deuteron : physical interest

- The smallest stable nucleus: M_D=1875.6 MeV, E_b=2.2 MeV

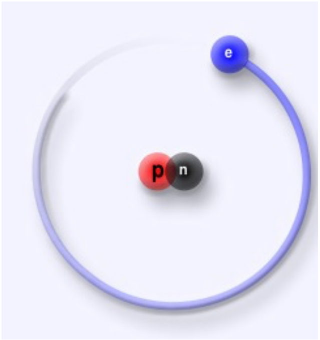
- a neutron and a proton
  in S=1, T=0 state (L=0 or 2)
  in : ≈96% S-state, ≈4% D state
  6q-states? exotics (L=1)?



Argonne



- At small momenta:
  - building of NN potentials
  - deuteron radius
- At large momenta:
  - quark configuration when *n* and *p* overlap?
    (r< 0.7 fm, q >0.3 GeV)



- *As a probe: 'an isoscalar photon' (isoscalar spin transitions)*

Our contribution

- Elastic scattering (e+d → **e+d**)
  - Electromagnetic form factors
  - The deuteron size
- Deuteron break-up (e+d → **e+n+p**)
  - The neutron form factor
- Coherent pion production (e+d → **e+d**+π^0)
  - Inelastic form factors

Cross sections, polarization observables, radiative corrections

Model independent formalism

Aim:

Test pQCD predictions

definition of the asymptotic regime

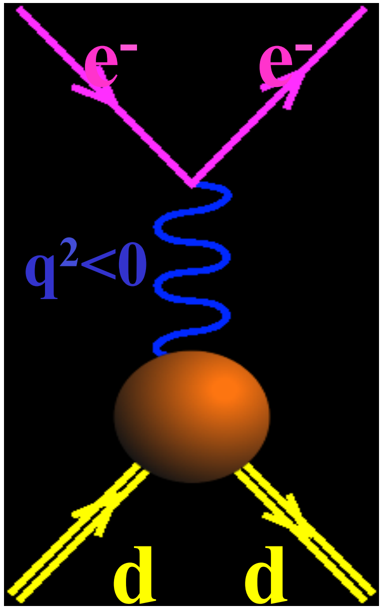
6-quark distribution in the deuteron

quantify deviations from the impulse approximation

Inelastic structure : *beyond S and D waves*

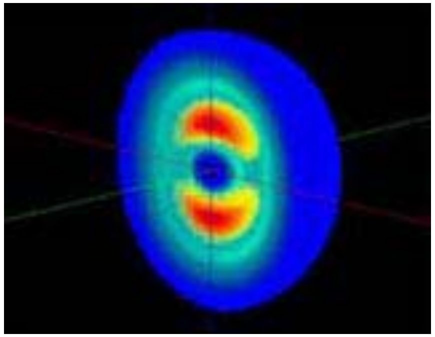
Elastic scattering

The deuteron (S=1, T=0)



$$e+d \rightarrow e+d$$

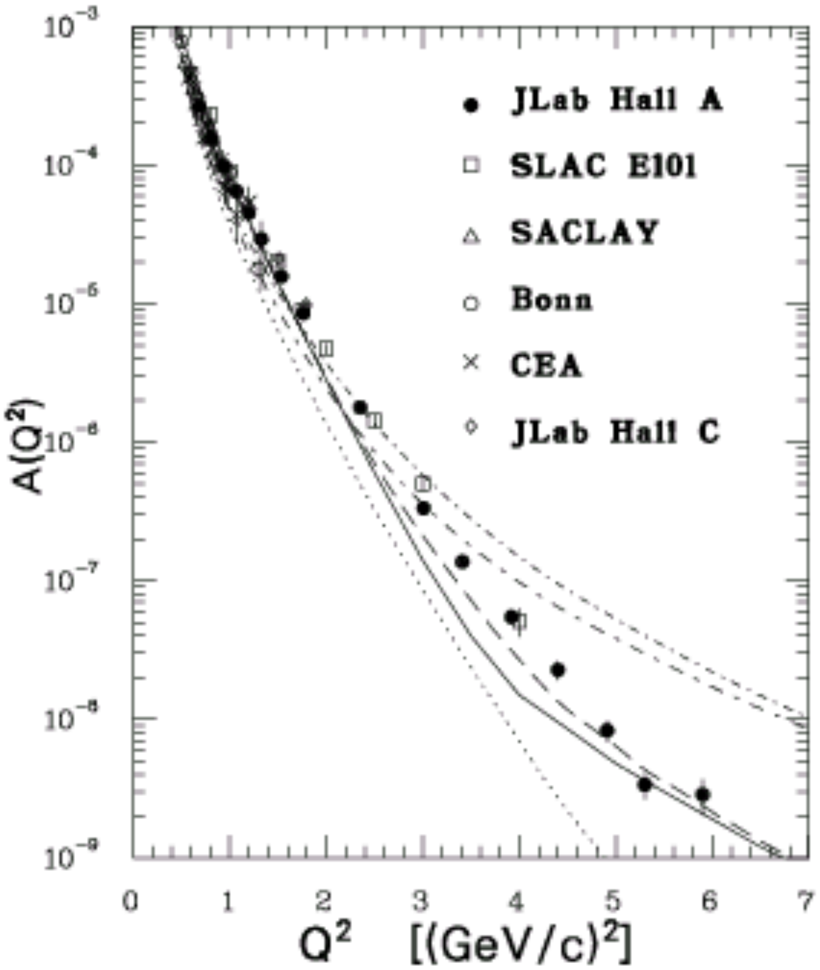
$$\frac{d\sigma}{d\Omega_e} = \sigma_0 \left[A(q^2) \cot^2\frac{\theta_e}{2} + B(q^2) \right]$$

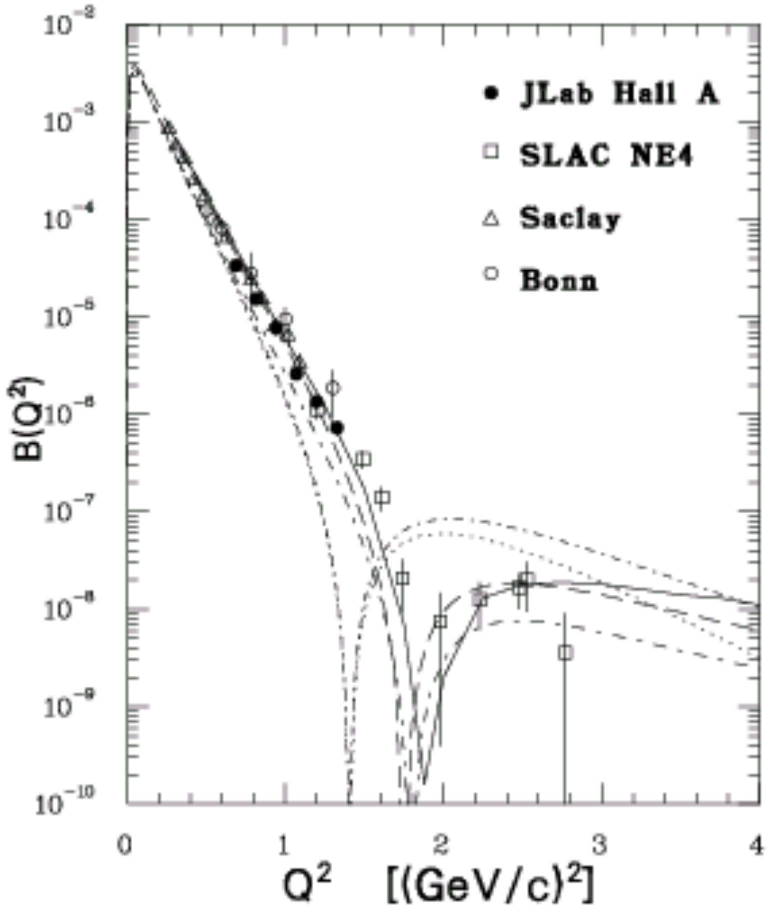


$$A(q^2) = G_C^2 + \frac{8}{9}\tau^2 G_Q^2 + \frac{2}{3}\tau G_M^2, \; B(q^2) = \frac{4}{3}\tau(1+\tau)G_M^2$$

$$W t_{20} = \frac{1}{2}\left[\frac{8}{3}\tau G_C G_Q + \frac{8}{9}\tau^2 G_Q^2 + \frac{\tau}{3}(1+2(1+\tau)\tan^2\frac{\theta_e}{2})G_M^2\right]$$

Cross section

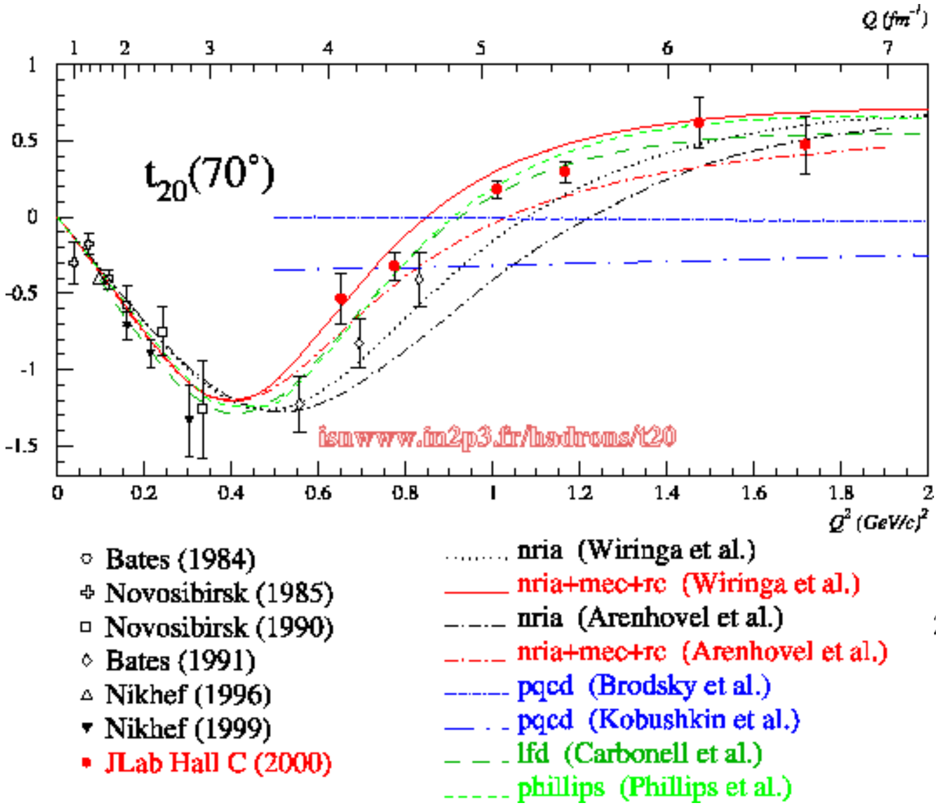




$B(Q^2)$

$A(Q^2)$

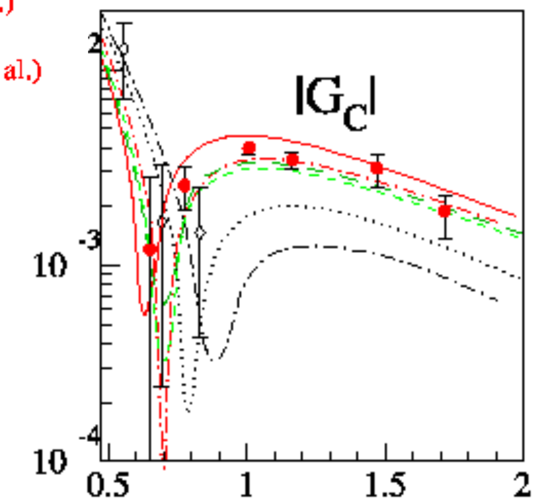
The Deuteron EM Form Factors

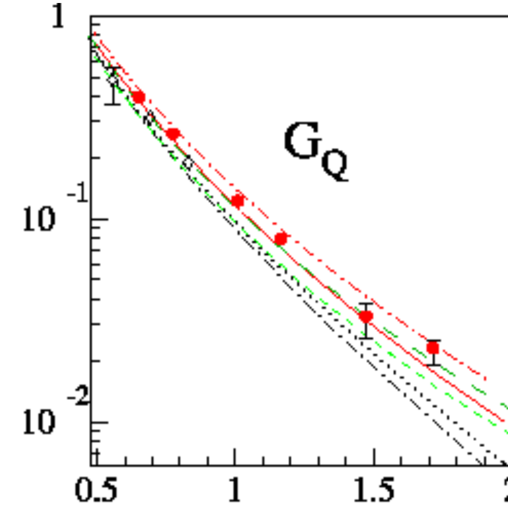


Jlab E94-018

Spokepersons:

