Physics with polarized targets in storage rings

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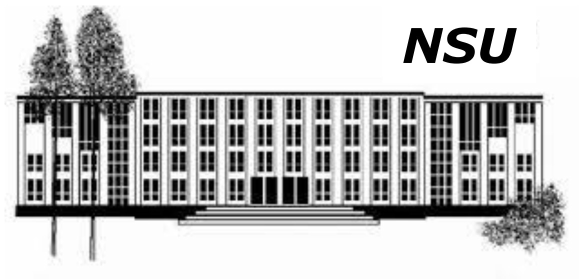
Spin2014, Beijing, October 20-24,2014

BINP



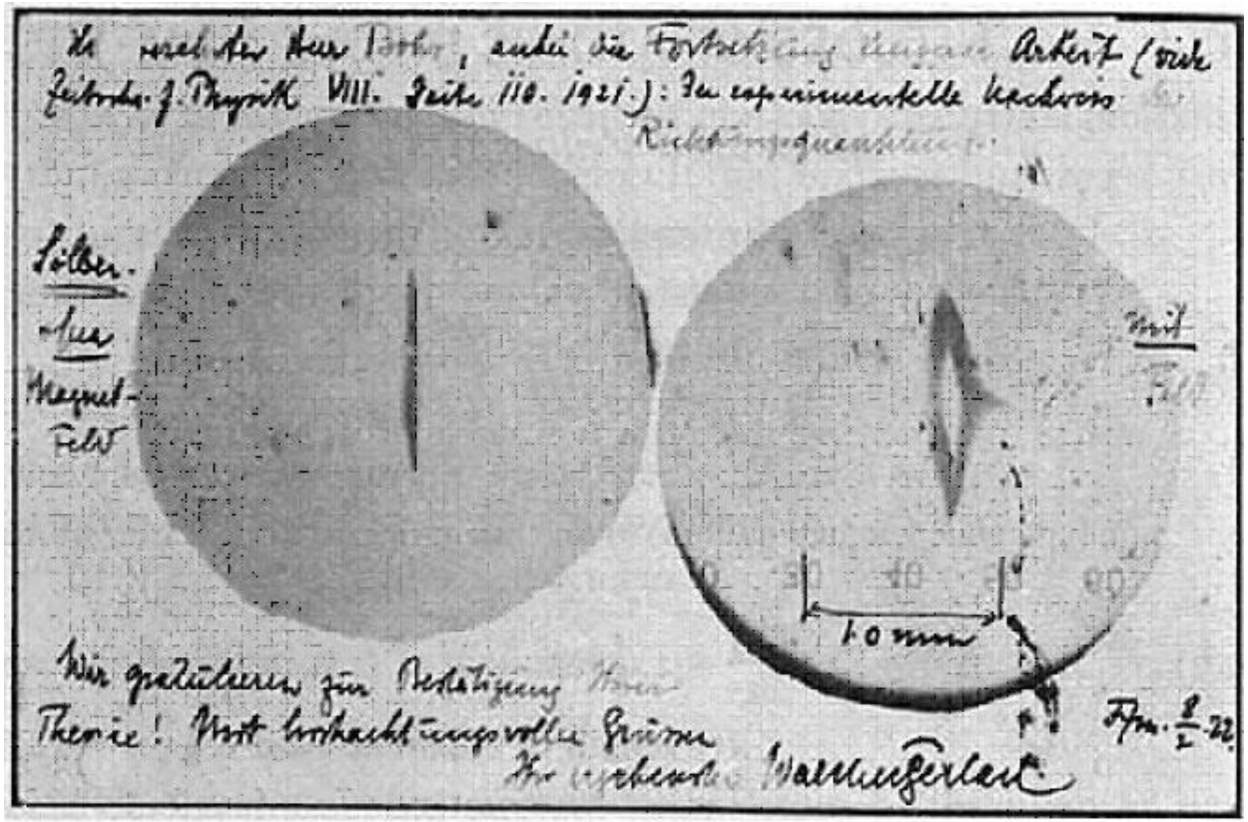
Plan of my talk

Physics with polarized targets in the storage rings

Technique of polarized targets for storage rings

Novosibirsk experiment on the measurement of the two-photon exchange contribution to the elastic $e^{+-}p$ scattering cross sections at the VEPP-3 storage ring

Conclusion



Gerlach's postcard, dated 8 February 1922, to Niels Bohr. It shows a photograph of the beam splitting, with the message, in translation: "Attached [is] the experimental proof of directional quantization. We congratulate [you] on the confirmation of your theory." (Physics Today December 2003)

