The structure of the deuteron as revealed by experiments at the DUBNA synchrophasotron and elsewhere

60th Anniversary of the Synchrophasotron Celebration, and 110th Anniversary of the birth of Vladimir Vechsler

Charles F. Perdrisat, Emeritus Professor
College of William and Mary in Virginia
Dubna, Russia, April 21, 2017

INTRODUCTION

I feel very honored to have been invited to present this talk on the structure of the deuteron.
As an introduction, I came to Dubna for the first time in June 1991, on the occasion of the 1991 Dubna-Deuteron Workshop.
I met Academician A.M. Baldin, who took me on a walk through the High Energy Lab. I met Drs. I. Sitnik, N. Piskunov, L. Strunov, E. Strokovsky and others. This visit turned out into a collaboration which is still very much alive 26 years later.

Academician A.M. Baldin's 70th birthday celebration in 1966.

Before starting, let me describe some fundamental properties of the deuteron, ^2H or D, one of the 3 isotopes of hydrogen.

D is made of 1 proton and 1 neutron, with spin 1, parity +.
In its ground state, the two nucleons can be in an S-state of orbital angular momentum (L=0), or in a D-state (L=2).
Its binding energy is only 2.2 MeV; it has no excited state.

But the ground state can also contain a component with L=1 (P-state); as parity of P state is -, requires one of the nucleons to be negative parity excited N*.

If probing the deuteron to short distance, the quark-structure of the nucleon may become "visible". An interesting possibility!

At this point in time, 1991, I had participated or organized a number of experiments, in close collaboration with Prof. Vina Punjabi, and closely related to what was going on in Dubna; among them:

1) Elastic scattering of polarized deuterons in Saclay (SATURNE): T_{20}, A_y and A_{yy} (Arvieux, 1984)
2) Large angle breakup D(p,2p) at 507 MeV cross section at TRIUMF (Canada) (Perdrisat, 1985)
3) D(p,2p)n in small recoil region at TRIUMF (Punjabi, 1986) and Inclusive H(d,p)X cross section and T_{20} at 3.5 GeV/c at SATURNE (Punjabi, 1989)
4) $H(\vec{d},\vec{p})X$, with vector polarized deuterons, measuring the proton polarization to obtain κ_0 at SATURNE (Cheung, 1992)

All experiments to be discussed here have one common and overwhelming motivation: *get information on the velocity (momentum) distribution of the nucleons inside the deuteron; equivalently the momentum densities, or probability to find a nucleon with a given momentum q; or the deuteron* **wave function.**

In quasi elastic D(p,2p)n, the neutron momentum p_n is its initial momentum, prior to the reaction, to the extent that nothing else occurred (no final state interation).

In $^1H(d,p)X$, inclusive breakup, p_p can be Lorentz transformed to the D-rest frame: q is then the corresponding internal momentum.

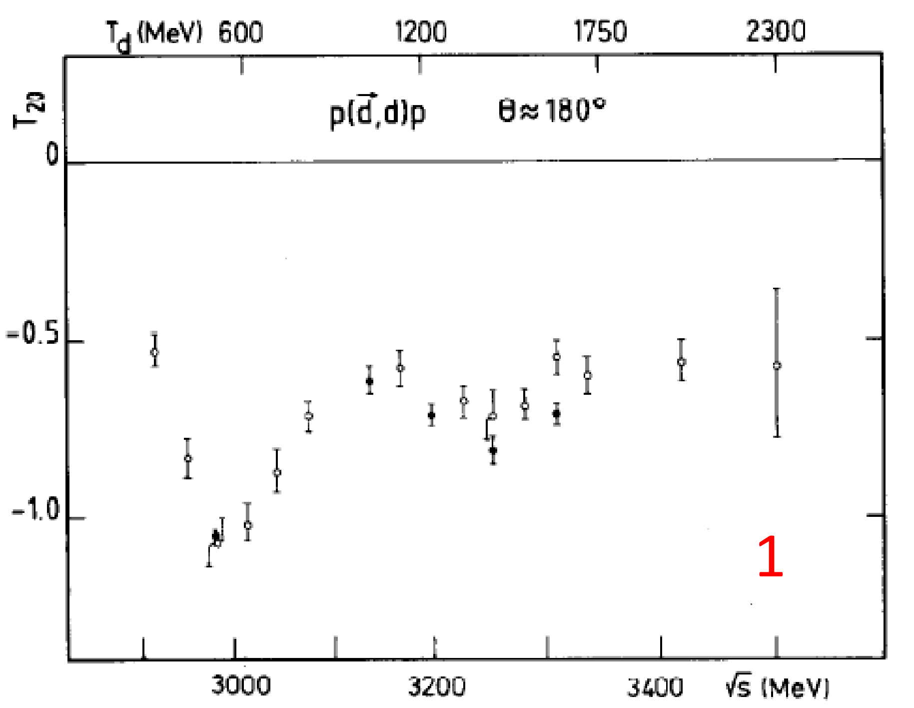
For very high energies one might use the infinite momentum frame instead, then $q \to k$ in figures to follow.

For a meaningful description of experimental results (and theoretical considerations) I will quickly describe 3 kinds of reactions involving a deuteron either as projectile or target, and the corresponding observables.

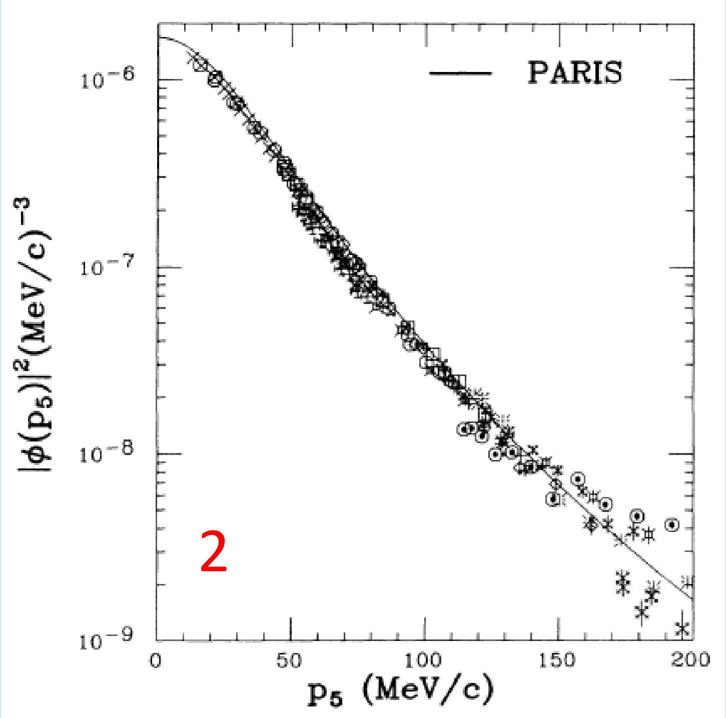
Quasi elastic breakup as in D(,p,2p)n: unpolarized cross section

Backward elastic: d+p→p+d, or 1H(d,p)D: cross section, tensor analyzing powers T_{20}, (T_{21} and T_{22}), vector analyzing power T_{11}.

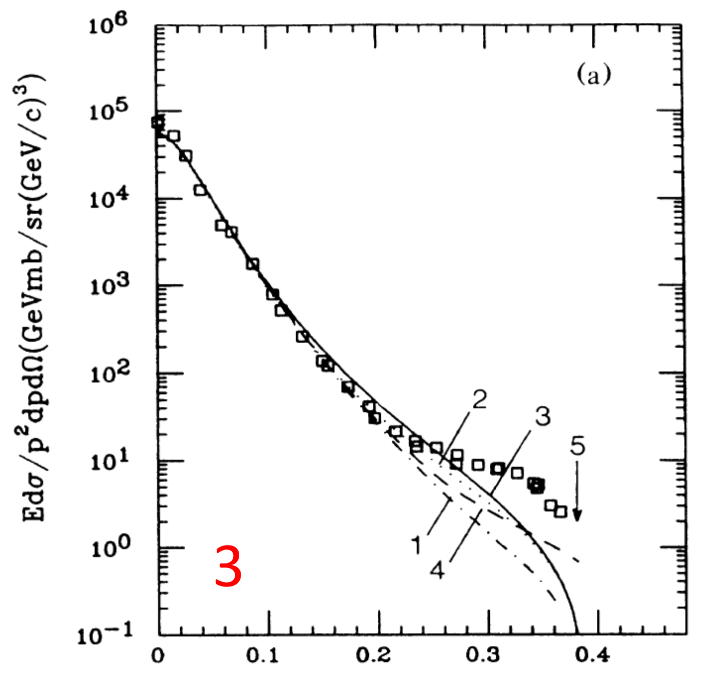
Breakup reaction, as in $^1H(d,p)X$ with p at 0^0, cross section, analyzing powers for tensor polarized deuterons, T_{20} ; and proton polarization for vector polarized deuterons, $\kappa_0 = P_p/P_d$.

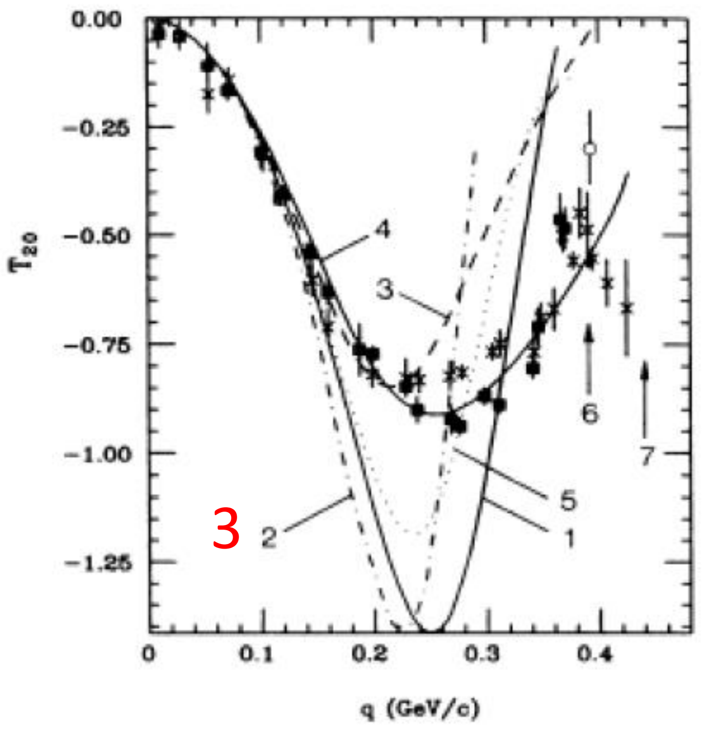


J. Arvieux et al, NP A431 (1984) 613.

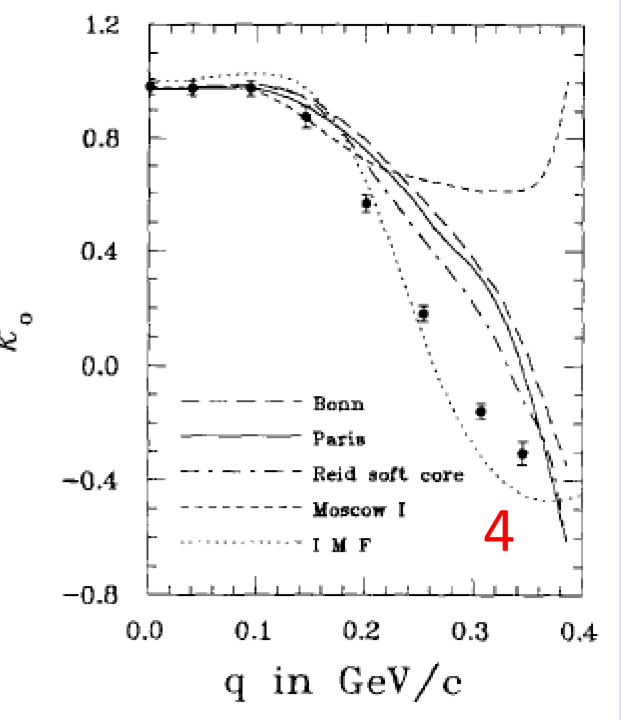


Punjabi et al PR C38, 2728 (1988)





C.F. Perdrisat etal, PRL 59, 2840 (1987)



E. Cheung et al, PLB284 (1992) 210

1 Saclay (SATURNE) $^1H(d,d)p$

2 Vancouver (TRIUMF) $^2H(p,2p)n$

3 Saclay (SATURNE) *A*(d,p)X

***A*=^{12}C and ^{1}H**

4 Saclay (SATURNE) $^1H(\vec{d},\vec{p})X$

In the mid 80ths we (in Virginia) were much aware of the tantalizing results from the SYNCHROPHASOTRON at JINR in Dubna:

"A Study of the Proton Momentum Spectrum from Deuteron Fragmentation at 8.9 GeV/c and an estimate of admixture parameters for the six-quark state in the Deuteron "

by V.G. Ableev and 15 authors, in 1983.

The first polarized deuteron beams at the synchrophasotron from the locally built POLARIS source had been first reported in 1981.