B. Beise, S. Kox

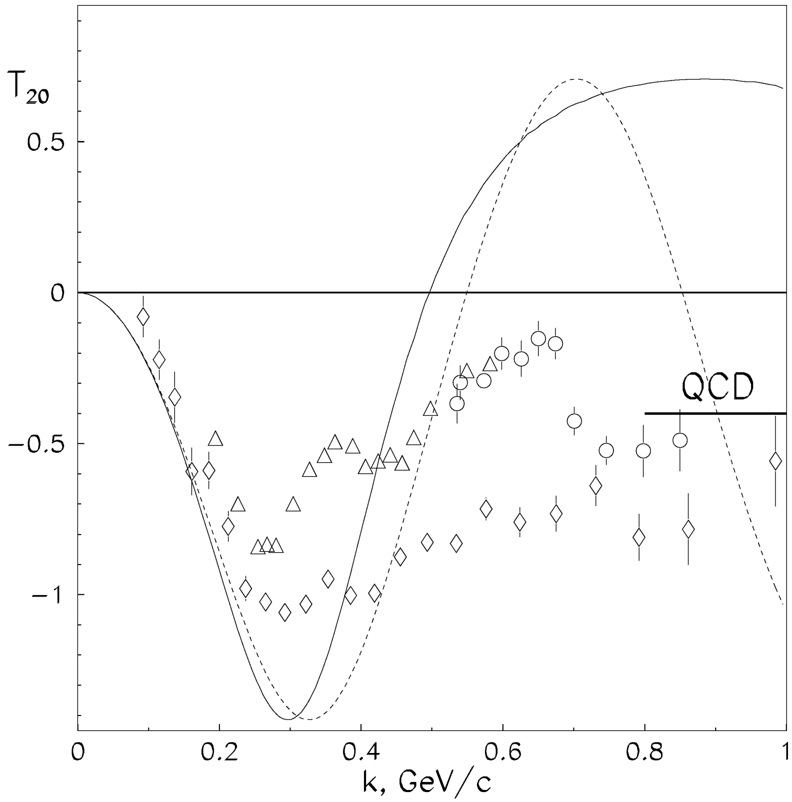


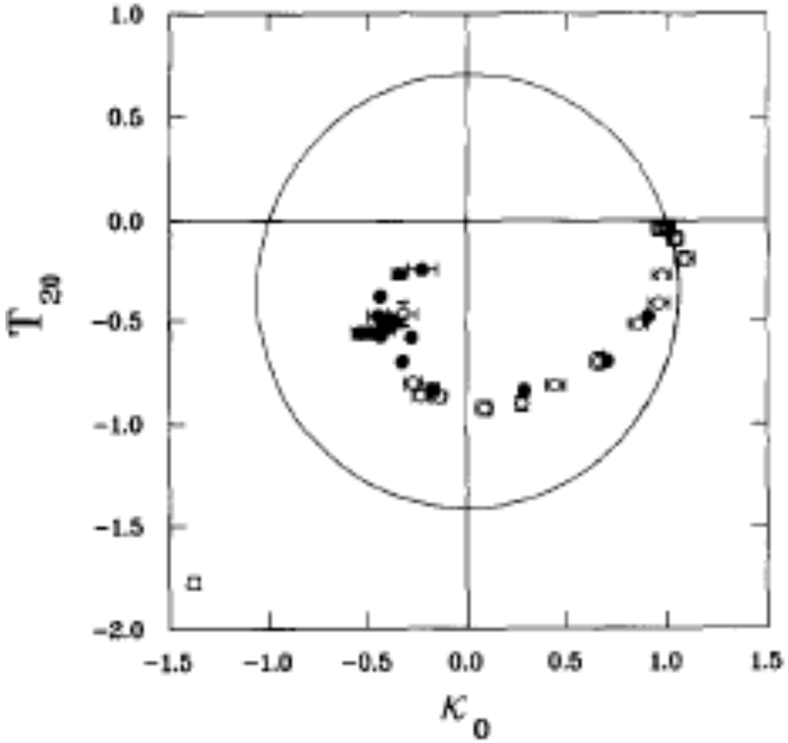


Polarimetry at SATURNE!

D. Abbott et ql. Phys. Rev. Lett. 84,5053 (2000)

Non nucleonic degrees of freedom?

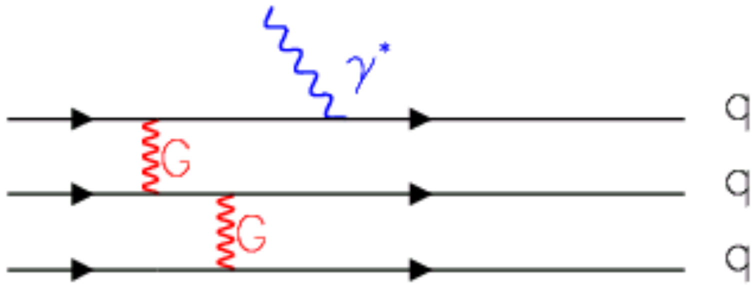




Backward elastic scattering $^1H(d,p)d$
Inclusive break up $^1H(d,p)X$ (0 deg)

V.Punjabi et al., Phys.Lett.B350 (1995) 178
L.S.Azhgirey et al., Phys.Lett.B391 (1997) 22
L.S.Azhgirey et al., Phys.Lett.B387 (1996)

Dipole Approximation and pQCD



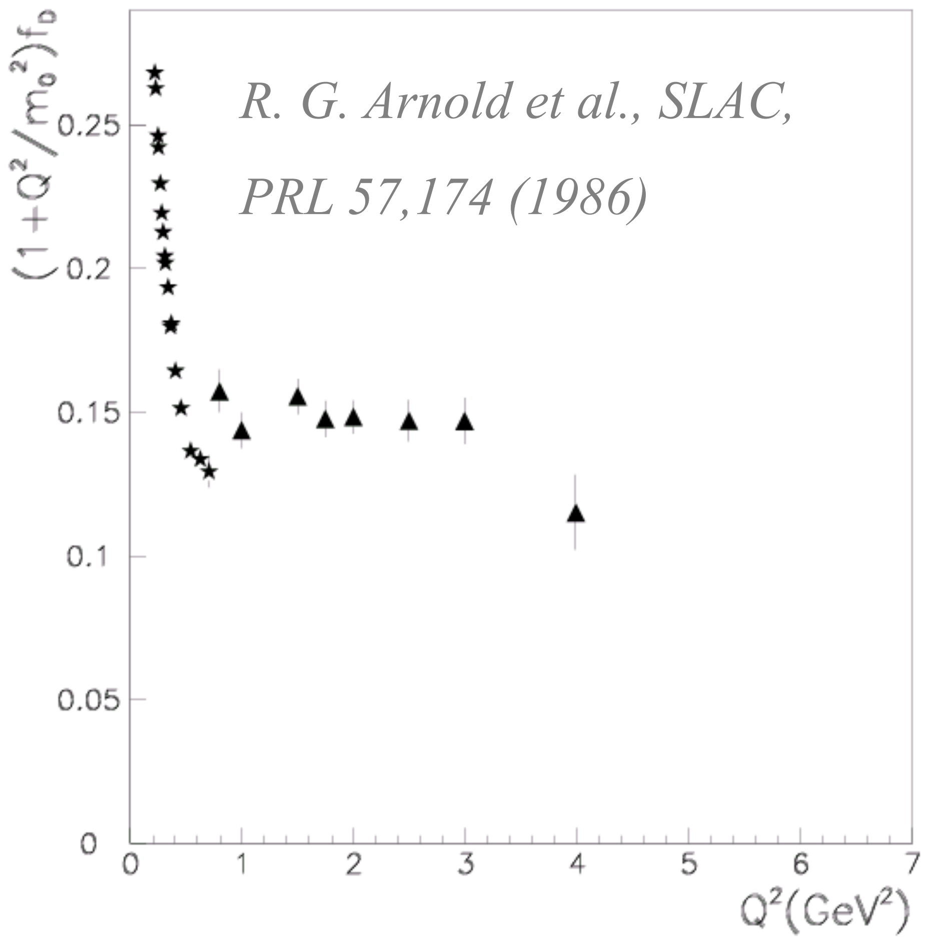
Dimensional scaling

– $F_n(Q^2) = C_n\,[1/(1+Q^2/m_n)^{n-1}]$,
  - $m_n = n\beta^2$, <quark momentum squared>
  - n is the number of constituent quarks

– Setting $\beta^2 = (0.471 \pm .010)$ GeV^2 *(fitting pion data)*
  - pion: $F_\pi(Q^2) = C_\pi\,[1/(1+Q^2/0.471\ \text{GeV}^2)^1]$,
  - nucleon: $F_N(Q^2) = C_N\,[1/(1+Q^2/0.71\ \text{GeV}^2)^2]$,
  - deuteron: $F_d(Q^2) = C_d\,[1/(1+Q^2/1.41\text{GeV}^2)^5]$

V. A. Matveev, R. M. Muradian, and A. N. Tavkhelidze (1973), Brodsky and Farrar (1973), Politzer (1974), Chernyak & Zhitnisky (1984), Efremov & Radyuskin (1980)…