Otto Stern - Nobel prize 1943

for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton

The suggestion to use a storage ring of charge particles for experiments with internal targets (including polarized) was discussed at the stage of the design of the first colliding beams

Beautiful research with polarized jet and storage cell targets has been performed in storage rings of charged particles

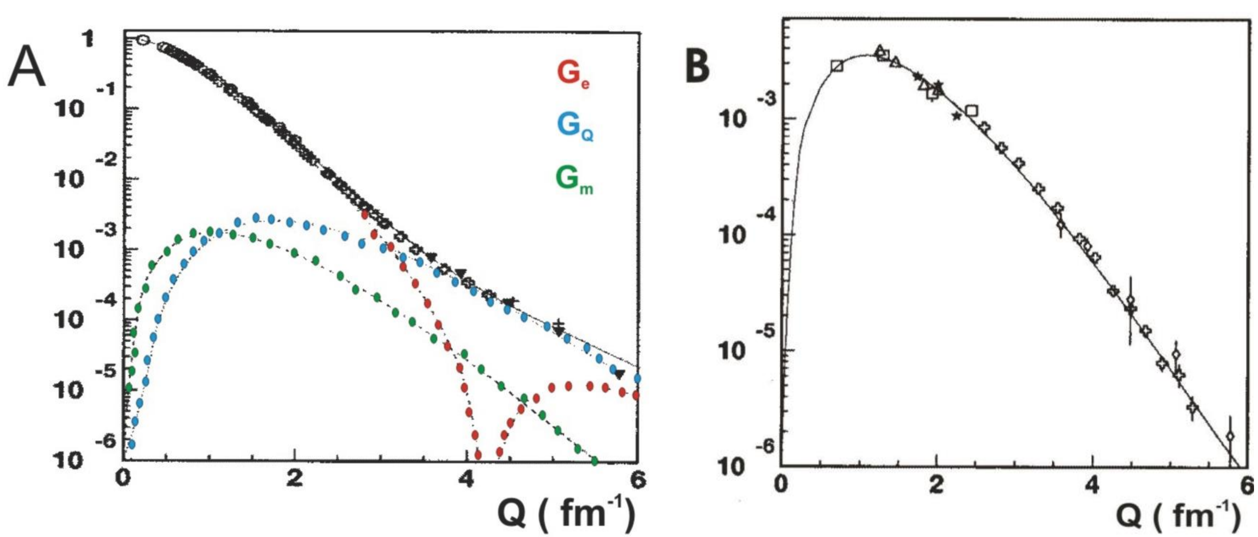
Proton Storage Rings:	***Electron Storage Rings:***
TSR,IUCF, COSY, RHIC	**VEPP-3, AmPS, MIT-Bates LAC, HERA**
Filter method, elastic and inelastic $\vec{p}\ \vec{p}$ and $\vec{p}\ \vec{d}$ scattering, polarimetry ($\vec{p}\ \vec{p}$ elastic scattering)	Elastic and inelastic e $\vec{d}$ scattering, photodisintegration, deep inelastic $\vec{e}\ \vec{p}$ scattering, polarimetry ($\vec{e}\ \vec{e}$ elastic scattering)