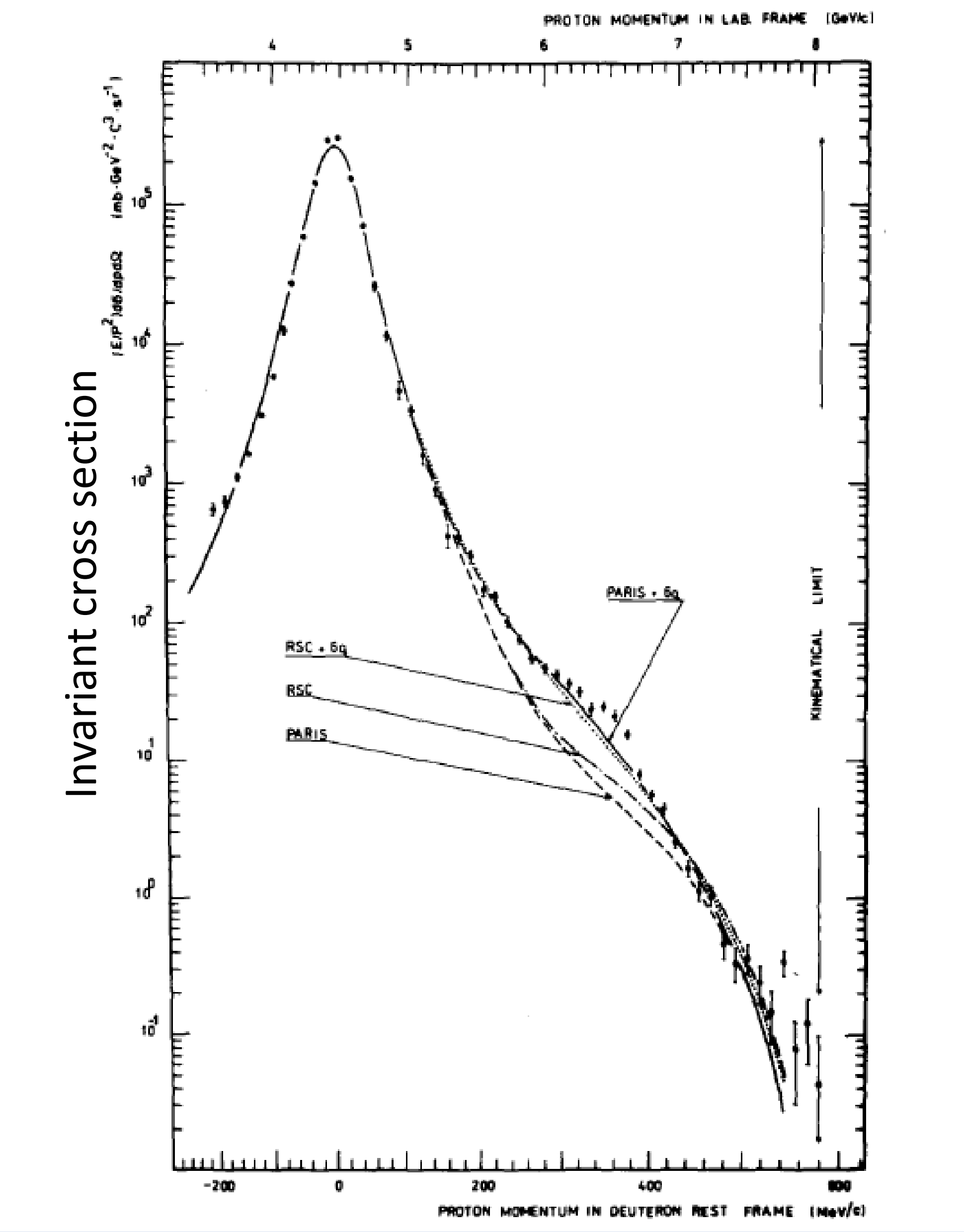
Inclusive D-stripping on ^{12}C, at 8.9 GeV/c

The significant discrepancy seen near q~360 MeV/c in $^{12}C(d,p)X$ could be explained in a number of ways:

1) Re-scattering of the proton in the carbon

2) Presence of a P-state in the deuteron, with excitation of an N* of negative parity.

3) Quark structure of the deuteron, in particular 6q state; curve “Paris and 6q” comes close to the data!



Proton momentum in deuteron rest frame

V.G. Ableev etal_NP A393, 491 (1983)

In quasi-free scattering

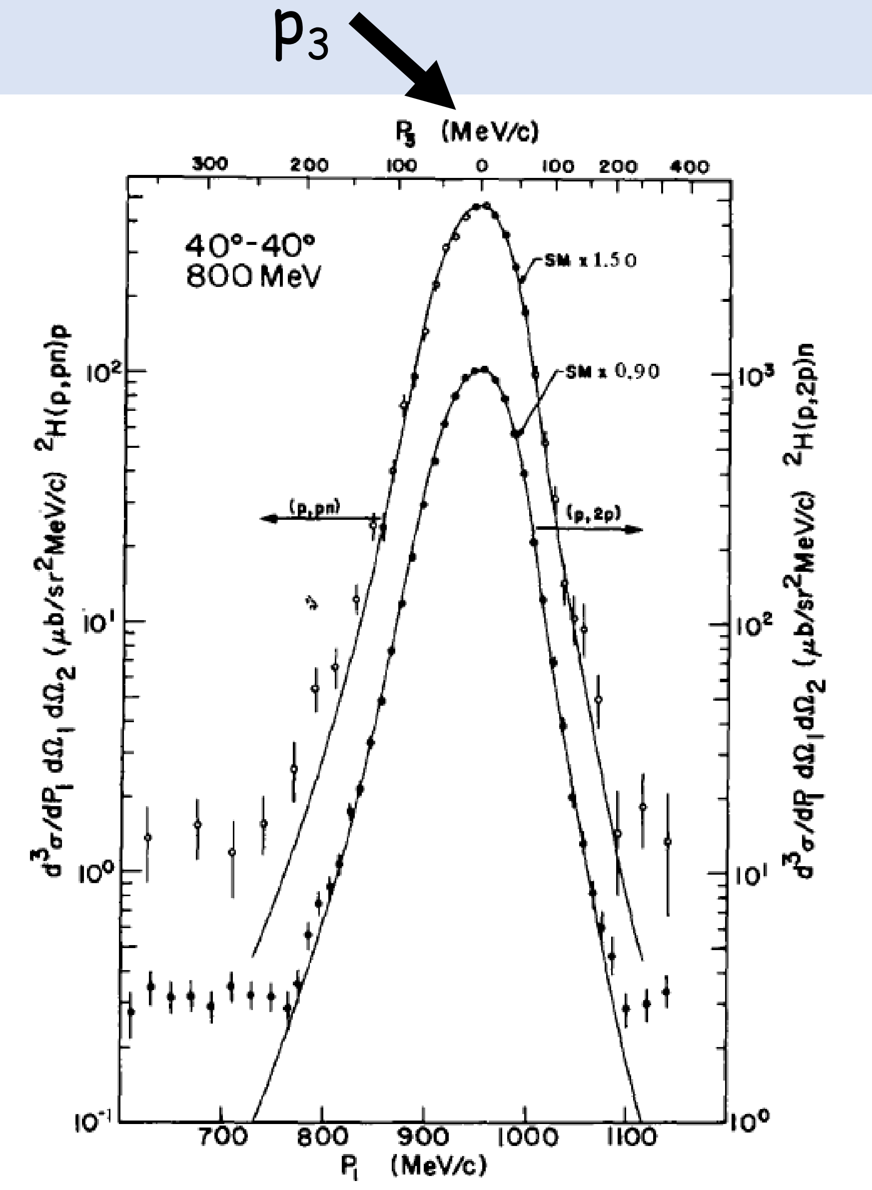
^{2}H(p,2p) and ^{2}H(p,np) deuteron breakup at 585 and 800 MeV (Felder in 1976!)

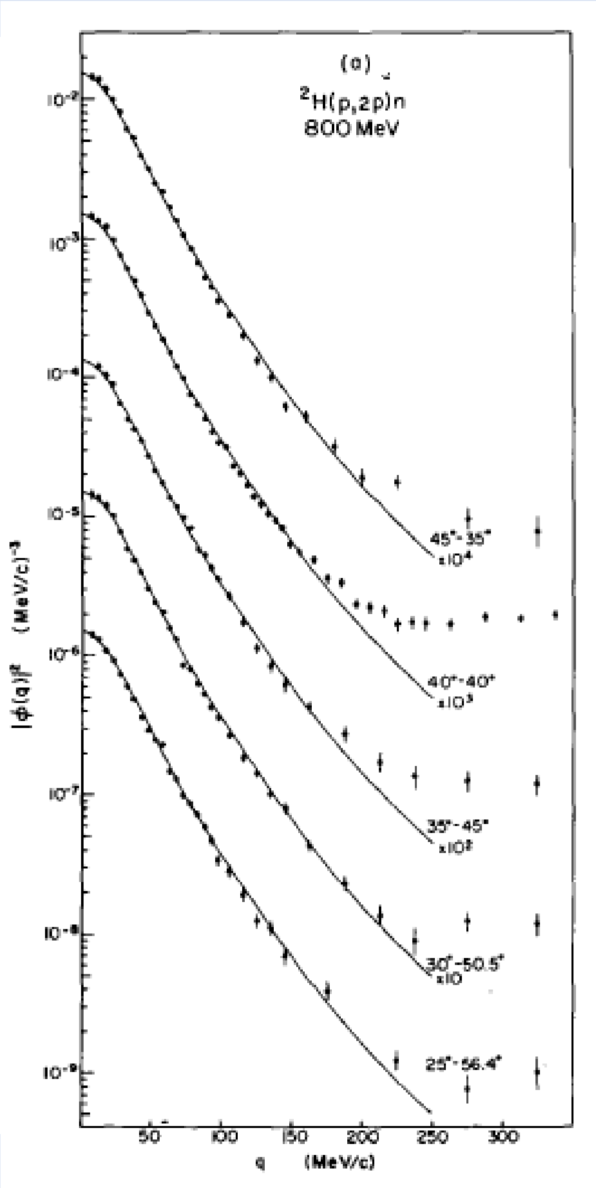
A "similar" enhancement near q=300 MeV/c, but much more drastic.

Similar to 1969 SREL data: same abrupt deviation from spectator model (Perdrisat).

RD Felder et al NP A264 (1976)

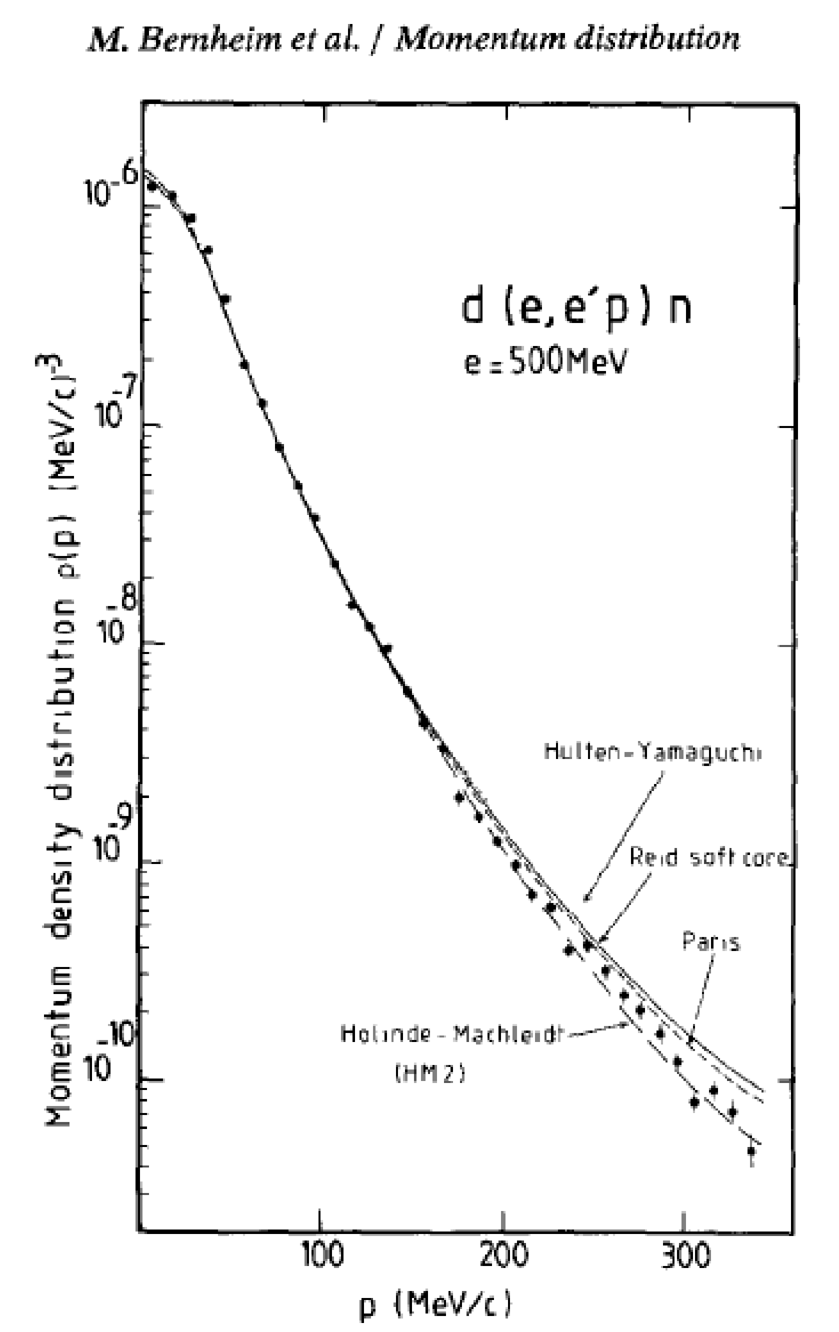
C.F. Perdrisat et al, PR 187 (1969)





D(e,e'p)n at 500 MeV

Another way to take the deuteron apart is with electrons, as in D(e,e'p)X.
Early experiment with the ALS in Saclay, 500 MeV electrons. Here p is the recoil momentum of the neutron in the lab frame. No anomaly is seen up to the largest p-values. Interpreted as the result of the weakness of the EM interaction. The data are compared to predictions based on popular Deuteron wave functions, like Hulthen, Reid soft-core, Paris and Bonn.