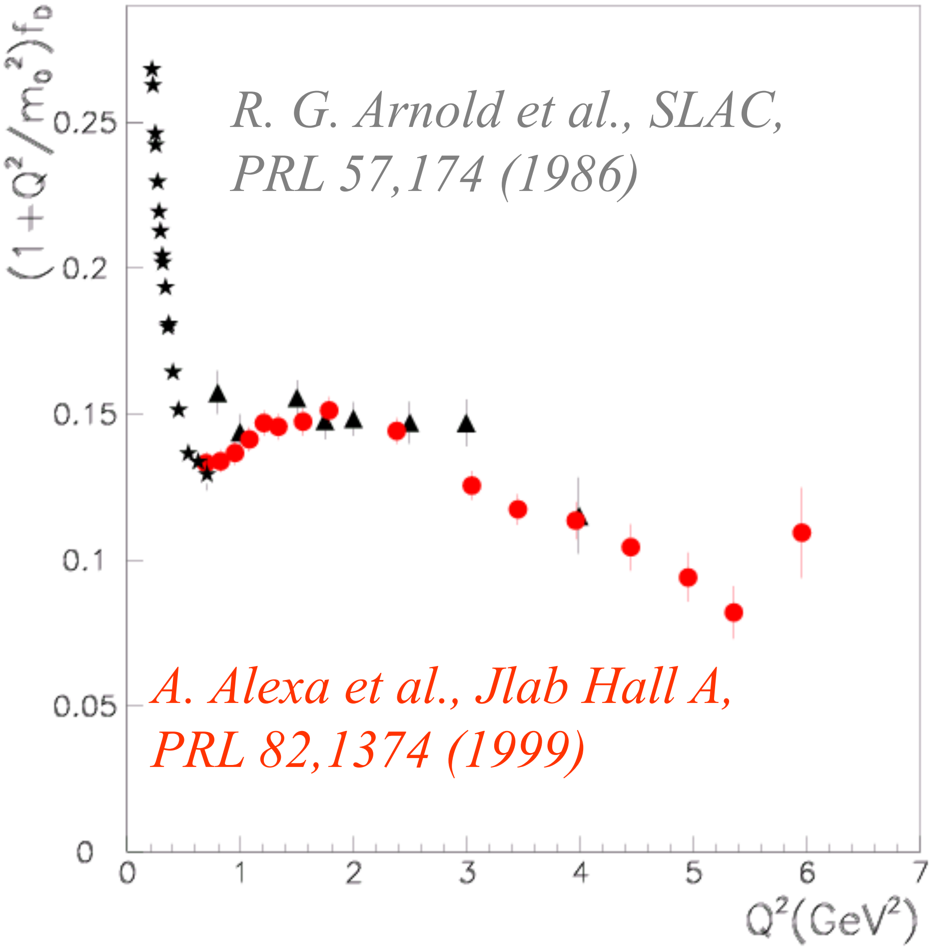
Reduced deuteron form factors



$$f_R = \left(1 + \frac{Q^2}{m_0^2}\right) f_D(Q^2) \simeq const$$

S. Brodsky and B.T. Chertok,
Phys. Rev. D 14, 3003 (1976)

Reduced deuteron form factors



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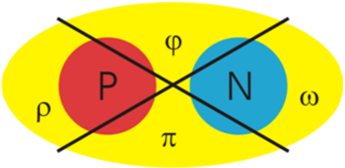
S. Brodsky and B.T. Chertok, Phys. Rev. D 14, 3003 (1976)

M.P. Rekalo and E. T.-G., Eur. Phys. J. A, (2003)

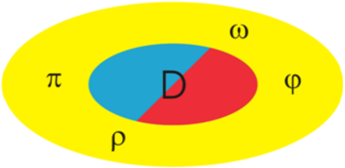
The Deuteron VMD: S=1, T=0

$$G_i(Q^2) = N_i g_i(Q^2) F_i(Q^2), \quad i = c, q, m$$



Normalization

$$N_c = G_c(0) = 1,$$
$$N_q = G_q(0) = M^2 Q_d = 25.83,$$
$$N_m = G_m(0) = \frac{M}{m}\mu_d = 1.714,$$



Intrinsic term
(common to the 3 FFs)

$$g_i(Q^2) = 1/[1 + \gamma_i Q^2]^{\delta_i},$$

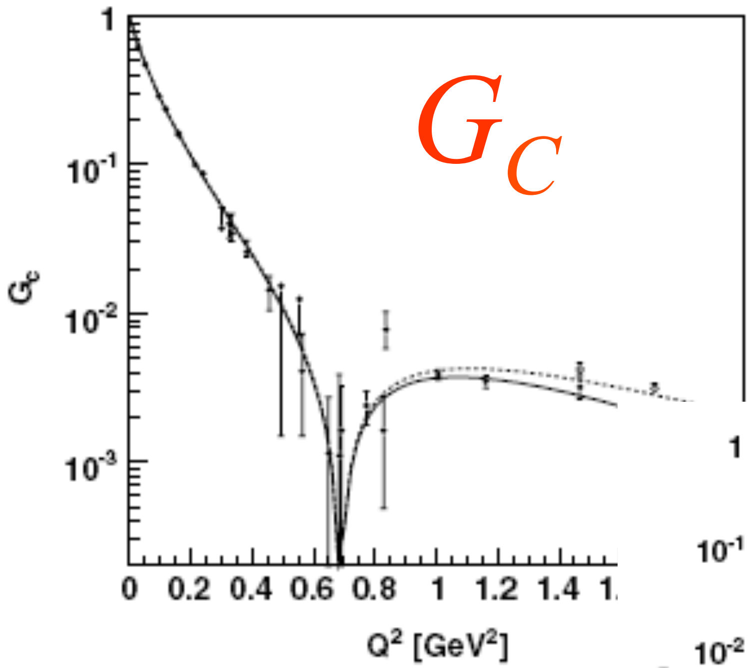
Meson cloud: isoscalar vector meson only

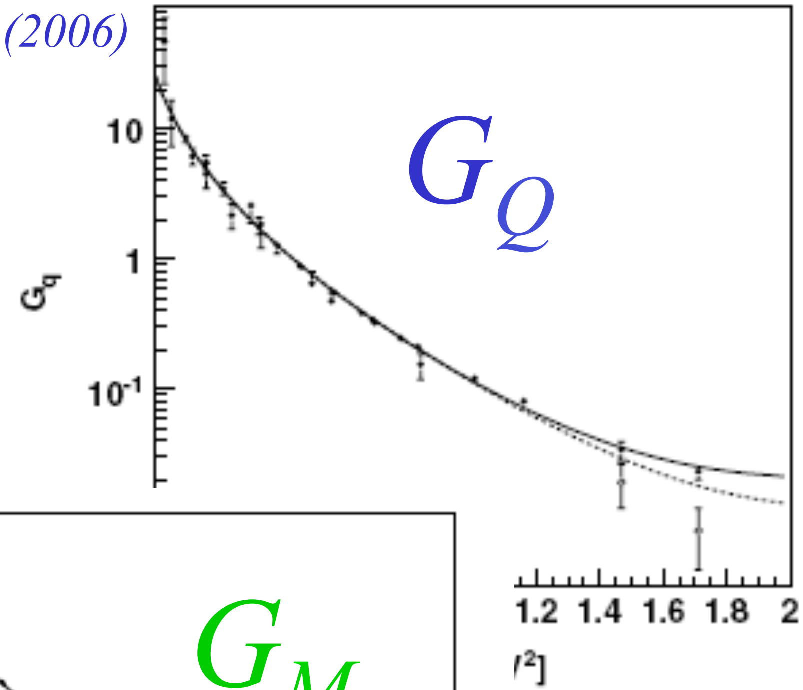
$$F_i(Q^2) = 1 - \alpha_i - \beta_i + \alpha_i \frac{m_\omega^2}{m_\omega^2 + Q^2} + \beta_i \frac{m_\phi^2}{m_\phi^2 + Q^2},$$

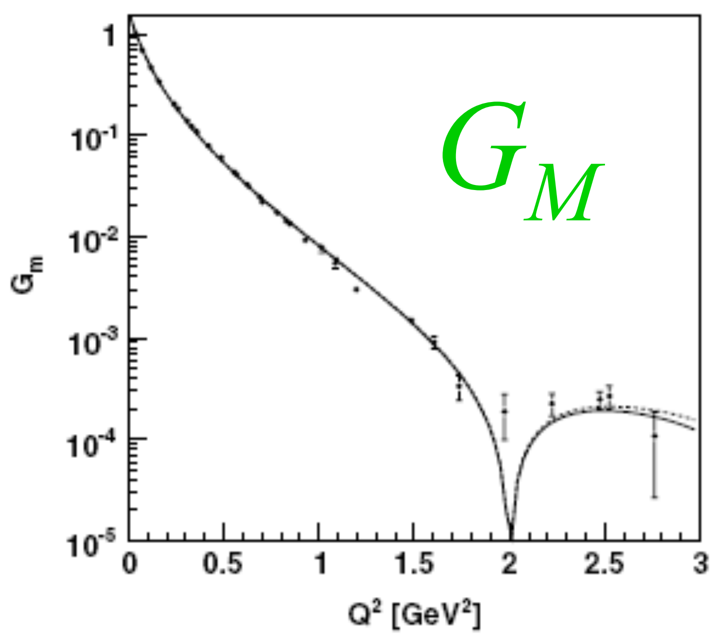
C. Adamuscin, G.I. Gakh and E.T-G. PRC ***73****, 045204 (2006)*

The best parametrization

C. Adamuscin, G.I. Gakh and E.T-G. PRC **73**, 045204 (2006)



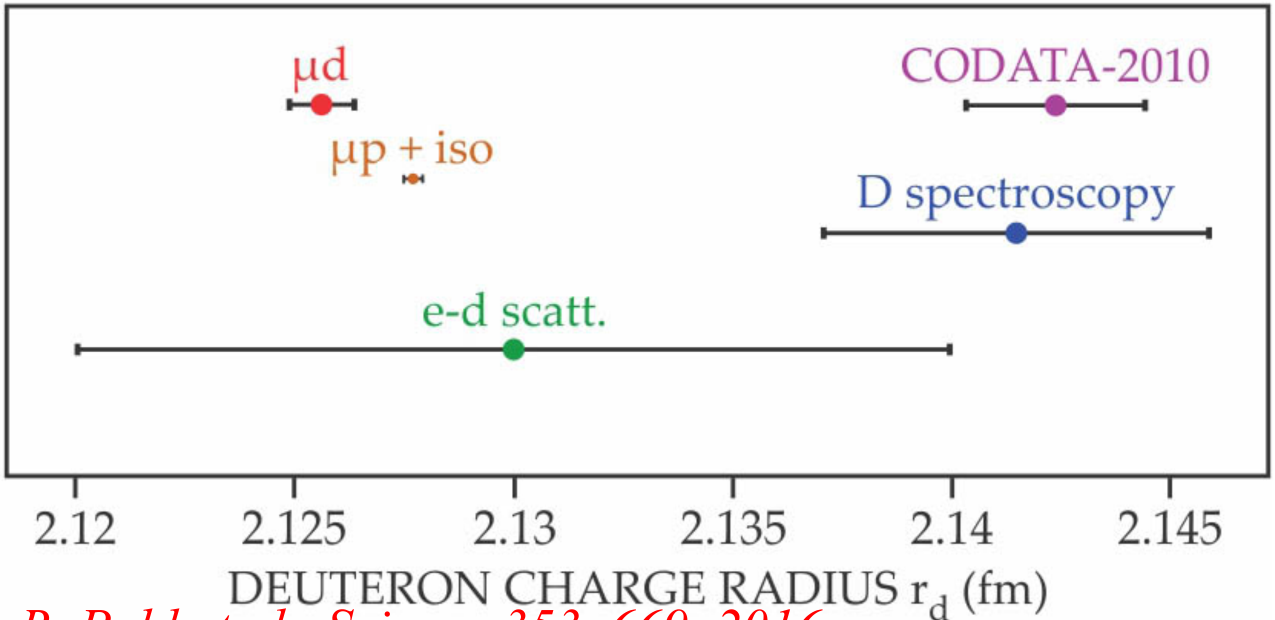




- 2 parameters fit
- best χ^2
- TL region !