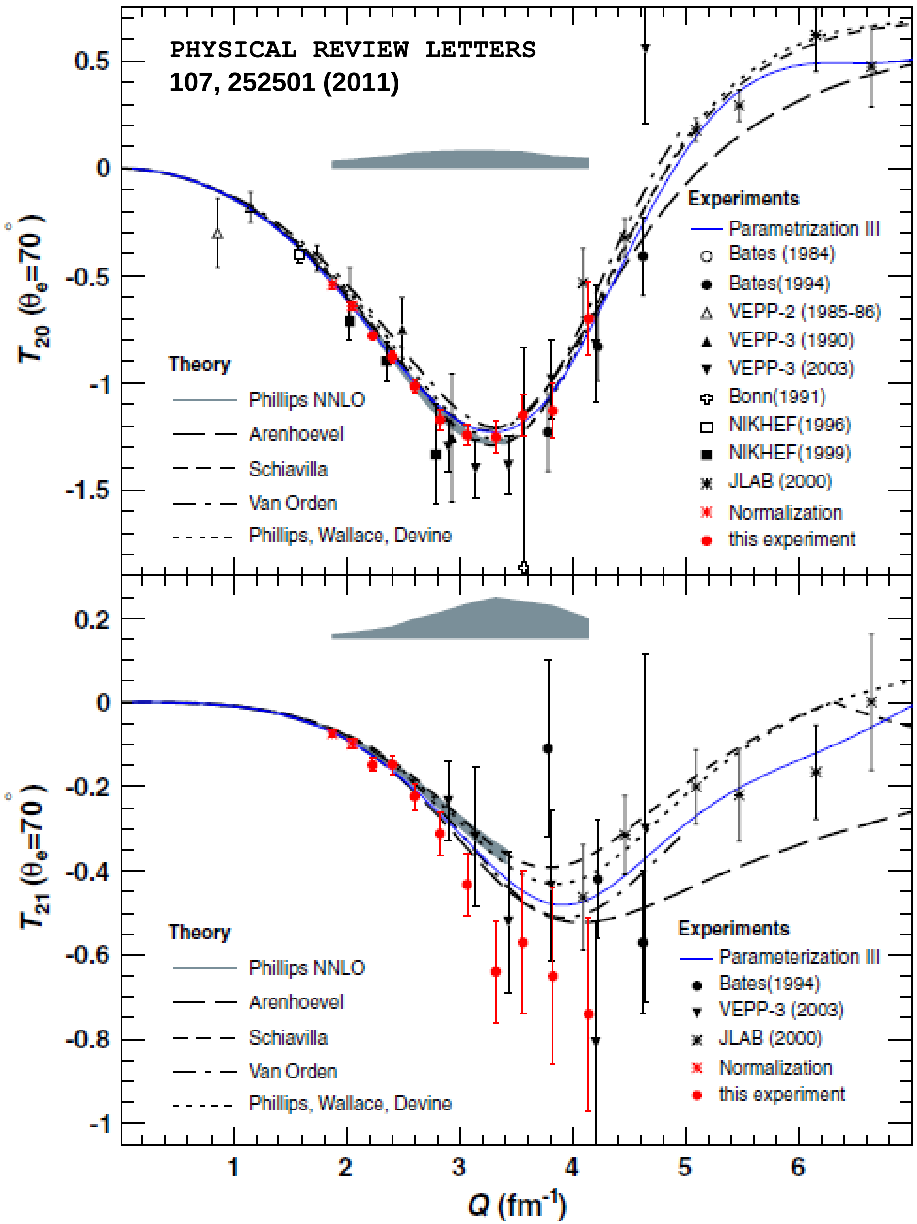
Historically the first polarized target used in a ring was tensor polarized deuterium target. The deuteron is the simplest nucleus and it theoretical and experimental investigation has an important role for the determination of the properties of the nucleon-nucleon interaction as well as for the study of non-nucleonic degrees of freedom.

$$d\sigma/d\Omega = \sigma_m(A+B\, tg^2(\theta_e/2))$$

$$A = G_C^2 + (8/9)\eta^2 G_Q^2 + (2/3)\eta G_M^2$$

$$B = (4/3)\eta(1+\eta)G_M^2$$





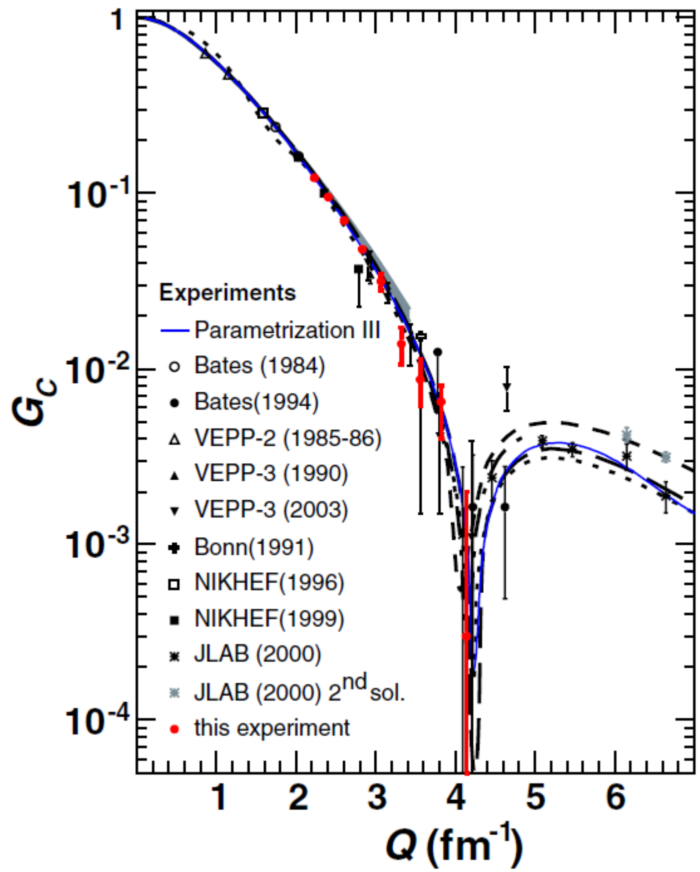
First measurement of the asymmetry in electron scattering by a jet target of polarized deuterium atoms
Physics Letters 157B (1985) 143
Experiment has been performed at VEPP-2, E=290, 400 MeV