M. Bernheim et al NP A365 349 (1981)

Of special interest at the time (1983) was the question of whether the JINR data were in fact revealing of the quark structure of the deuteron.

In particular the hybrid model proposed by A.M. Baldin (1977), and discussed at length by Frankfurt and Strickman, Matveev and Sorba, and by Kobushkin, led to the hypothesis that the anomaly may be the result of the superposition of the two (3q) bound nucleons, with a (6q) cluster.

Discussion of polarization observable in backward elastic dp to pd, in one nucleon exchange picture, or ONE.

AP Kobushkin et al PR C50, (1994) 2627

Refer to the T_{20} vs κ_0 relationship first presented by Kuehn at DUBNA-DEUTERON 93.

In the ONE approximation, T_{20} and κ_0 for 180° backward elastic scattering $^1H(d,d)p$ (BES) are identical to the same observables in the breakup reaction A(d,p)X at 0°.

Kuehn, Perdrisat and Strokovsky, Dubna-Deuteron, 1993

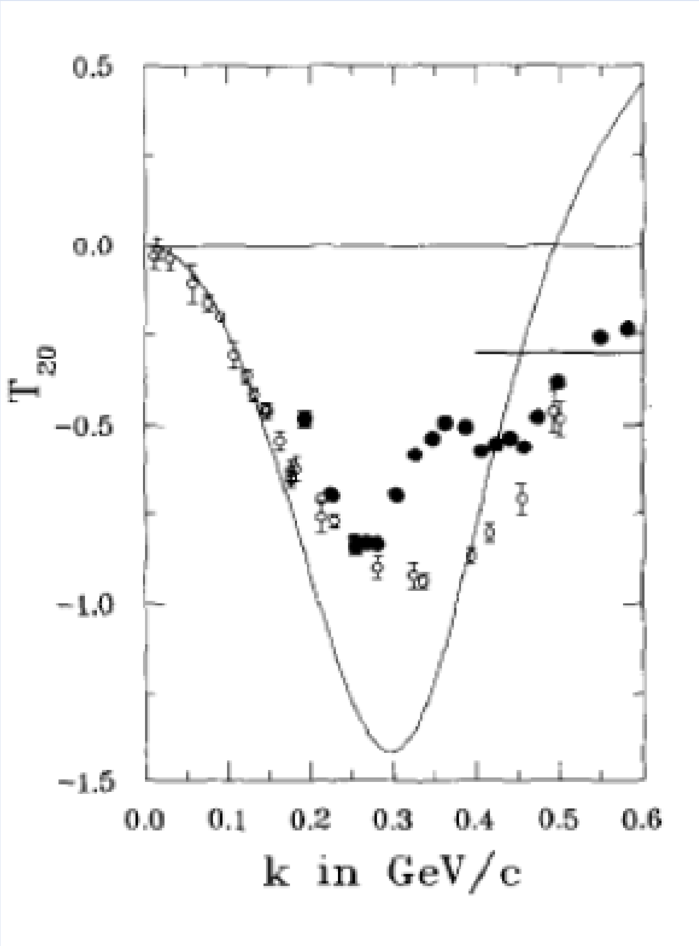
As first pointed out by Kuehn, Perdrisat and Strokovsky, for both reactions T_{20} and κ_0 are related through the equation:

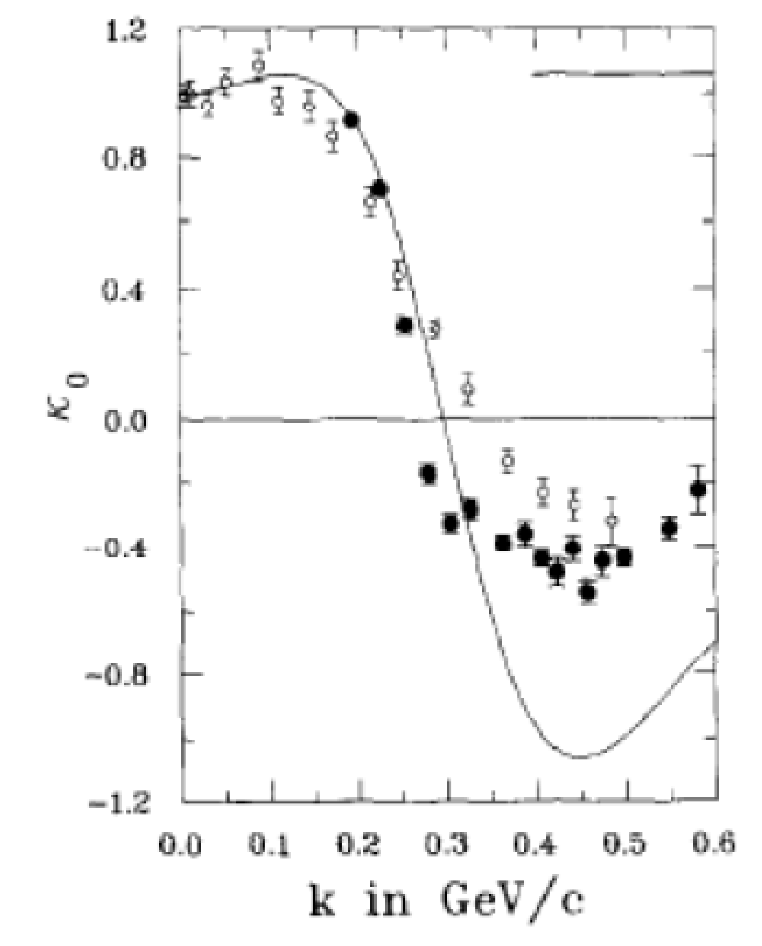
$$(T_{20}+\frac{1}{2\sqrt{2}})^2 + \kappa_0^2 = \frac{9}{8}$$

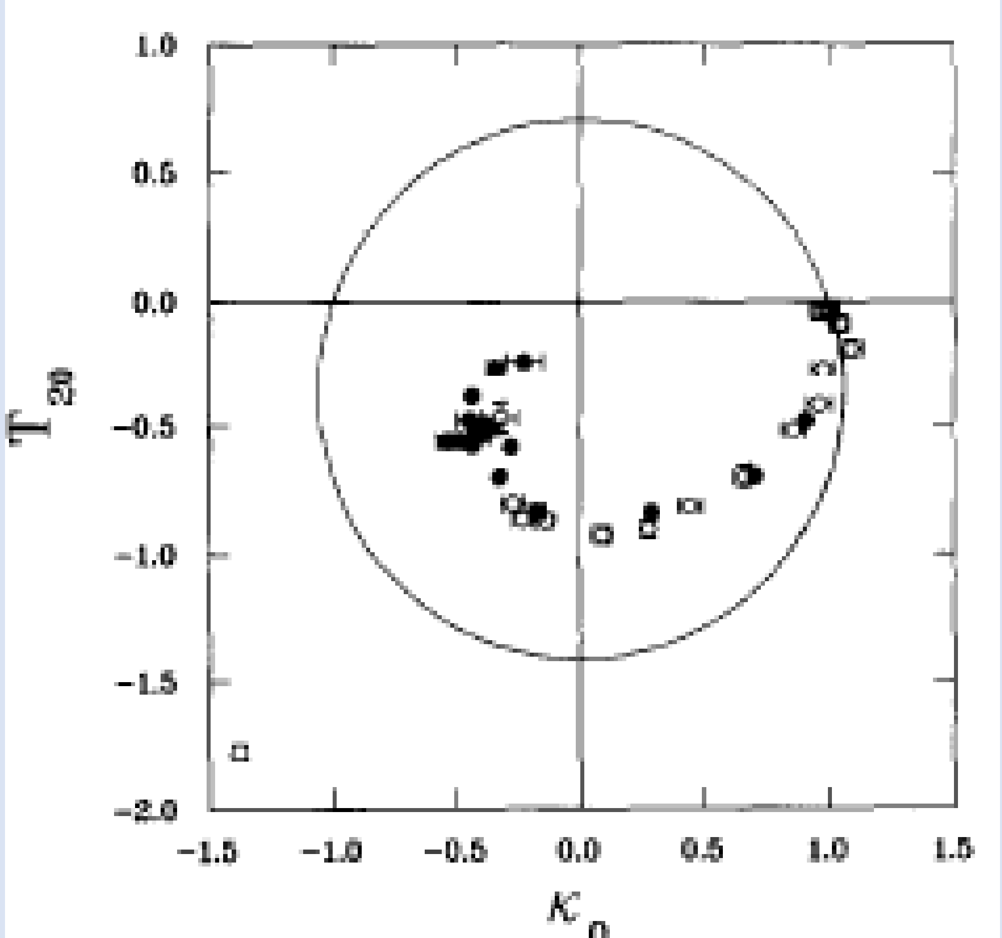
T_{20} and κ_0: backward elastic 1H(d,p)d •, inclusive breakup ^{1}H(d,p)X °

Almost undistinguishable in the T_{20} versus κ_0 representation. All data from SPES-IV with POMME polarimeter (Dubna participation: Ladygin, Pentchev, Piskunov, Sitnik, Strokovsky).

(Punjabi, PL B350(1995)178).

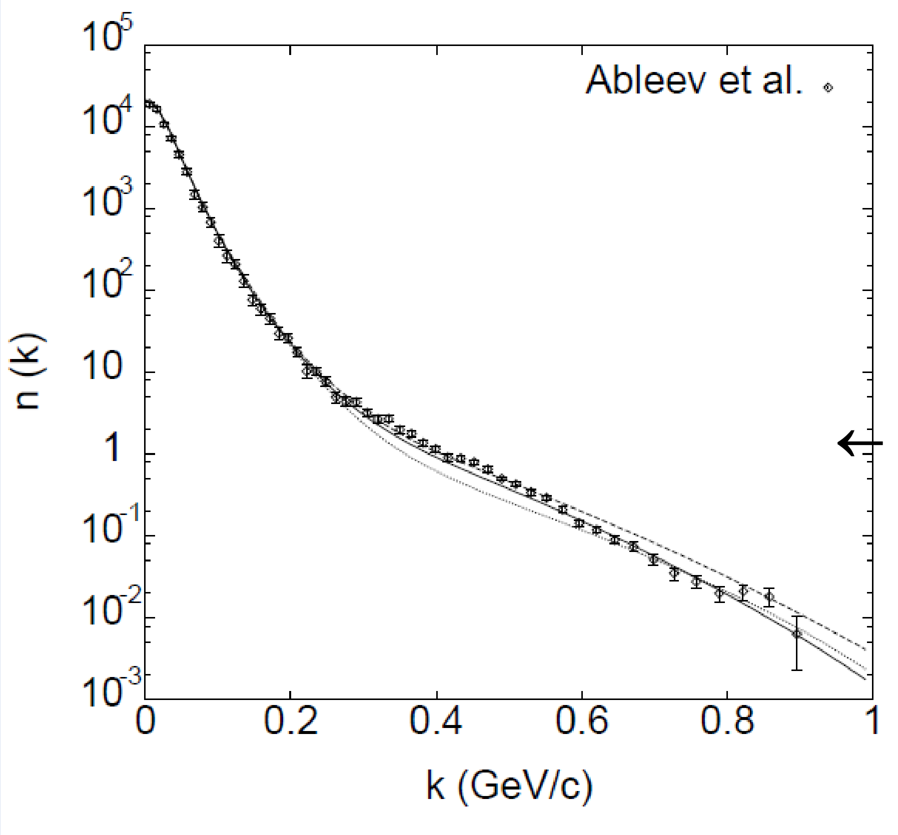




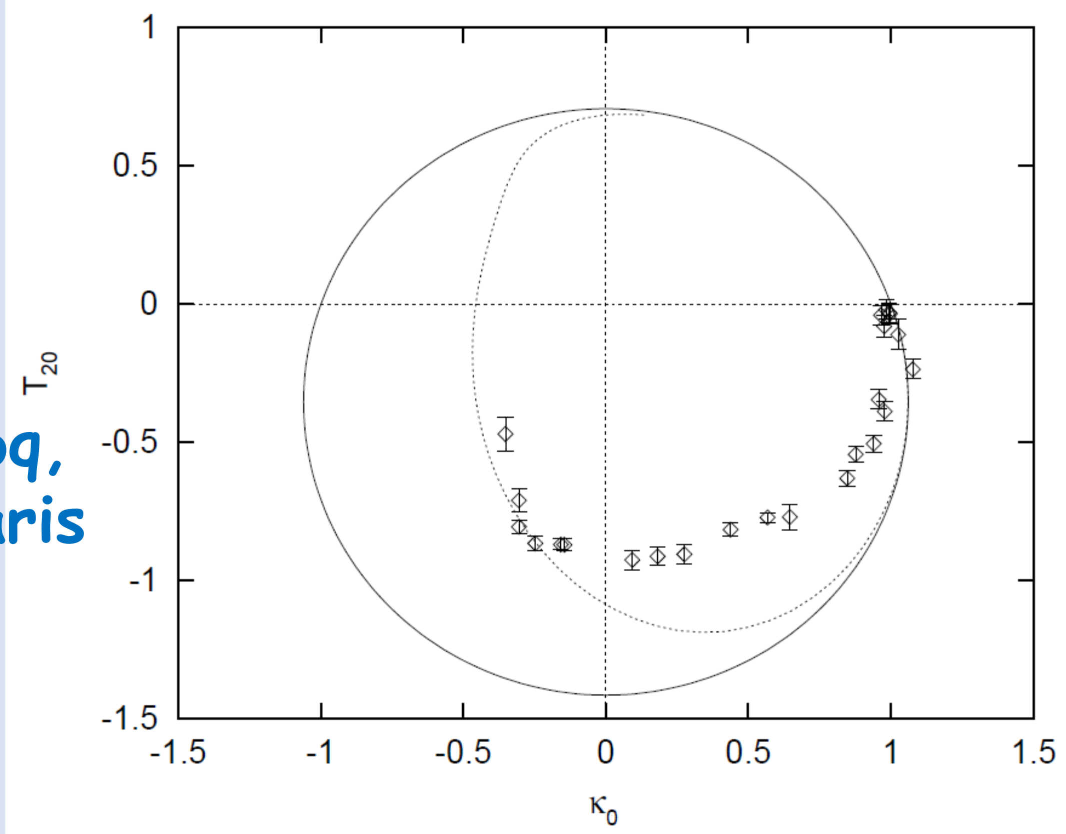


The quark exchange effect affects observables noticeably. Both the anomaly in the momentum space density at q=350, or k=450 MeV/c, and the discrepancy between the IA prediction and the data for the T_{20}-κ_0 correlation, are partially explained.