The deuteron size

- Discrepancy between the determination of the proton radius:
  - CODATA (ep scattering & H) and muonic hydrogen
  - ep elastic scattering and μH
  - Recent and previous Hydrogen Lamb shift experiments
  - Tension between analysis of ep-scattering: extrapolation to $Q^2=0$!!!



R. Pohl et al., Science 353, 669, 2016.

Similar situation for the deuteron !

Deuteron joins proton as smaller than expected

PHYSICS TODAY

11 Aug 2016 in Research & Technology

Our contribution

PHYSICAL REVIEW C

Polarization observables in lepton-deuteron elastic scattering including the lepton mass

G. I. Gakh, A. G. Gakh, and E. Tomasi-Gustafsson
Phys. Rev. C **90**, 064901 – Published 2 December 2014

Model independent radiative corrections to elastic deuteron-electron scattering

G.I. Gakh, M.I. Konchatni N.P. Merenkov, E. T.-G.

arXiv.org>>hep-ph > arXiv:1804.01399
To appear in PRC

The IA deuteron structure: S=1, T=0

$$G_c = G_{Es} C_E, \quad G_q = G_{Es} C_Q, \quad G_m = \frac{M_d}{M_p}\left(G_{Ms} C_S + \frac{1}{2} G_{Es} C_L\right)$$

$$C_E = \int_0^\infty dr\ j_0\left(\frac{Qr}{2}\right)\left[u^2(r) + w^2(r)\right],$$

$$C_Q = \frac{3}{\sqrt{2}\tau}\int_0^\infty dr\ j_2\left(\frac{Qr}{2}\right)\left[u(r) - \frac{w(r)}{\sqrt{8}}\right] w(r),$$

$$C_S = \int_0^\infty dr\left[u^2(r) - \tfrac{1}{2} w^2(r)\right] j_0\left(\tfrac{Qr}{2}\right) + \tfrac{1}{2}\left[\sqrt{2} u(r) w(r) + w^2(r)\right] j_2\left(\tfrac{Qr}{2}\right),$$

$$C_L = \frac{3}{2}\int_0^\infty dr\ w^2(r)\left[j_0\left(\frac{Qr}{2}\right) + j_2\left(\frac{Qr}{2}\right)\right],$$

1) The nucleon form factors:

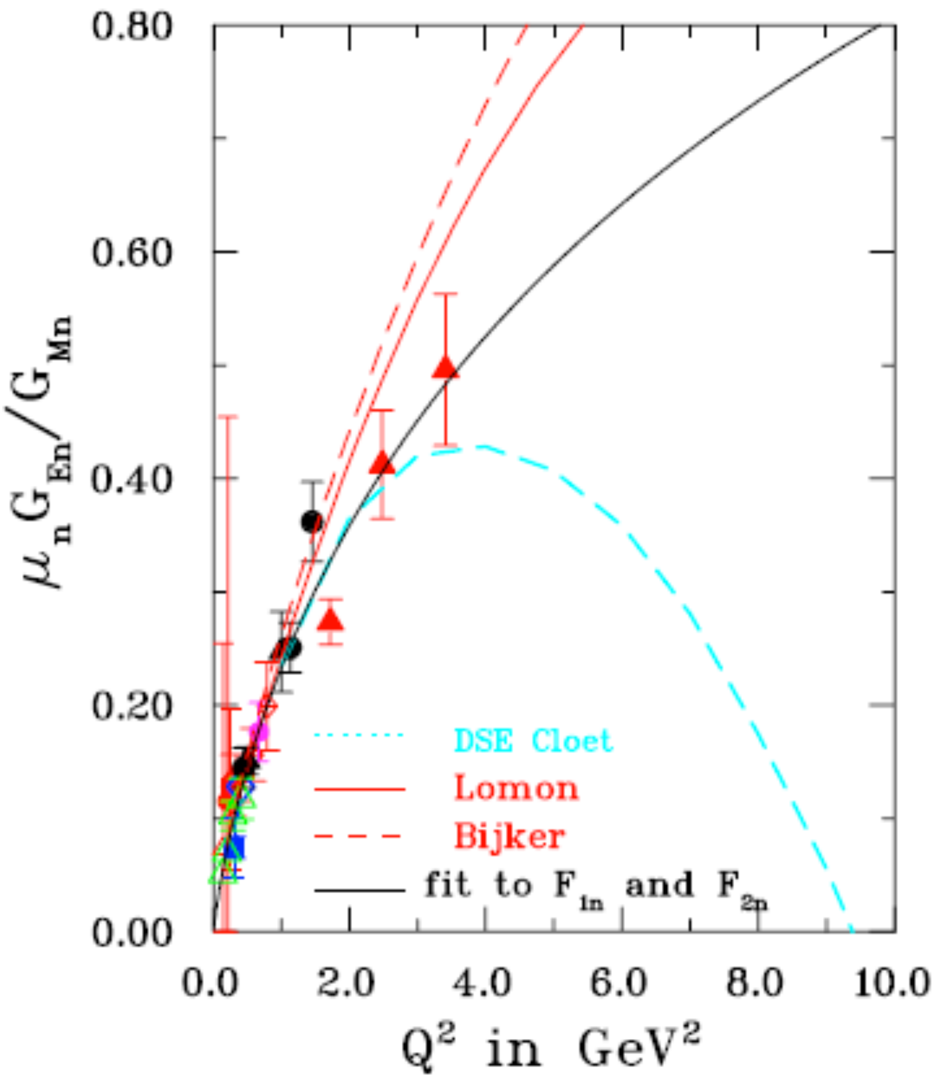
$$G_{Ms} = G_{Mp} + G_{Mn}$$

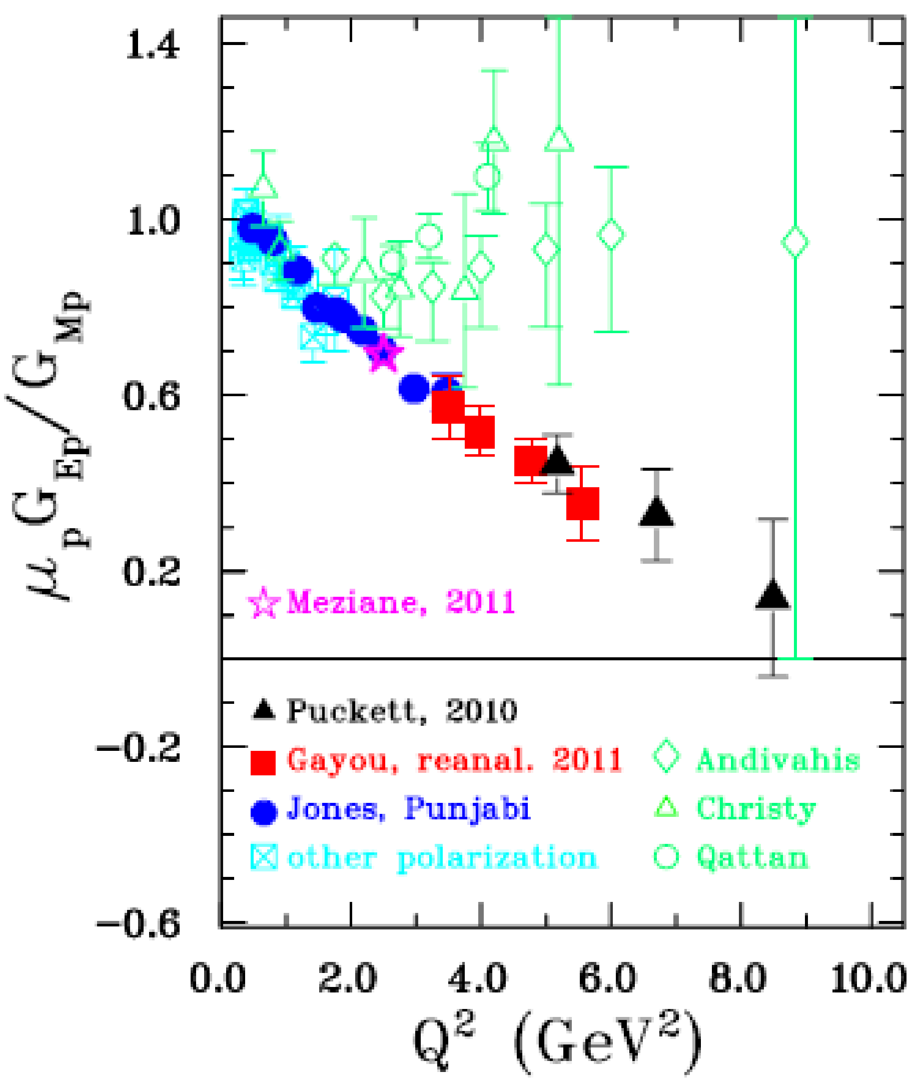
$$G_{Es} = G_{Ep} + G_{En}$$

2) The S (u) and D (w) deuteron wave function

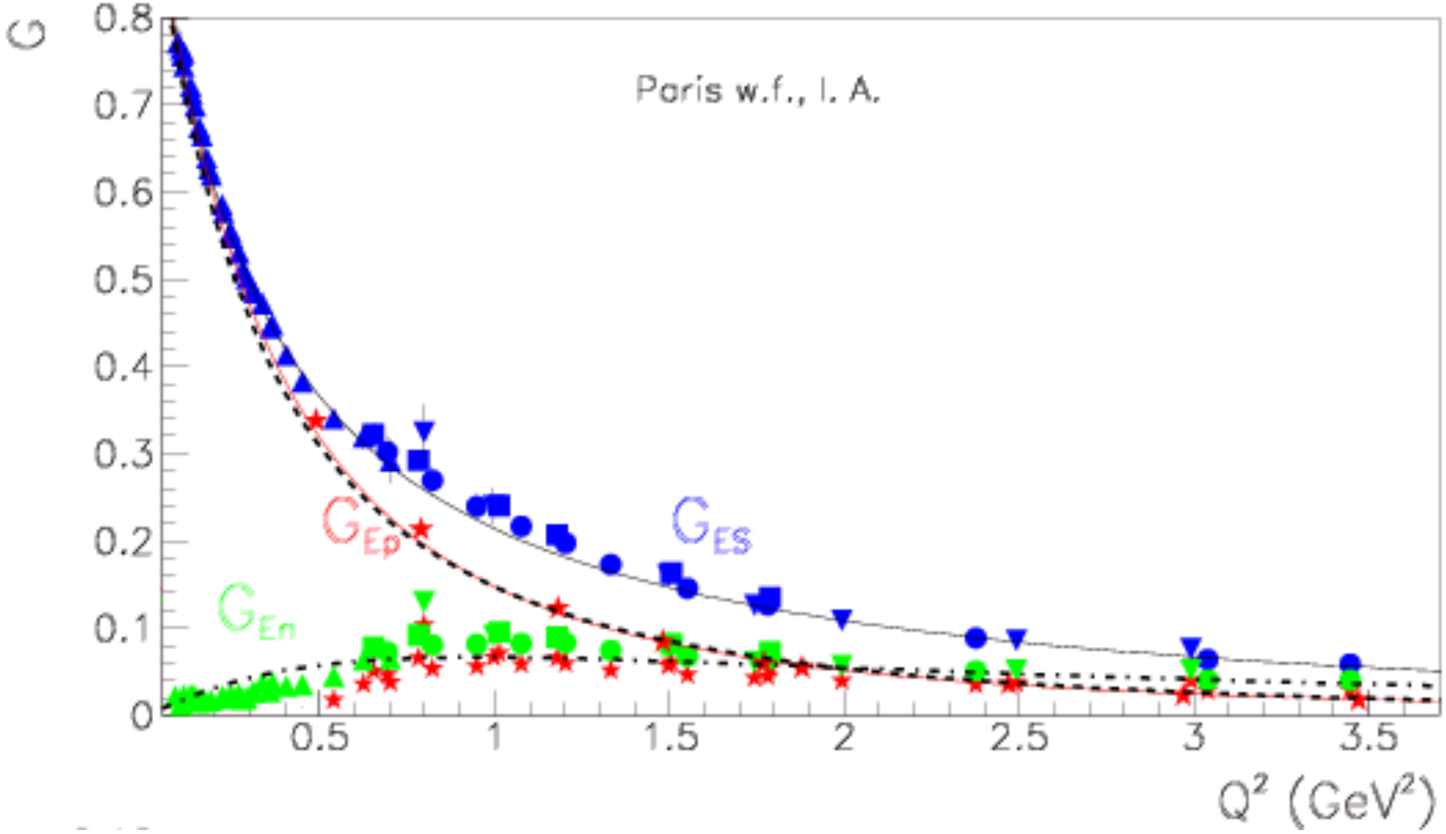
$$\int_0^\infty dr\ \left[u^2(r) + w^2(r)\right] = 1.$$