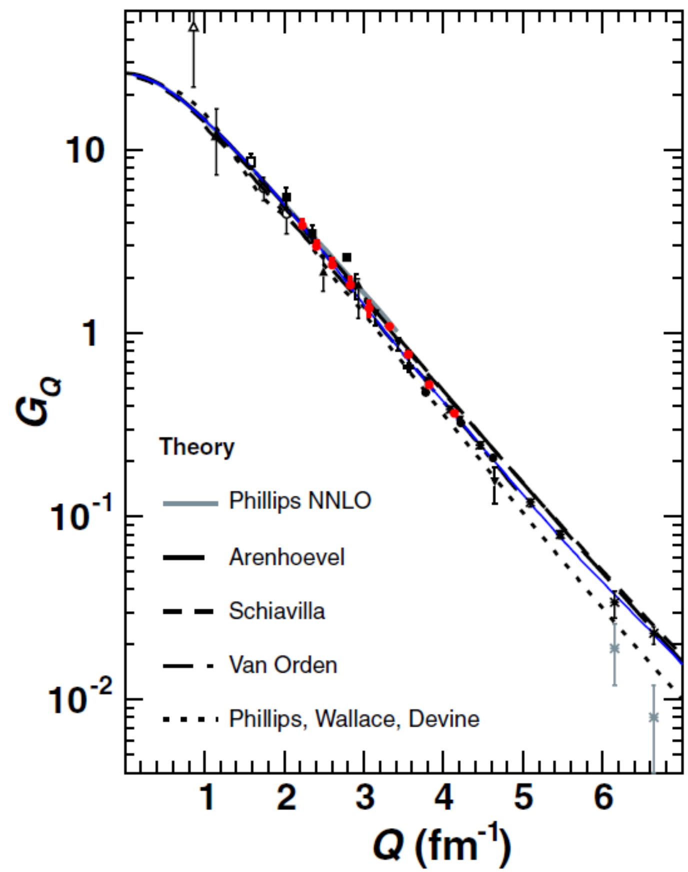
$$\frac{d\sigma_{pol}}{d\Omega} = \frac{d\sigma_0}{d\Omega}\left[1+\frac{P_{zz}}{\sqrt{2}}\sum_{i=0}^{2} d_{2i}(\theta^*)T_{2i}\right]$$