A.P.Kobushkin, A.I. Syamtomov and L.I Glozman
Phys. Atom. Nclei 59 (1996) 795



← Solid Paris,
dashed Reid with 6q,
dotted IA with Paris

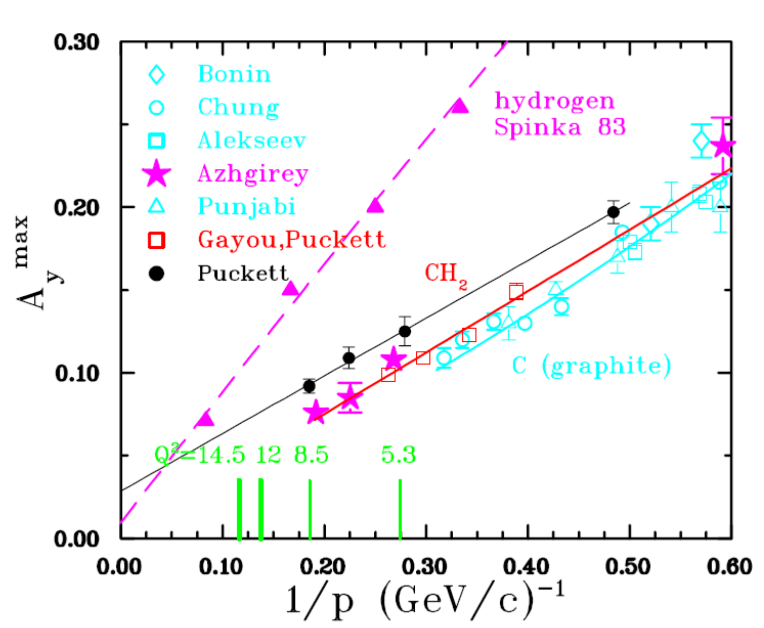


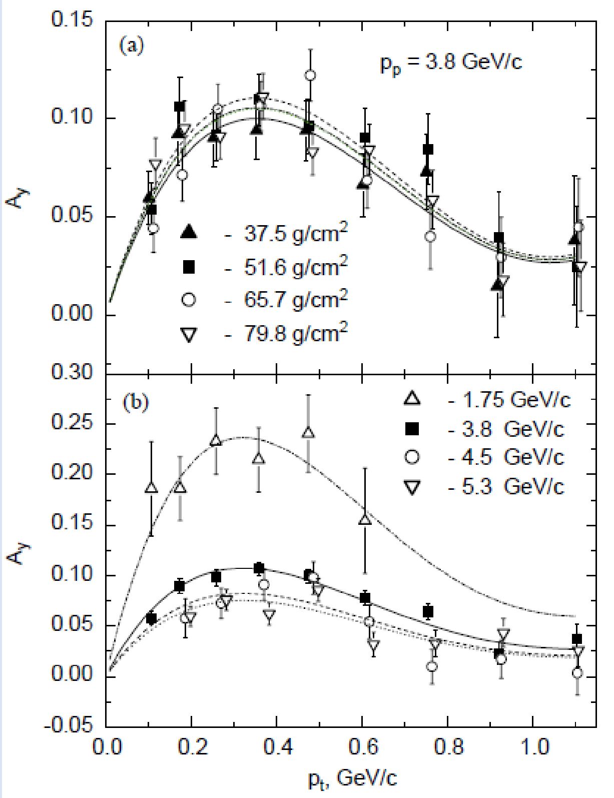
To get the 3rd elastic form factor experiment to the highest 4-momentum transfer approved at Jefferson Lab, analyzing power A_y up to 5.3 GeV/c were obtained at the SYNCHROPHASOTRON with ALPOM at ALPHA setup.

9 GeV/c vector polarized deuterons broken, giving vector polarized protons:

1) observed A_y^{max} proportional to 1/p,

2) A_y^{max} occurs at constant p_t.





L.S. Azhgirey et al, NIM in NR A 538 (2005), 431

$$p_t = p_p \sin\vartheta$$

Ongoing activity within the VBLHEP, William and Mary, Norfolk State U, Jefferson Lab, IN2P3/IPN Orsay and Glasgow collaboration.

Measurements of A_y for neutrons up to 4.5, and protons up to 7.5 GeV/c, with the Dubna NUCLOTRON and the polarimeter ALPOM_II.

CONCLUSIONS

I hope to have given you a sense of the research, progress, results achieved in the 26 years of our collaboration, starting in 1991.

The driving force of this collaborative activity was motivated by the general interest at the time, for the structure of the deuteron, in particular the hope that information on the 6-quark component would be revealed when probing this two-nucleon system with very large momentum transfers.

This collaboration was enriched when the Dubna team came to Virginia to participate in the 3 experiments at the Jefferson Lab electron accelerator, obtaining proton elastic form factors from electron to recoil proton polarization transfer data.

The End

As a parenthesis, the non-relativistic momentum distribution of the proton (or neutron) in the deuteron, ρ (p), where *p* is its (Fermi) momentum:

$$\rho(\mathbf{p})=\left|\int u(r) j_0(pr) r dr\right|^2 + \left|\int w(r) j_2(pr) r dr\right|^2$$

where u(r) and w(r) are the S- and D-state radial deuteron wave functions, and $j_{0,2}(pr)$ the Bessel functions of order 0 and 2, respectively.

$$T_{20}=\frac{1}{\sqrt{2}}\frac{\sqrt{8}uw-w^2}{u^2+w^2} \qquad T_{20}=0 \text{ if } w=0$$

$$\kappa_0=\frac{u^2-w^2-uw/\sqrt{2}}{u^2+w^2} \qquad \kappa_0=1 \text{ if } w=0$$

The experiment which attracted great interest was the breakup of unpolarized high momentum deuterons on ^{12}C: $^{12}C(d,p)X$ for small angles proton, by Ableev et al, here at VBLHEP, and published in 1983.

Nowhere else were deuterons of 9 GeV/c (or 7.3 MeV) available.

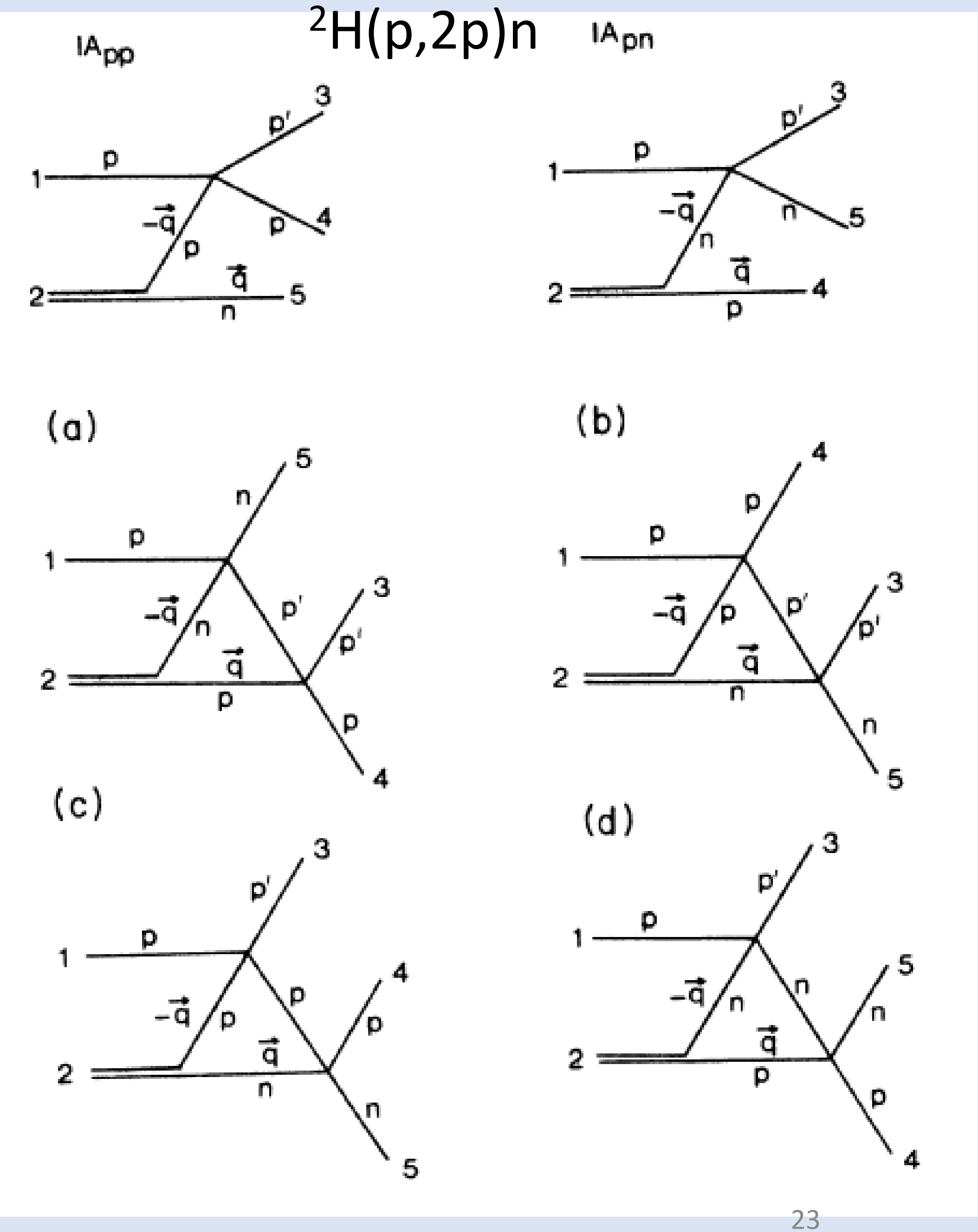
The highest deuteron momentum available at SATURNE was 3.8 GeV/c (or 2.34 GeV).

On the next page, a peculiarity of the momentum density distribution from the cross section data, at an internal momentum of 360 MeV/c was the source of great interest.