G_{En} from e-deuteron elastic scattering





G_{En} from e-deuteron elastic scattering



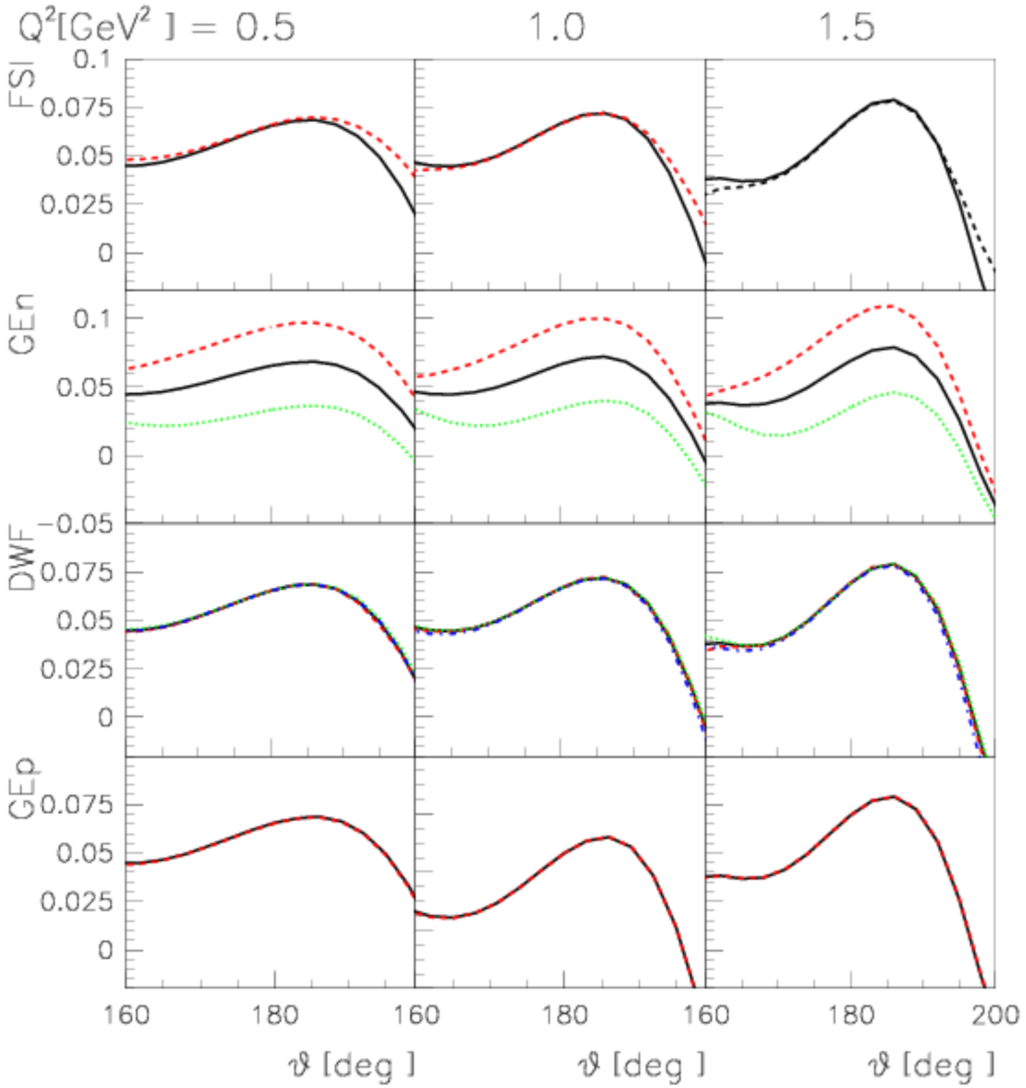
- $G_{En} > G_{Ep}$ starting from 2 GeV^2 !

E. T-G. and M. P. Rekalo, Europhys. Lett. 55, 188 (2001)

Deuteron electrodisintegration

The reaction d(e,e'n)p - A_x

-The KHARKOV model:
- Impulse Approximation
- Fully relativistic
- Kinematics: proton spectator
- Polarization observables



- *Select the quasi-elastic kinematics*
- *Large dependence of the asymmetry on GEn!*
- *Polarized electron beam, polarized target or neutron polarimeter*

G.I. Gakh, A. P. Rekalo, E. T.-G. Annals of Physics (2005)

Coherent pion electroproduction on the Deuteron

Annals of Physics **295**, 1–32 (2002)
doi:10.1006/aphy.2001.6208, available online at http://www.idealibrary.com on IDEAL®

Coherent π^0 Electroproduction on the Deuteron

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Received December 21, 2000; revised August 14, 2001

$e+d \to e+d+P^0$

In general

Hadronic tensor :

$$H_{ab} = H_{ab}^{(0)} + H_{ab}^{(1)} + H_{ab}^{(2)},$$

$$(4_0 + 8_1 + 16_2 = 28) \text{ SF's},$$

$H_{ab}^{(0)}$: Unpolarized tensor depends on 4 SF

$H_{ab}^{(1)}$: Vector polarized deuteron … 8 SF

$H_{ab}^{(2)}$: Tensor polarized deuteron … 16 SF

Longitudinally polarized electrons: $1_0 + 5_1 + 7_2 = 13 \text{ SF's}.$

41 SF:

$$1_0 + 8_1 + 7_2 = 16 \text{ T-odd}$$

$$4_0 + 5_1 + 16_2 = 25 \text{ T-even}$$

$e+d \to e+d+P^0$

General expressions for the unpolarized cross section:

$$\frac{d^2\sigma}{dE_2 d\Omega_e} = \frac{\alpha^2}{16\pi^2}\frac{E_2}{E_1}\frac{|\vec{q}|}{M\sqrt{s}}\frac{1}{1-\kappa}\frac{X^{(t)}}{(-k^2)},$$

$$X^{(t)} = H_{xx}^{(t)} + H_{yy}^{(t)} + \kappa\left(H_{xx}^{(t)} - H_{yy}^{(t)}\right) - 2\kappa\frac{k^2}{{k_0}^2}H_{zz}^{(t)} - \sqrt{2\kappa\,(1+\kappa)\,\frac{(-k^2)}{{k_0}^2}}\left(H_{xz}^{(t)} + H_{zx}^{(t)}\right)$$

$$-\lambda\sqrt{1-\kappa}\left(\sqrt{1+\kappa}\left(H_{xy}^{(t)} - H_{yx}^{(t)}\right) + \sqrt{2\kappa\frac{(-k^2)}{{k_0}^2}}\left(H_{yz}^{(t)} - H_{zy}^{(t)}\right)\right),$$

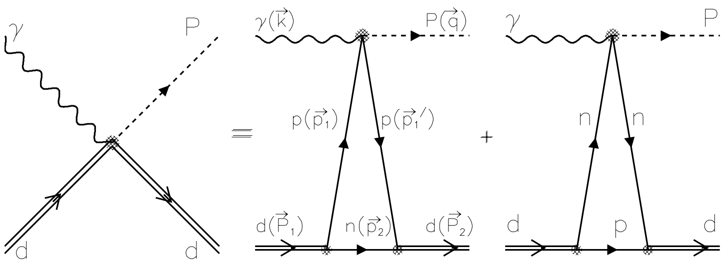
And for all polarization observables…

..to be then calculated according to a model: IA

G.I. Gakh, A. P. Rekalo, E. T.-G. Annals of Physics 295, 1 (2002)

Impulse approximation for $\gamma + d \rightarrow \gamma + d + P^0$

$$\mathcal{M}(\gamma^* d \to dP^0) = \vec{D}_1 \vec{D}_2^* \hat{L} F_1(\vec{Q}^2) + 2\left(3\vec{D}_1 \cdot \hat{\vec{Q}} \vec{D}_2^* \cdot \vec{Q} - \vec{D}_1 \cdot \vec{D}_2\right) \hat{L} F_2(\vec{Q}^2)$$
$$+ i\hat{\vec{K}} \cdot \vec{D}_1 \times \vec{D}_2^* \left(F_3(\vec{Q}^2) + F_4(\vec{Q}^2)\right) - 3i\hat{\vec{K}} \cdot \hat{\vec{Q}} \hat{\vec{Q}} \cdot \vec{D}_1 \times \vec{D}_2^* F_4(\vec{Q}^2),$$



Inelastic Form Factors

$$F_1(\vec{Q}^2) = \int_0^\infty dr\ j_0\left(\frac{Qr}{2}\right)\left[u^2(r) + w^2(r)\right],$$

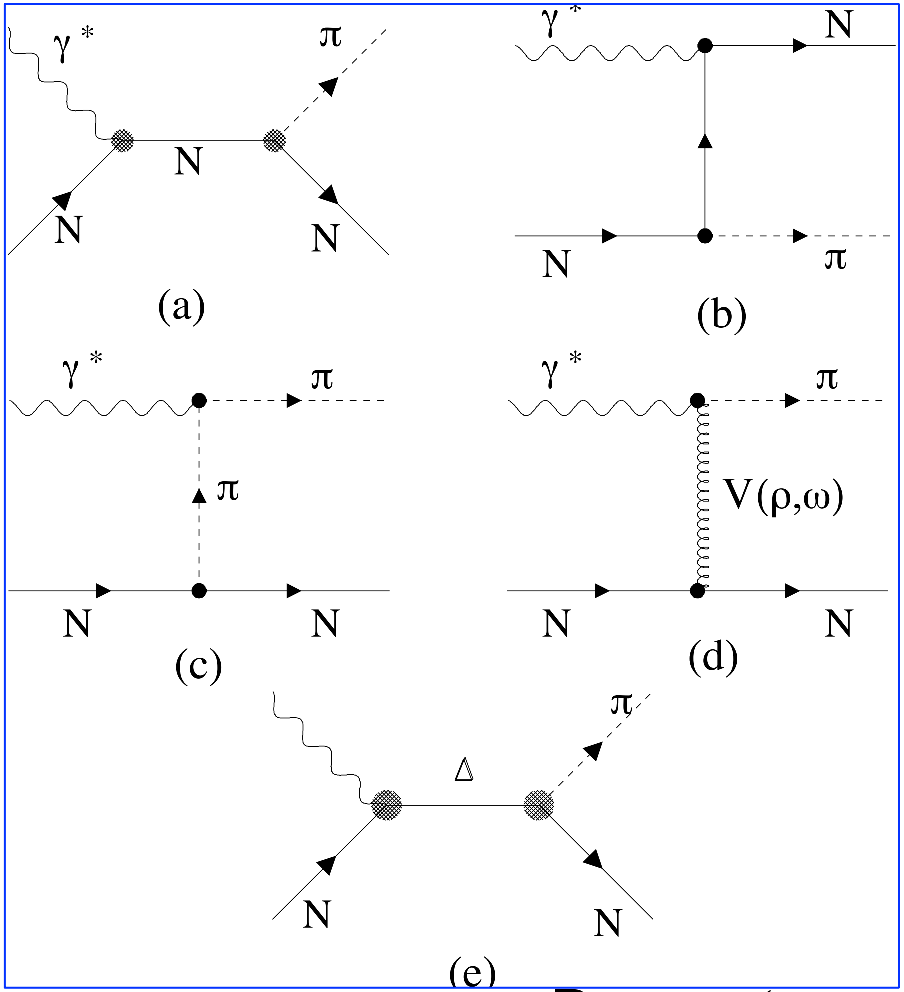
$$F_2(\vec{Q}^2) = \int_0^\infty dr\ j_2\left(\frac{Qr}{2}\right)\left[u(r) - \frac{w(r)}{\sqrt{8}}\right] w(r),$$

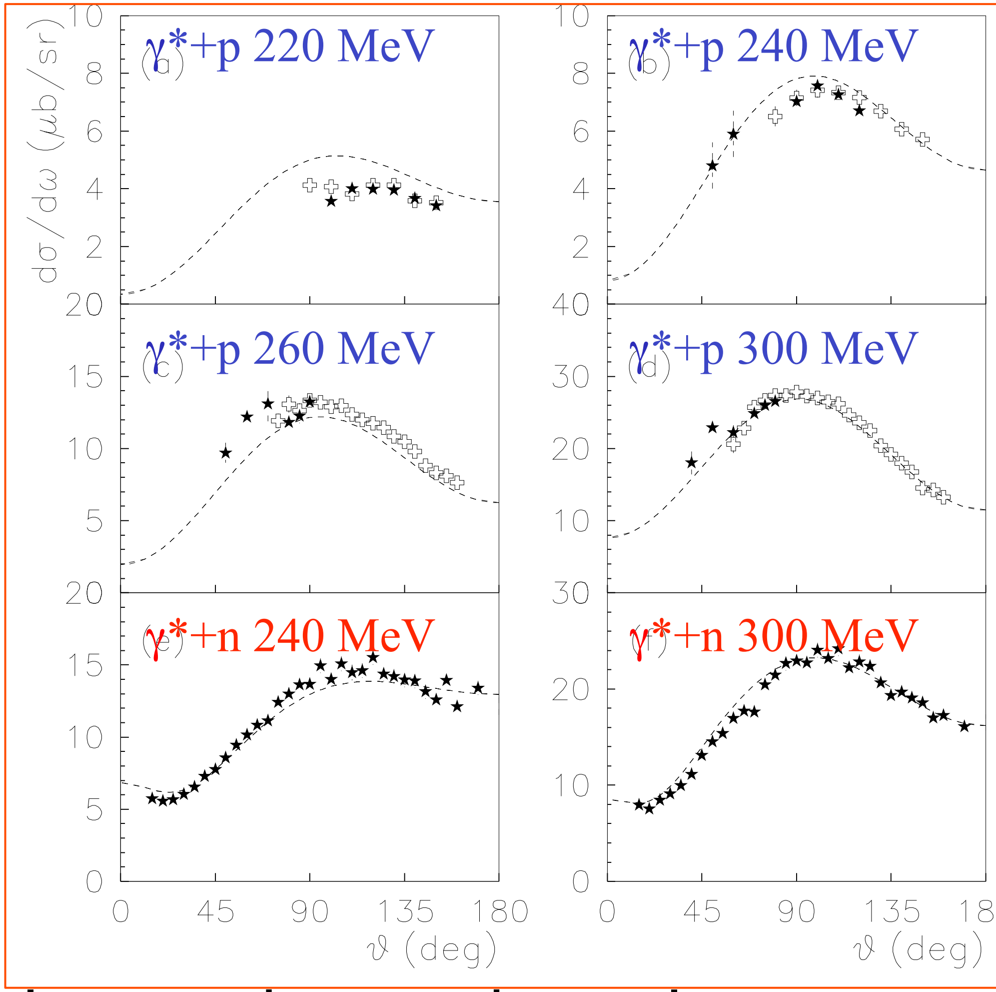
$$F_3(\vec{Q}^2) = \int_0^\infty dr\ j_0\left(\frac{Qr}{2}\right)\left[u^2(r) - \frac{1}{2}w^2(r)\right],$$

$$F_4(\vec{Q}^2) = \int_0^\infty dr\ j_2\left(\frac{Qr}{2}\right)\left[u(r) + \frac{1}{\sqrt{2}}w(r)\right] w(r),$$

$$j_0(x) = \frac{\sin x}{x},\quad j_2(x) = \sin x\left(\frac{3}{x^3} - \frac{1}{x}\right) - 3\frac{\cos x}{x^2}.$$

$\gamma^*+N \rightarrow \gamma^*+N+P^0$



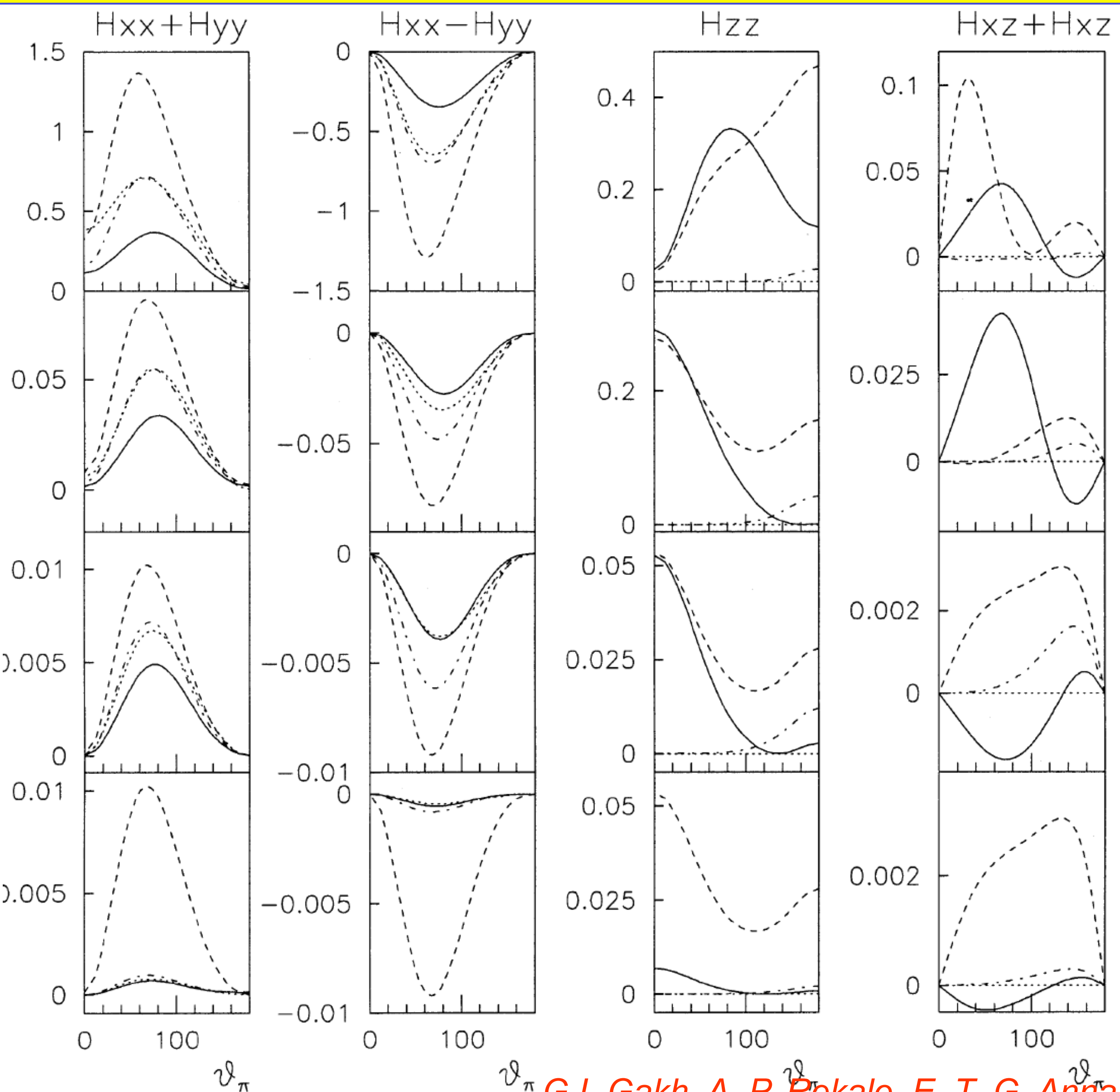


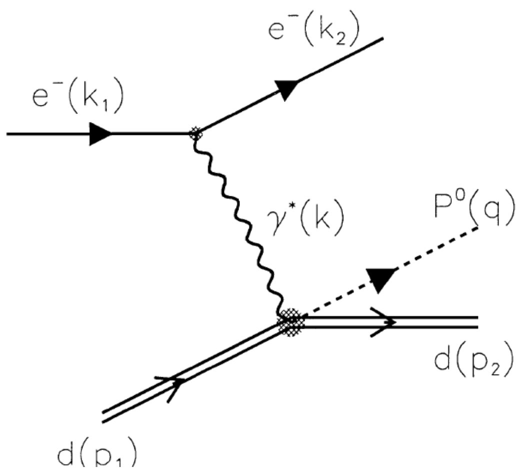
VMD model:

(near threshold)

- Born *s,t,u* nucleon exchange channels
- t-channel π, ρ, ω , exchange
- Δ exchange

$e+d \rightarrow e+d+P^0$





Polarization phenomena in progress !