Lowest order D(p,2p)n reaction in IA

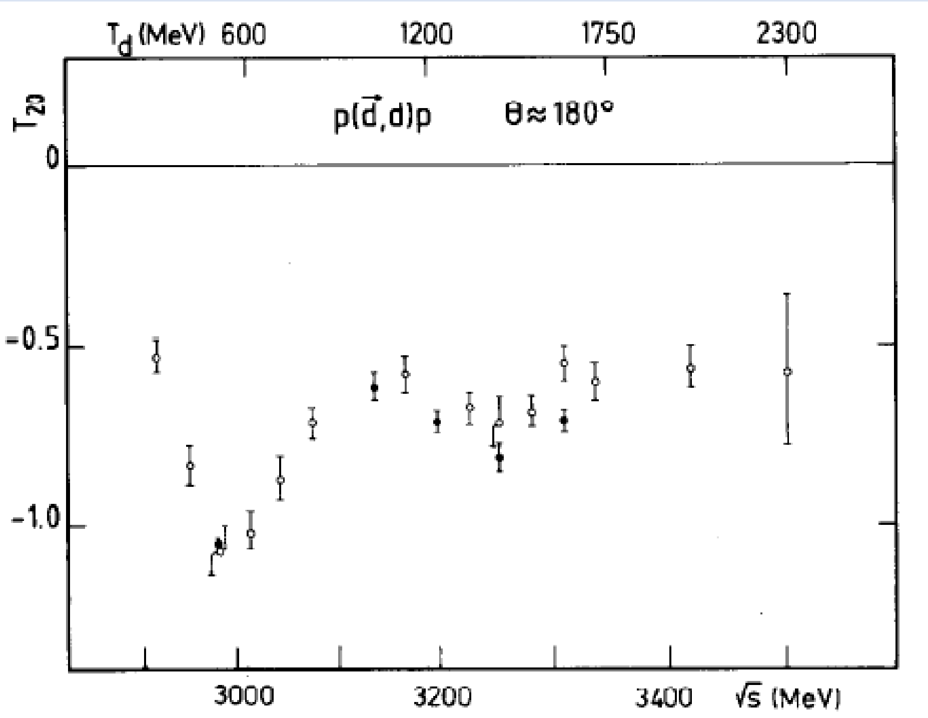
Same final state but with re-scattering, pp or np

Same final state but with final state interaction, either pn or np

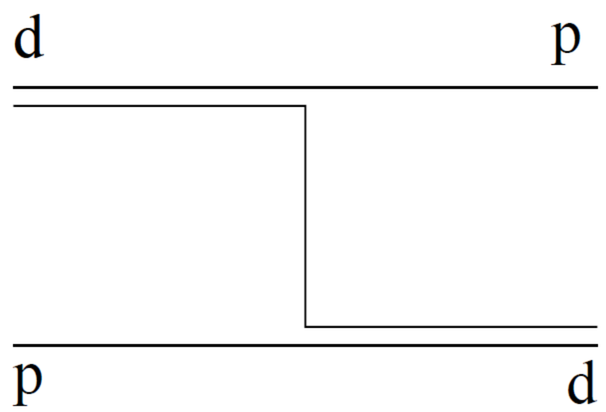


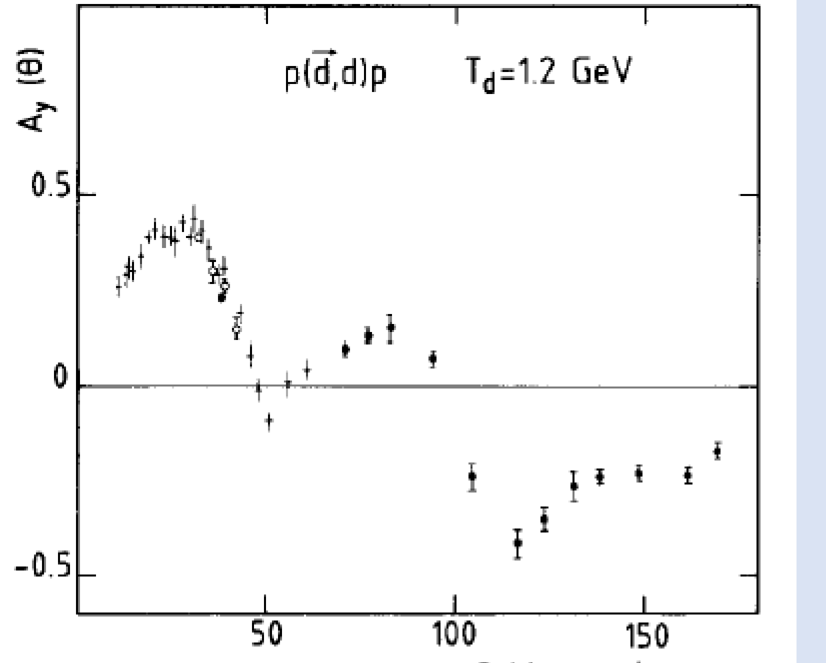
Punjabi et al PR C38, 2728 (1988)

First extensive study of backward elastic *dp* with tensor polarized deuterons from SATURNE at 0.3 to 2.3 GeV. Shown is tensor analyzing power T_{20}. X-scale total energy in CMS; top scale recoil energy T_d.



The A_y analyzing power at fixed deuteron energy of 1.2 GeV, versus Deuteron angle.





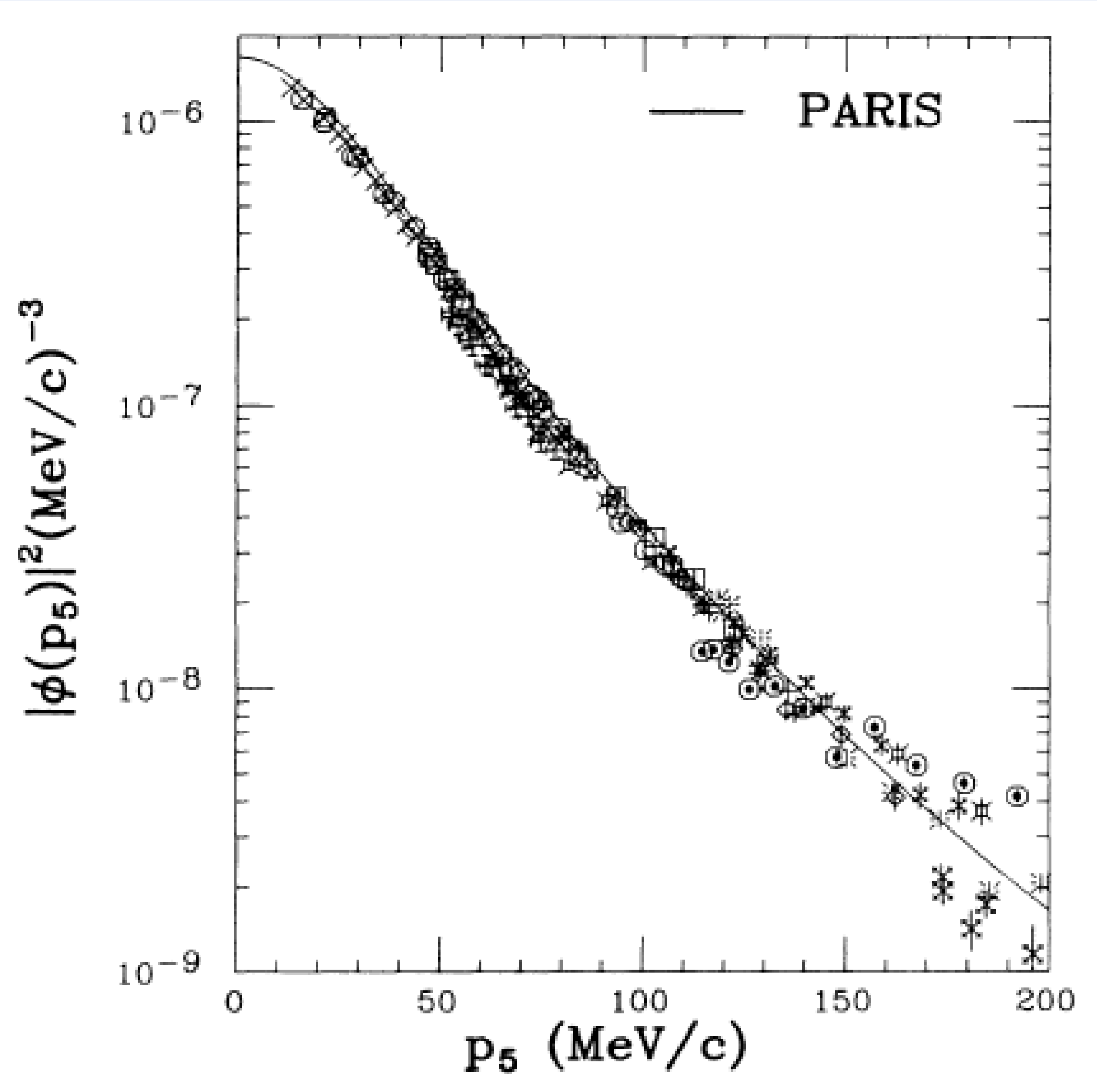
J. Arvieux et al, NP A431 (1984) 613.

All TRIUMF D(p,2p)n data in 11 different proton angle pairs at 508 MeV incident proton energy.

Compared to the IA Paris potential expectation (solid line) The data are systematically ~10% below expectation, and very homogeneous.

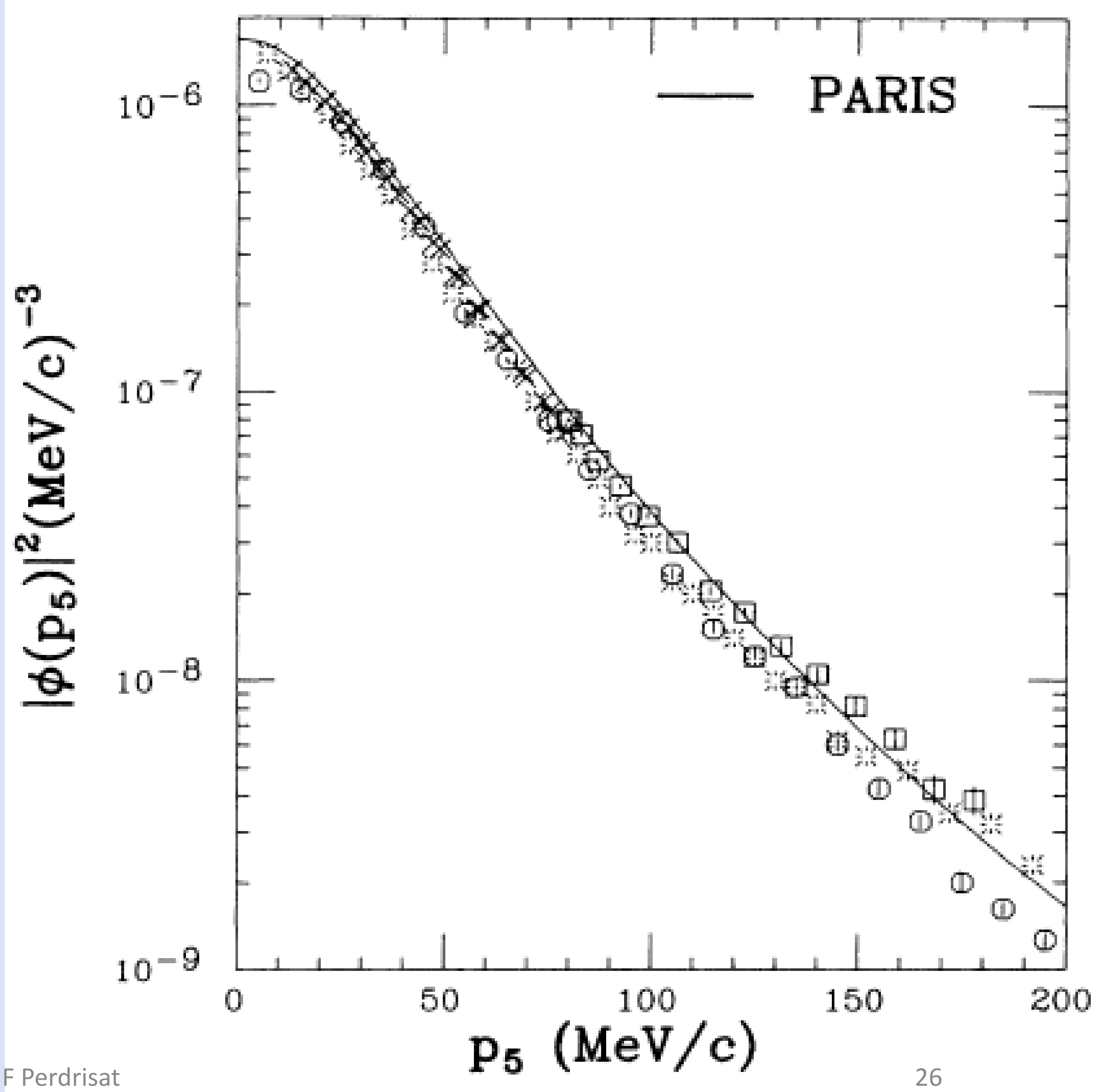
P_5 is the recoil neutron momentum in the lab frame (<200 MeV/c).

Punjabi et al PR C38, 2728 (1988)



Momentum distribution versus neutron recoil from the 508 MeV D(p,2p) TRIUMF experiment (squares and crosses), compared with same from Felder et al. with star symbols, 800 MeV LAMPF. Also shown are (e,e'p) data from Bernheim 500 MeV ALS data shown as open circles.