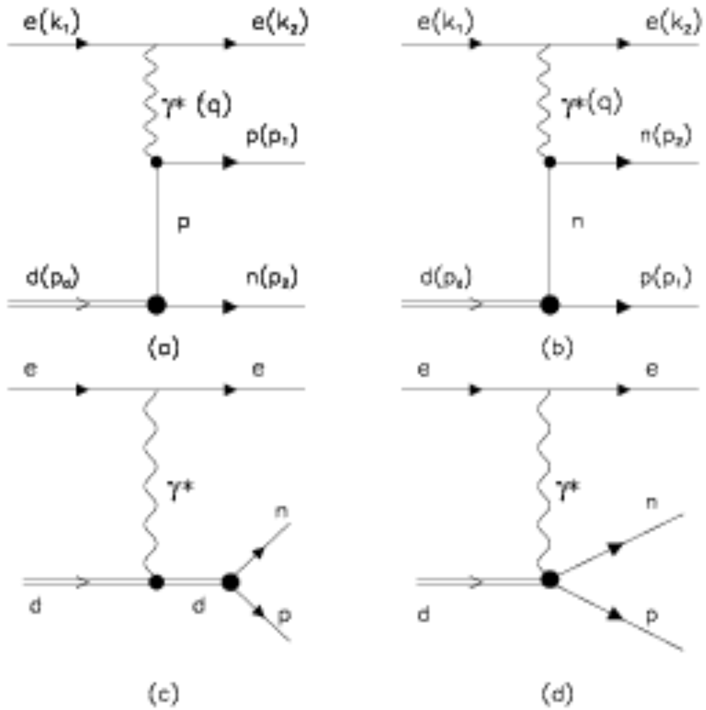
G.I. Gakh, A. P. Rekalo, E. T.-G. Annals of Physics 295, 1 (2002)

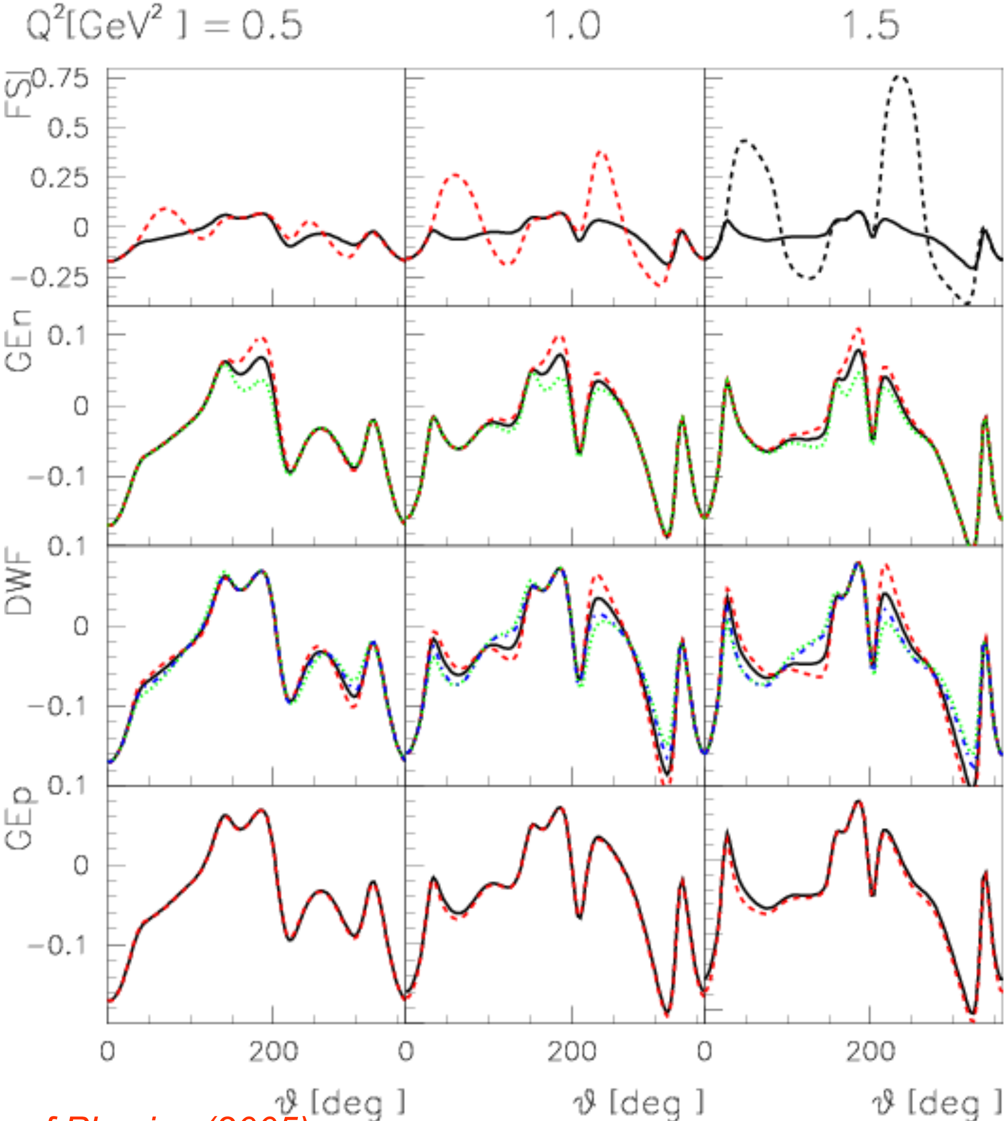
Conclusion

Jefferson Lab

- eD elastic scattering at large Q^2 with the 11 GeV Jlab upgrade
- Measurements of neutron FFs
- Deuteron: lightest nucleus to study quark and hadron dynamics at short distances:
  - ✓ short range correlations
  - ✓ three body forces
  - ✓ six quarks states
  - ✓ ……
- Polarized deuteron beam at 13 GeV already available at Dubna Nuclotron.
- NICA Collider soon 8

The reaction d(e,e'n)p - A_x

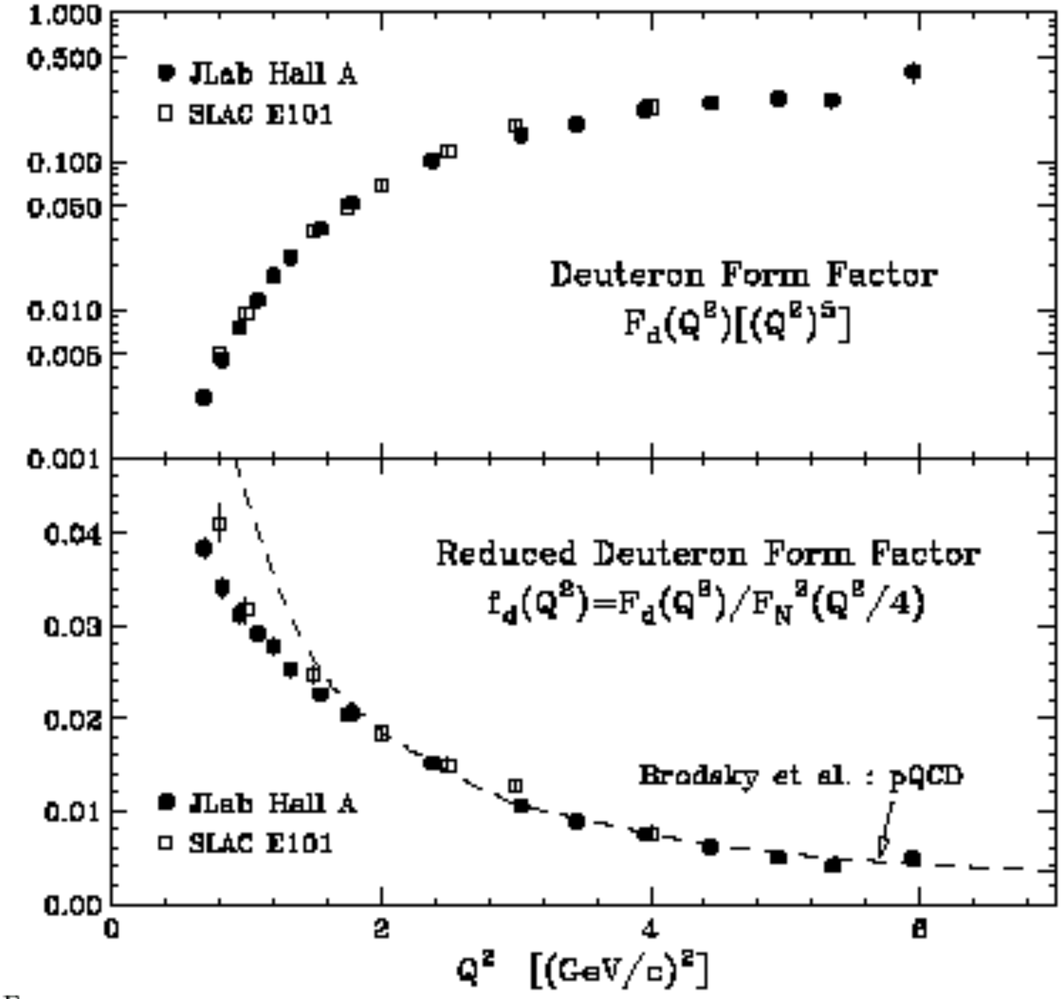




-The KHARKOV model:
- Impulse Approximation
- Fully relativistic
- Kinematics: proton spectator
- Polarization observables

G.I. Gakh, A. P. Rekalo, E. T.-G. Annals of Physics (2005)

Reduced deuteron form factors



$$f_D(Q^2) = \frac{F_D(Q^2)}{F_N^2(Q^2/4)},$$

$$F_D(Q^2) = \sqrt{A(Q^2)}$$

$$f_D(Q^2) = N\frac{\alpha_s(Q^2)}{Q^2}\left(ln\frac{Q^2}{\Lambda^2}\right)^{-\Gamma}, \qquad \Gamma = -\frac{8}{145}.$$

L.Alexa et al., PRL 82, 1374 (1999), HallA, JLab

Results

From 12 to 6 parameters fit

1) Constrains on the nodes:

$Q^2{}_{0C}=1.7\ GeV^2,\ \ Q^2{}_{0M}=2\ GeV^2$

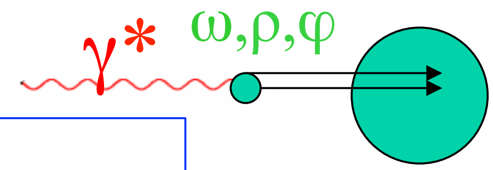
$$\alpha_i = \frac{m_\omega^2 + Q_{0i}^2}{Q_{0i}^2} - \beta_i \frac{m_\omega^2 + Q_{0i}^2}{m_\phi^2 + Q_{0i}^2}.$$

2) Intrinsic part common to the 3 FFs:

$\delta=1.04 \pm 0.03,\ \gamma=12.1 \pm 0.5$

	α	β	$\chi 2/ndf$
G_c (I)	5.75 ± 0.07	-5.11 ± 0.09	0.9
G_c (II)	5.50 ± 0.06	-4.78 ± 0.08	1.3
G_q(I)	4.21 ± 0.05	-3.41 ± 0.07	0.9
G_q(II)	4.08 ± 0.07	-3.25 ± 0.09	1.6
$G_m(I)$	3.77 ± 0.04	-2.86 ± 0.05	1.6
$G_m(II)$	3.74 ± 0.04	-2.83 ± 0.05	1.7

VDM: Iachello, Jakson and Landé (1973)



- Isoscalar and isovector FFs

$$
\begin{aligned}
F_1^s(Q^2) &= \frac{g(Q^2)}{2}\left[(1-\beta_\omega-\beta_\phi)+\beta_\omega\frac{\mu_\omega^2}{\mu_\omega^2+Q^2}+\beta_\phi\frac{\mu_\phi^2}{\mu_\phi^2+Q^2}\right],\\
F_1^v(Q^2) &= \frac{g(Q^2)}{2}\left[(1-\beta_\rho)+\beta_\rho\frac{\mu_\rho^2+8\Gamma_\rho\mu_\pi/\pi}{(\mu_\rho^2+Q^2)+(4\mu_\pi^2+Q^2)\Gamma_\rho\alpha(Q^2)/\mu_\pi}\right],\\
F_2^s(Q^2) &= \frac{g(Q^2)}{2}\left[(\mu_p+\mu_n-1-\alpha_\phi)\frac{\mu_\omega^2}{\mu_\omega^2+Q^2}+\alpha_\phi\frac{\mu_\phi^2}{\mu_\phi^2+Q^2}\right],\\
F_2^v(Q^2) &= \frac{g(Q^2)}{2}\left[(\mu_p-\mu_n-1)\frac{\mu_\rho^2+8\Gamma_\rho\mu_\pi/\pi}{(\mu_\rho^2+Q^2)+(4\mu_\pi^2+Q^2)\Gamma_\rho\alpha(Q^2)/\mu_\pi}\right],
\end{aligned}
$$

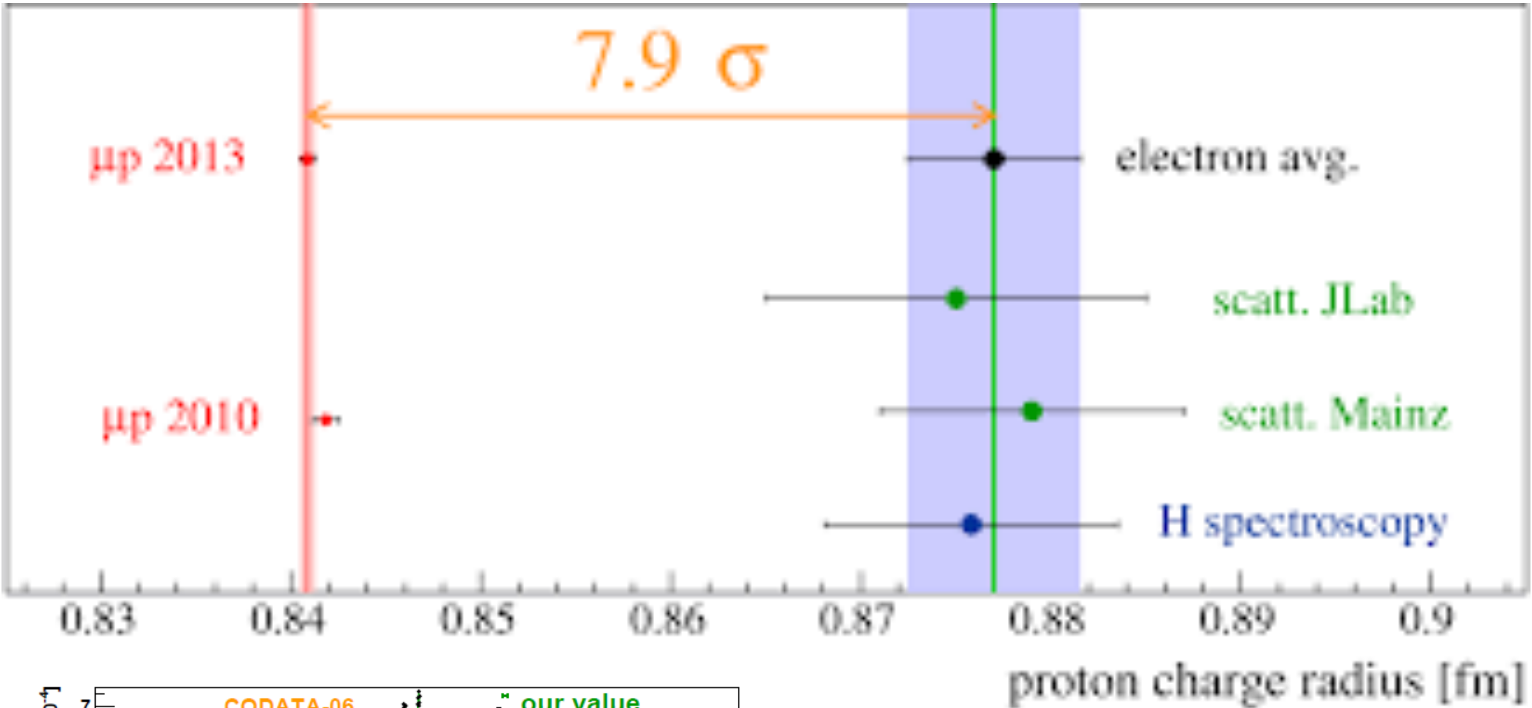
$$
2F_i^p = F_i^s + F_i^v,\qquad 2F_i^n = F_i^s - F_i^v
$$

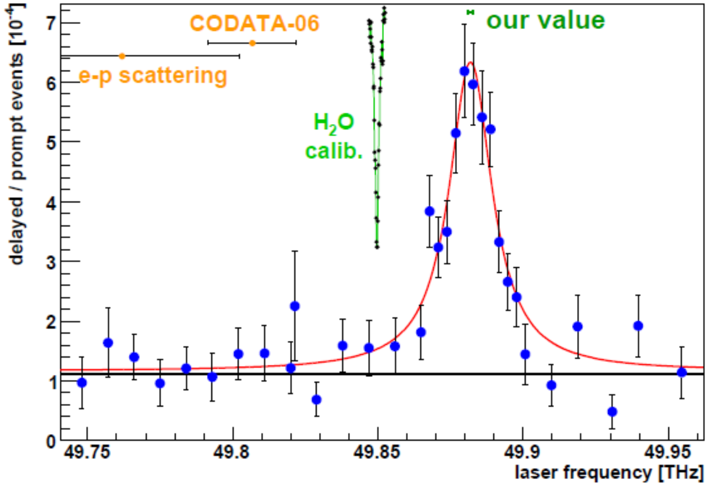
- Intrinsic FF

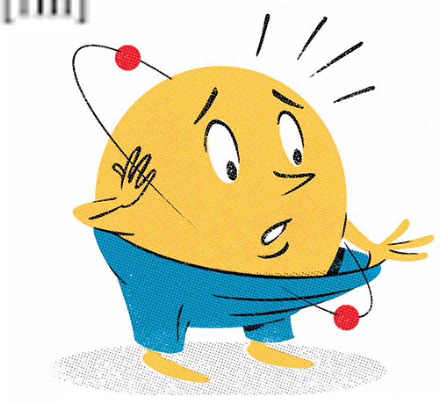
$$
g(Q^2) = \frac{1}{(1+\gamma e^{i\theta}Q^2)^2}
$$

$$
\alpha(Q^2) = \frac{2}{\pi}\sqrt{\frac{Q^2+4\mu_\pi^2}{Q^2}}\,ln\left[\frac{\sqrt{(Q^2+4\mu_\pi^2)}+\sqrt{Q^2}}{2\mu_\pi}\right]
$$

The Proton Size (Radius)

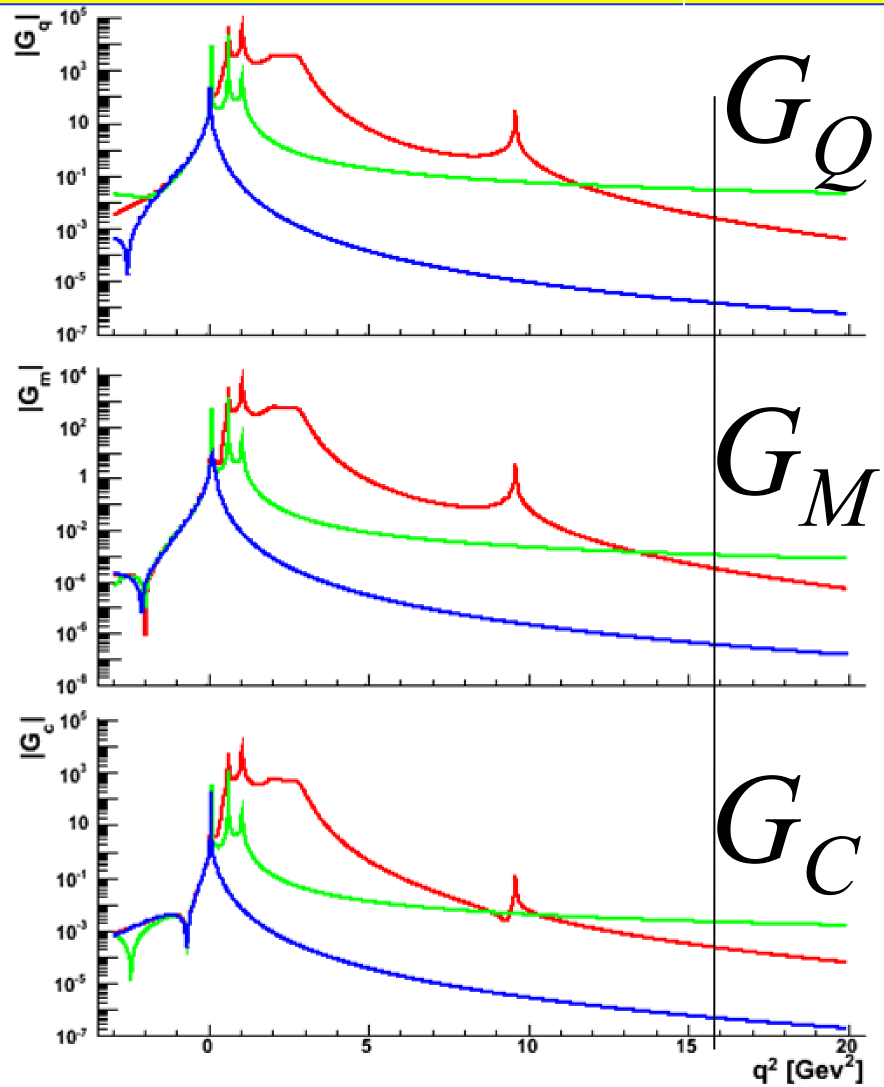






The New York Times

The time-like region: $e^+ + e^- \to d + \bar{d}$



Imaginary part from the intrinsic term

No finite width for ρ,ω mesons

U&A (Dubnicka)

Parametrization I (real part) [Abbott, EPJA 2000]

G. I. Gakh, E. T-G, C. Adamuščín, S. Dubnička, and A. Z. Dubničková PRC 74, 025202 (2006)

Electric NEUTRON Form Factor

- Smaller then for proton, but not so small
– New results, based on polarization method

SOVIET PHYSICS – DOKLADY VOL. 13, NO. 6 DECEMBER, 1968

PHYSICS

POLARIZATION PHENOMENA IN ELECTRON SCATTERING BY PROTONS IN THE HIGH-ENERGY REGION

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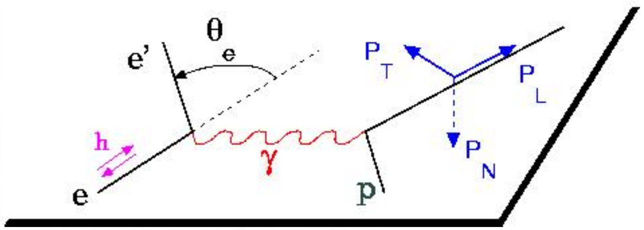
Translated from Doklady Akademii Nauk SSSR, Vol. 180, No. 5, pp. 1081–1083, June, 1968
Original article submitted February 26, 1967



The polarization induces a term in the cross section proportional to $G_E G_M$
Polarized beam and target or polarized beam and recoil proton polarization