D(p.2p) (TRIUMF),1986, D(e,e'p) (ALS) + Felder

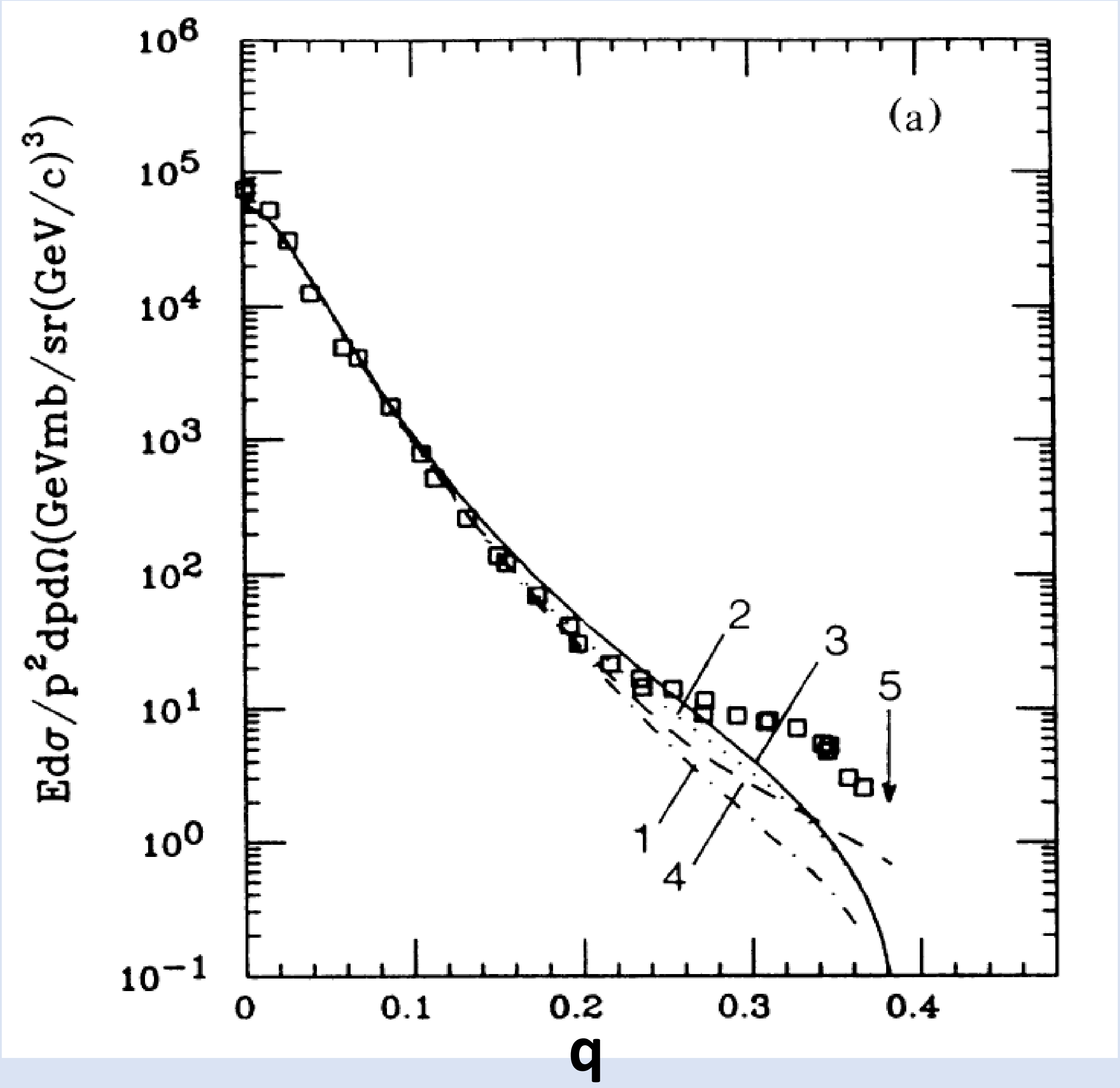


Cross section and T_{20} in D breakup on H at zero degrees

Raising the same question next, the SATURNE-2 experiment in Saclay obtained cross section and T_{20} analyzing power for inclusive 2.1 GeV deuteron breakup on HYDROGEN rather than carbon.

$^{1}H(d,p)X$

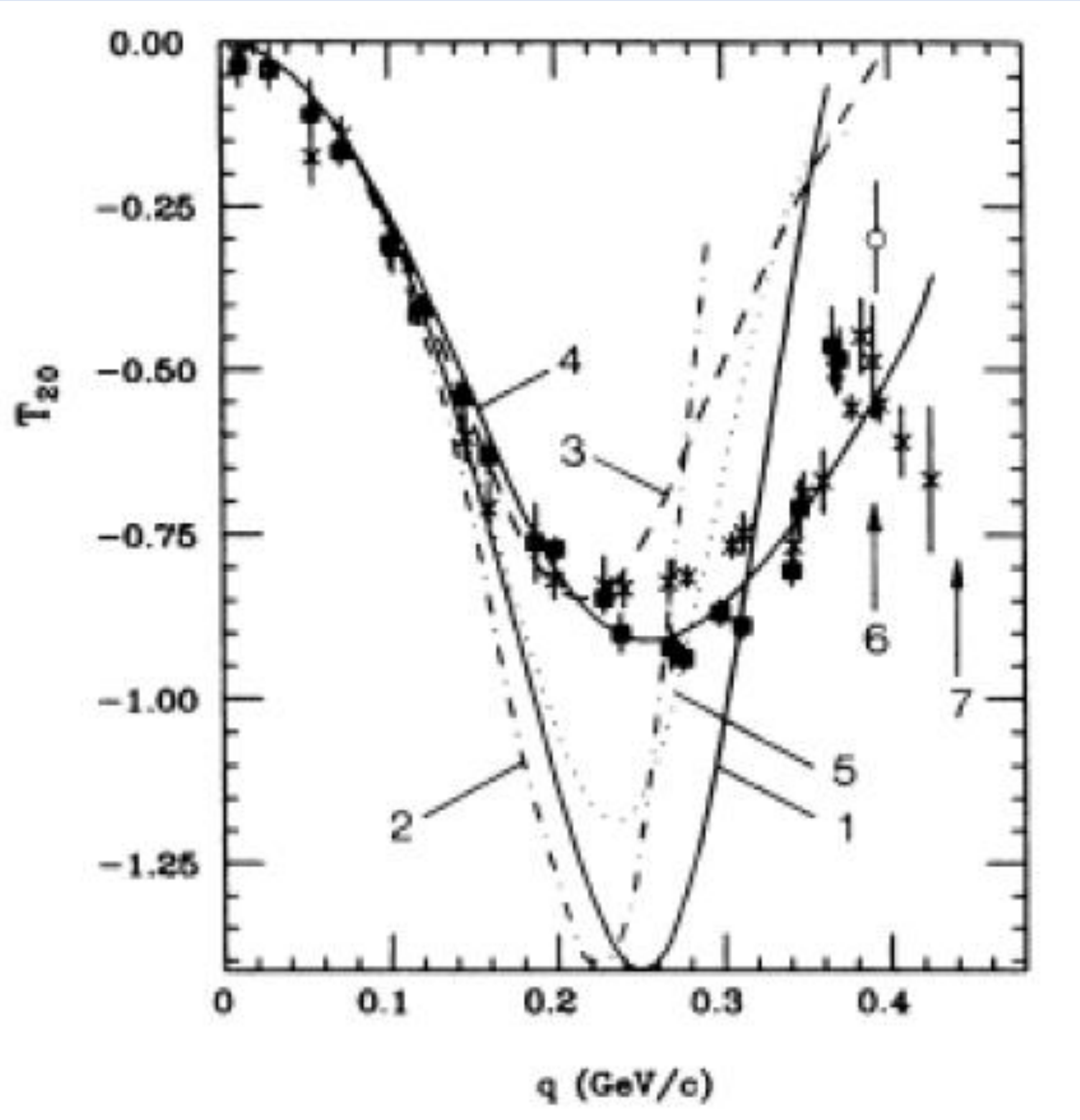
Showing an enhancement at the same q as the Ableev data. Curve 3) as in Ableev, with P_{6q}=0.04.



C.F. Perdrisat etal, PRL 59, 2840 (1987)

(Continued from last page)

In the same SATURNE experiment, the tensor analyzing power T_{20} was obtained; shown as squares for ^1H, and as stars for C-target.
Curves 1) and 2): Paris and Moscow w.f. in IA. Curve 4), hybrid Glauber-Sitenko ref. Ableev 1982; includes 6q component. Dotted line 5) for ΔΔ-component.
Note that 4) agrees with the data: 6q?



C.F. Perdrisat etal, PRL 59, 2840 (1987)

Vector polarization transfer κ_0 in inclusive, 0° degree 1H($\vec{d}$,$\vec{p}$)X at SATURNE.

One of the earliest use of the polarimeter POMME on the SPES4 beam line, measuring polarization of forward (breakup) data for 2.1 GeV (3.5 GeV/c) incident, vector polarized deuterons.

Lower figure, compare with Infinite Momentum Frame calculations of Lykasov and Dolitze, but still plotted versus non relativistic q.

E. Cheung et al, PLB284 (1992) 210

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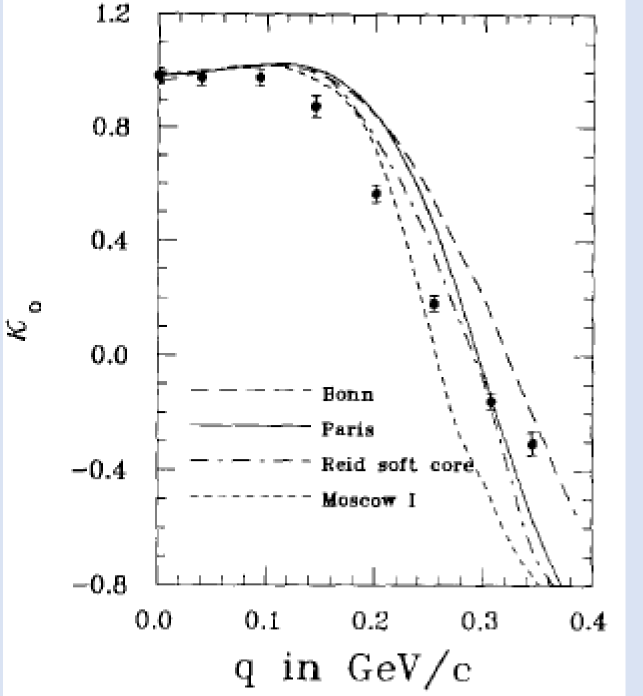
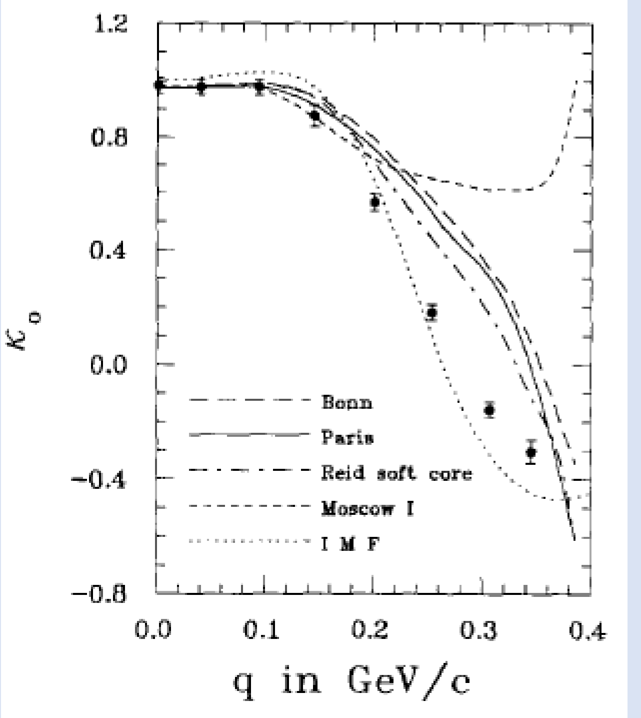
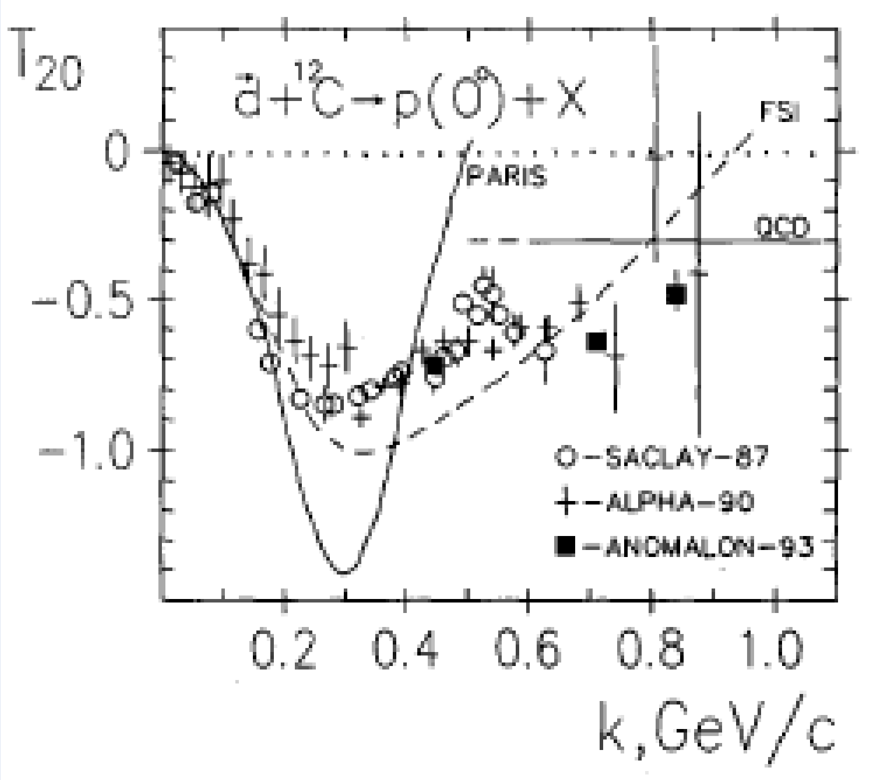
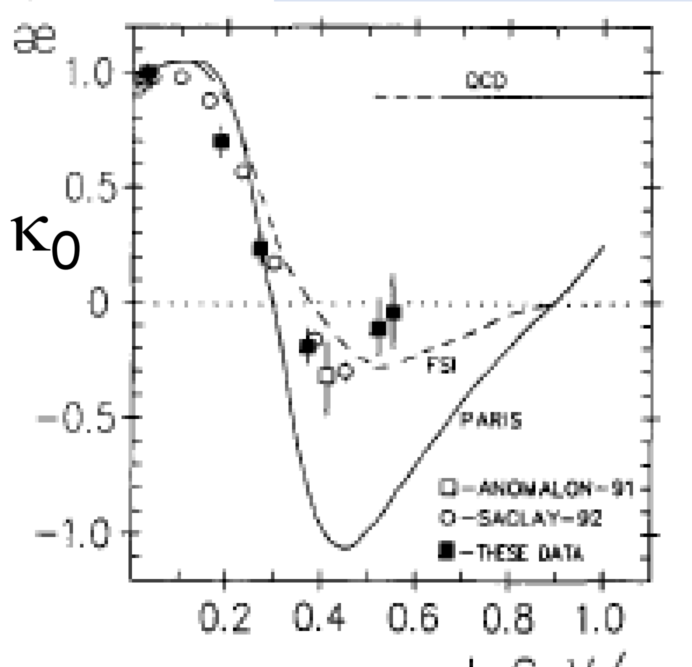




The SATURNE κ_0 data on previous page would become very useful for future experiments at JINR (both SYNCHROPHASOTRON and NUCLOTRON) , and at JLab in Virginia.
In the first case allowing to generate vector polarized beams of neutrons and protons from the breakup of polarized deuterons, with more than half the deuteron momentum, taking advantage of the internal momentum of the either nucleon in the deuteron.
In the second case to plan future electric form factor ratio measurements at JLAB at yet larger momentum transferred squared,
And later (i.e. currently) to obtain analyzing powers both for protons and neutrons to yet larger momenta.

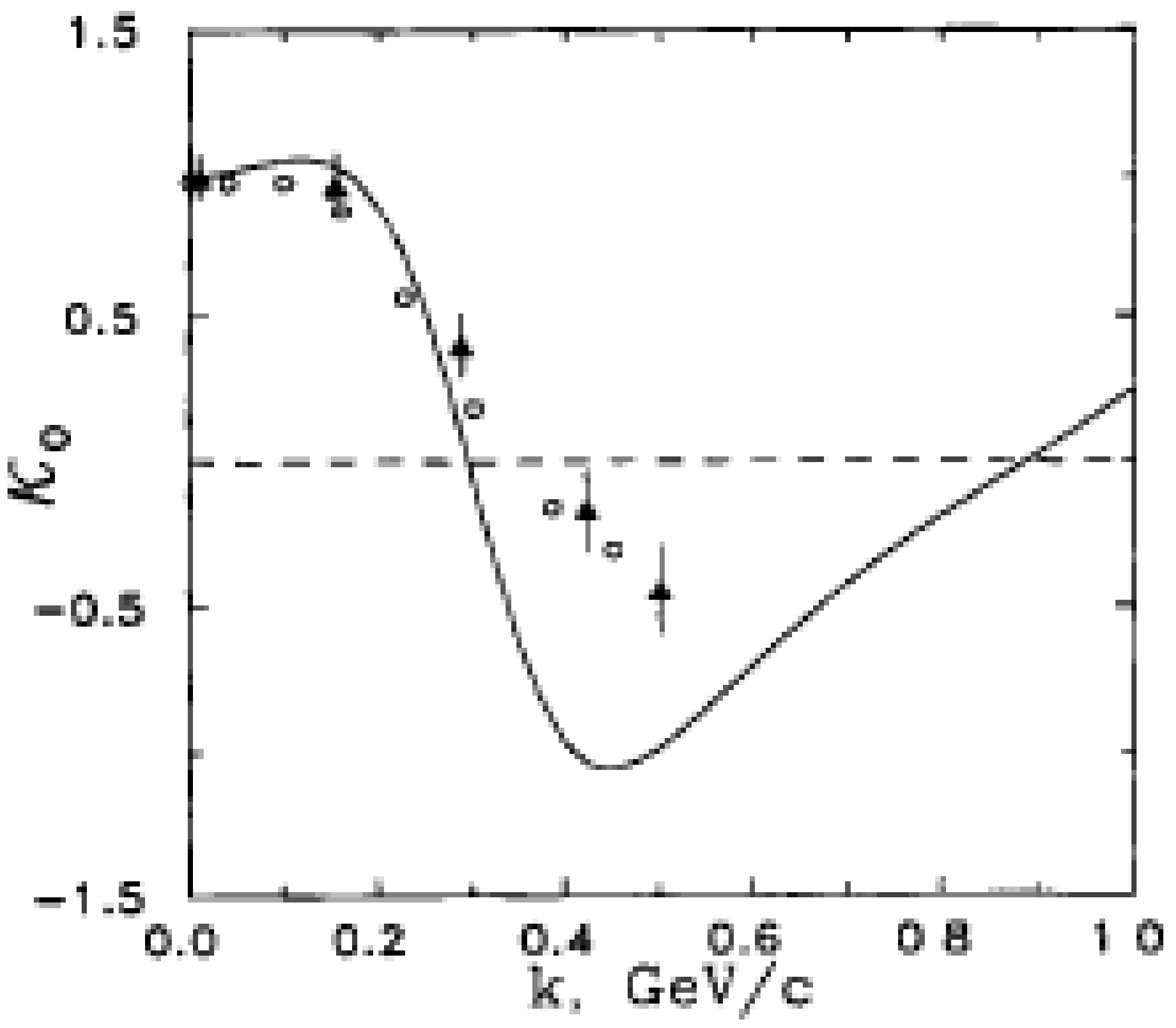
T_{20} and κ_0 in inclusive breakup with ANOMALON setup at the JINR SYNCHROPHASOTRON, with 9 GeV/c deuteron beam, in inclusive breakup $^{12}C(d,p)X$ at 0^0. Here k is the infinite momentum frame proton momentum.





Nomofilov etal, Physics Letters B 325 (1994)

Yet another inclusive breakup $^{12}C(d,p)X$ experiment. This one with the ALPHA setup at the SYNCHROCYCLOTRON, with fixed final proton momentum of 4.5 GeV/c, but variable beam momentum, 6.0 to 9.0 GeV/c. k is the infinite momentum frame momentum:



$$k(\alpha)=\sqrt{\frac{m^2}{4\alpha(1-\alpha)}-m^2} \quad \alpha=\frac{E_p+p_p}{E_d+p_d}$$

Solid curve IA with Paris N-N potential

(Lacombe ea. PL B101 (1981) 139)

B. Kuehn ea, PL B334 (1994)

Discussion of polarization observable in backward elastic dp to pd, in single nucleon exchange picture. AP Kobushkin et al PR C50, (1994) 2627

Refer to the T_{02} vs κ_0 relationship first presented by Kuehn at DUBNA-DEUTERON 93.

In the ONE approximation, T_{20} and k_0 for 180° (BES) are identical to the same observables in the breakup reaction A(d,p)X at 0°, in the IA.

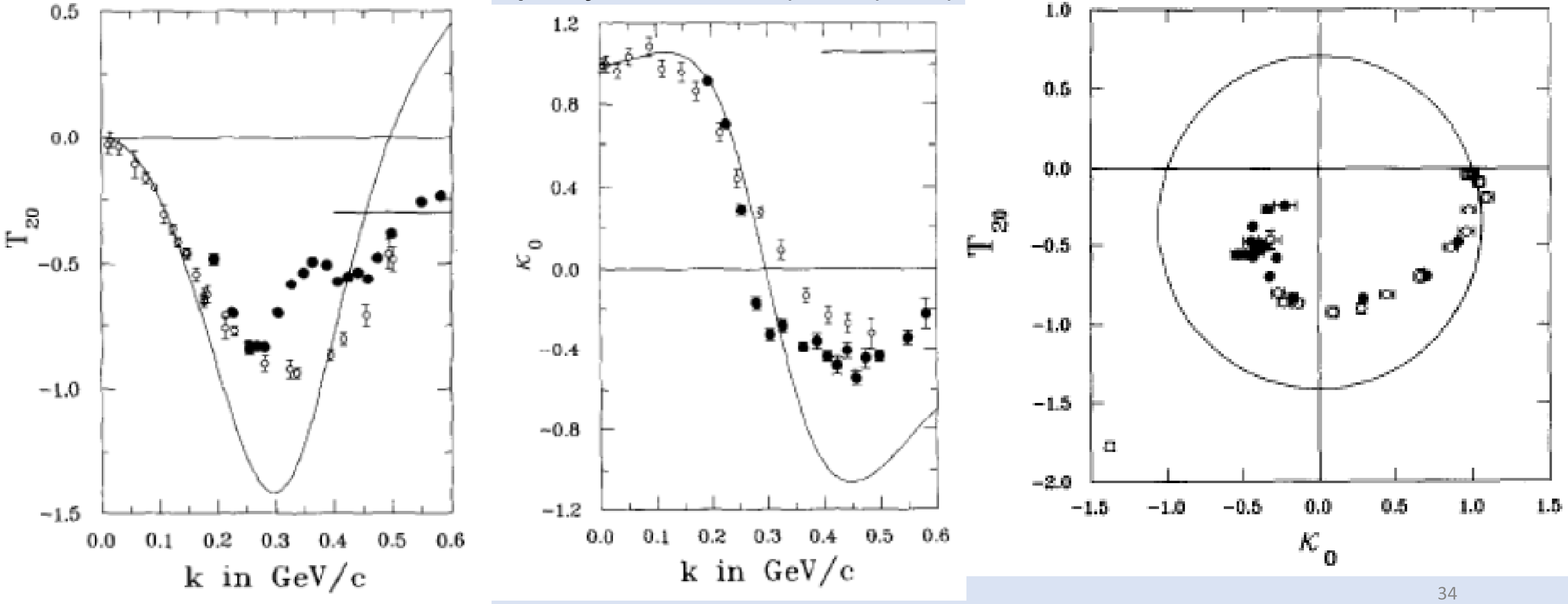
As first pointed out by Kuehn, Perdrisat and Strokovsky, for both reactions these same two observables are related through:

$$\left(T_{20}+\frac{1}{2\sqrt{2}}\right)^2 + \kappa_0^2 = \frac{9}{8}$$

T_{20} and κ_0 from backward elastic 1H(d,p)d • , and inclusive breakup ^{1}H(d,p)X o

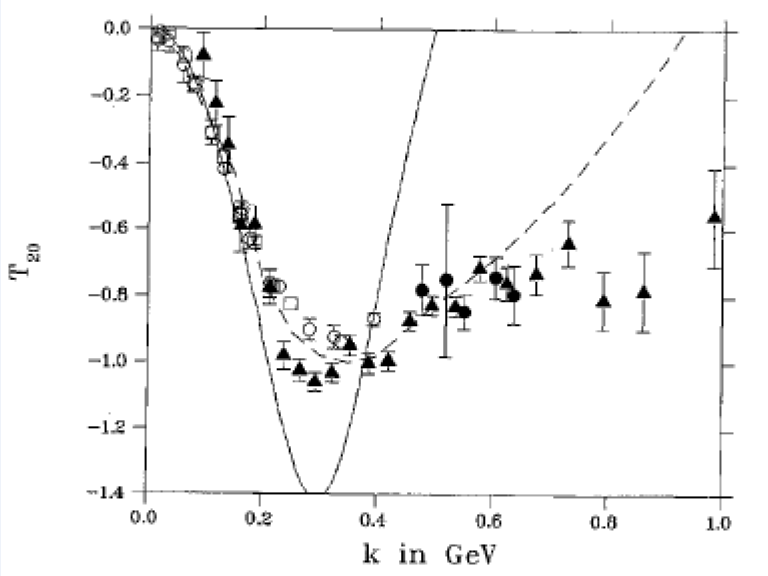
Almost undistinguishable, in the T_{20} versus κ_0 representation.

(Punjabi, PLB350(1995)178).

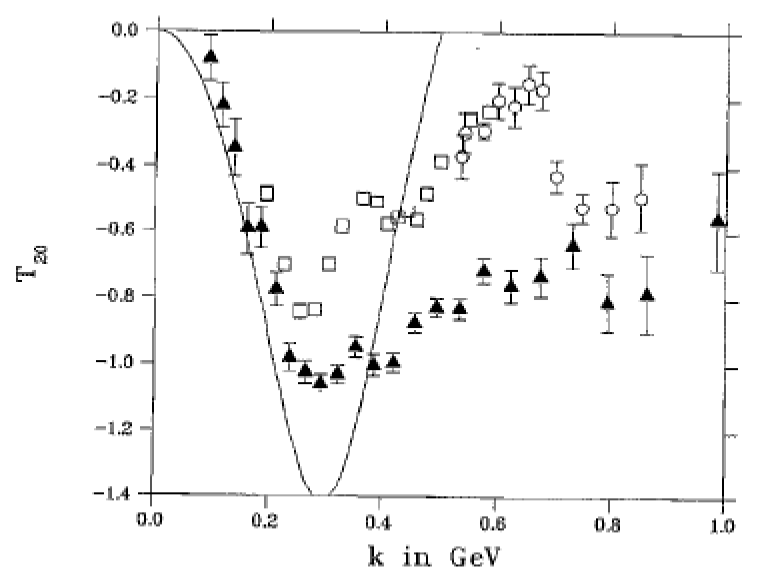


T_{20} in inclusive breakup at 9 GeV/c and 0^0

T_{20} in inclusive breakup at 9 GeV/c (Azhgirey) shown together with Saclay data at 2.5 and 3.5 GeV/c (Perdrisat (1987) and Punjabi (1989)), showing good **beam momentum independence**.
Solid line IA (Lacombe ea, PL B101, 139 (1981).
Dashed line: IA with rescattering (Lykasov)

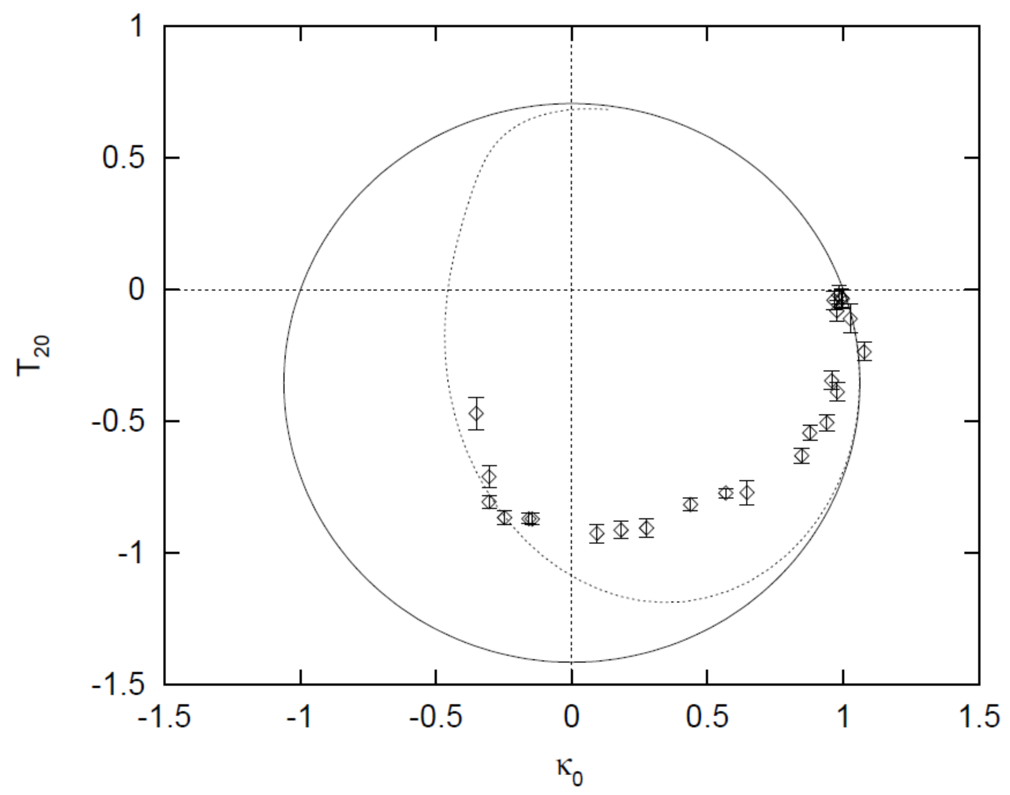


The same 9 GeV/c T_{20} data Azhgirey (1994) For 3.5 to 6.5 GeV/c, together with the **backward elastic** $^1H(d,p)d$ from Saclay of Punjabi (1995) demonstrating the **non-conformity** with the IA prediction.



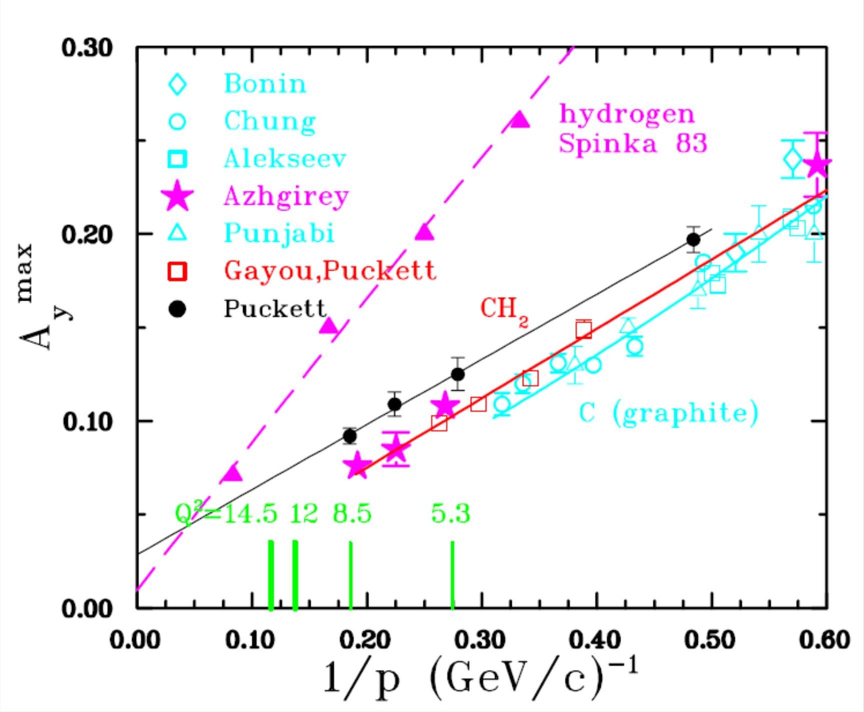
LS Azhgirey etal, PL B387 (1996)
GI Lykasov and MG Dolitze, Z. Phys A336 (1990)

Fully anti-symmetric 6q state, as
In A.P.Kobushkin, A.I. Syamtomov and L.I Glozman
Phys. Atom. Nuclei 59 (1996) 795

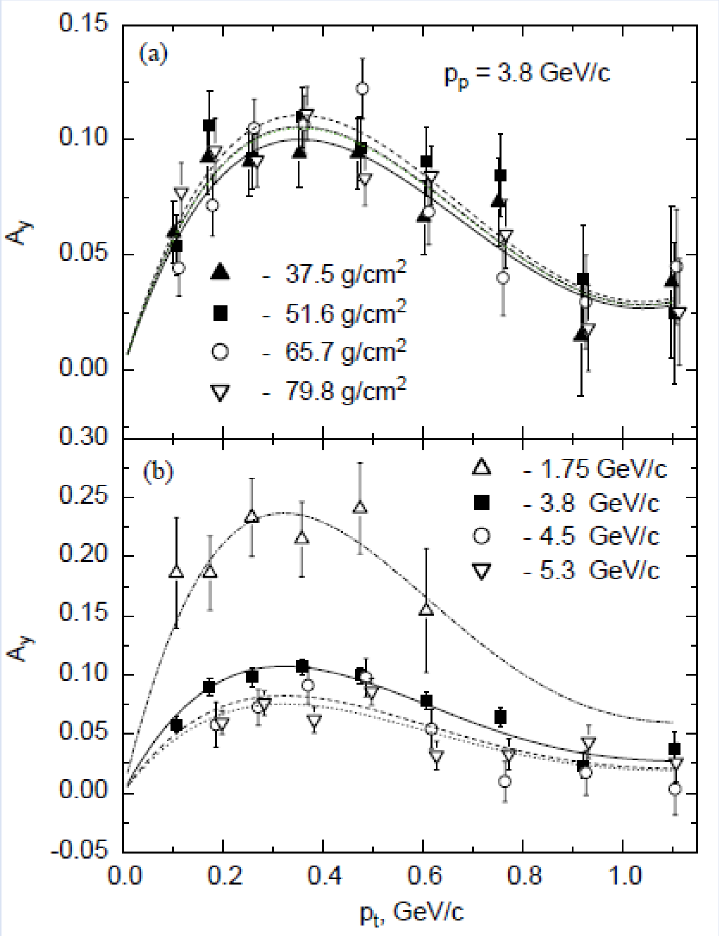


Results of 2001 Dubna analyzing power A_y measurement

To get the GEp(3) Jlab experiment approved, needed to measure A_y up to 5.3 GeV/c with the SYNCHROPHASOTRONin 2000-2001, with 9 GeV/c polarized deuterons and breaking them to produce a polarized beam of protons: 1) observed A_y^{max} proportional to 1/p, and 2) maximum value of A_y occurs at constant p_T value.



L.S. Azhgirey et al, N.I.M. in Nucl. Res. A 538 (2005), 431



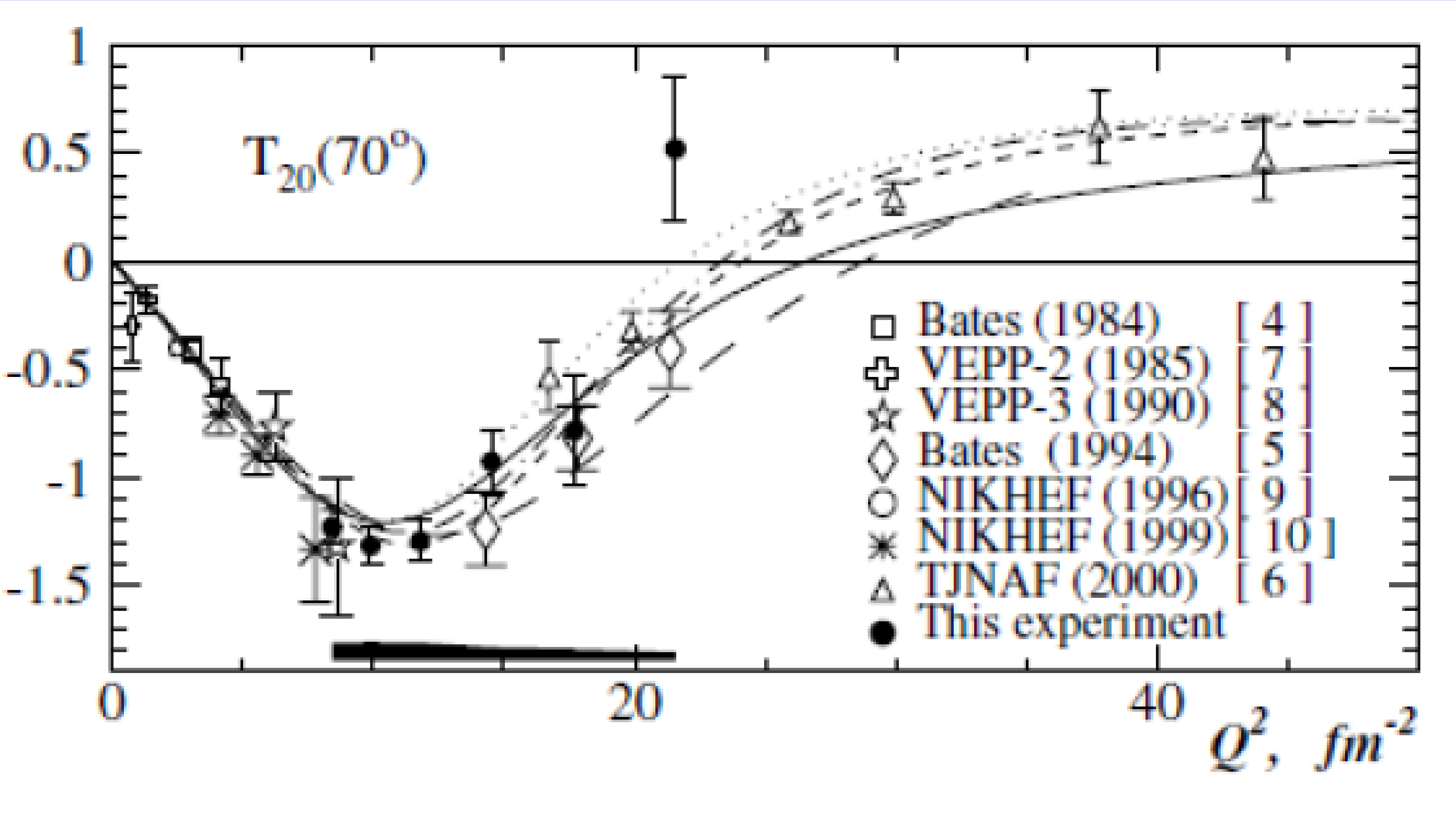
$$p_t = p_p \sin \vartheta$$

Beginning in the late nineties as CEBAF, now Jefferson Lab, has seen a number of experiments with the deuteron as a target, polarized and not polarized. In particular **elastic ep**, and ^{2}H(e,e'p)X, but also ^{2}H(γ,p)X.

In elastic scattering all observables are described by 3 form factors, charge monopole G_C, charge quadrupole G_Q and magnetic dipole G_M.The 3 tensor analyzing power components T_{20}, T_{21} and T_{22} can be expressed in terms of these 3 form factors.

For example, the VEEP-3 elastic ed data (Nikolenko ea. PRL 90, 72501 (2003) and PPN 48, (2017)) show small deviations from predictions based on the Paris potential (Lacombe ea, PL 101B, 139(1981)), Thanks to a highly polarized tensor polarized D-target.

or models with relativistic corrections and MEC contribution (Arenhoevel ea.PR C61, 034002(2000)) and (Wiringa ea. PR C, 51, 38 (1995)); or even relativistic as (Phillips e.a. PR C58, 2261 (1998)), and Krutov and Troitsky (hep ph/0202183).



Approved proposal:

Measurement of analyzing power for the reaction p+ch2 at polarized protons momentum of 7.5 GeV/c

Collaboration JINR, William and Mary, Norfolk State University, Jefferson Lab, Christopher Newport University in Virginia, and IN2P3/IPN Orsay.

Currently ongoing measurements of A_y for neutrons up to 4.5, and protons up to 7 GeV/c from the Dubna NUCLOTRON. Using breakup of polarized deuteron beams produced in the NUCLOTRON,