$$T_{20} = -\sqrt{2}\,\frac{x(x+2)+y/2}{1+2(x^2+y)}$$

$$x = \frac{2}{3}\eta G_Q / G_C$$

$$y = \frac{2}{3}(1+2(1+\eta)tg^2(\theta_e/2))G_M^2 / G_C^2$$

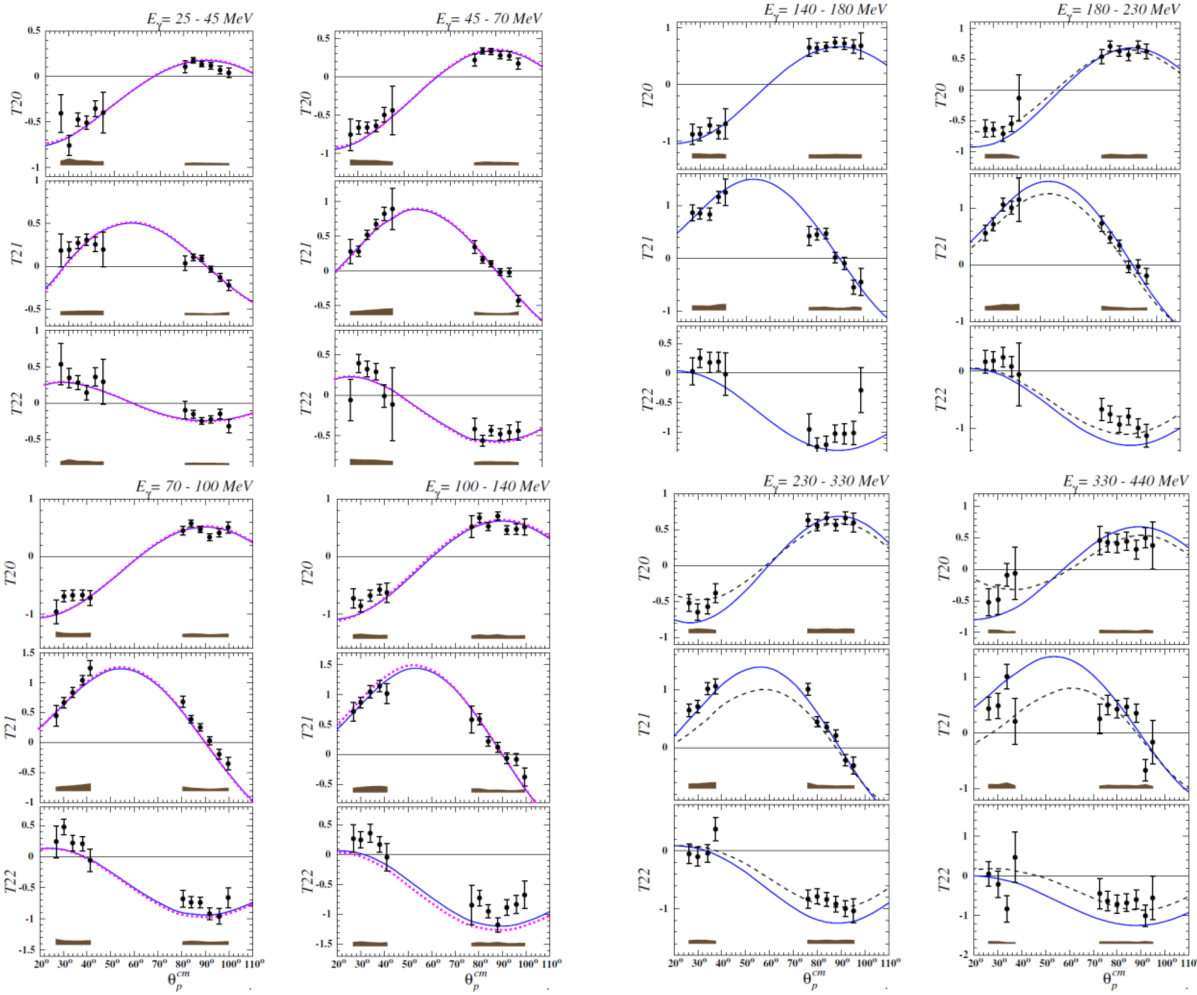




The location of the first node of G_C was confirmed at $Q=4.19\pm0.05$ fm $^{-1}$

Measurement of tensor analyzing powers in deuteron photodisintegration

PHYSICAL REVIEW LETTERS
98, 182303 (2007)



One of the most fundamental processes on the deuteron is two-body photodisintegration. The tensor analyzing powers of this reaction were among the most poorly known.

Solid line - H. Arenhovel and K.-M. Schmitt, Few Body Syst. 8 (1990) 77.
Dotted line - M.I. Levchuk, Few Body Syst. 19 (1995) 77.

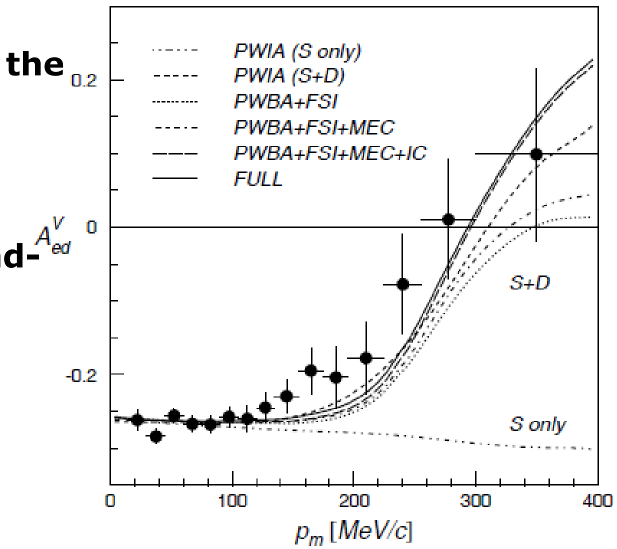
Solid line - H. Arenhovel and K.-M. Schmitt, Few Body Syst. 8 (1990) 77.
Dotted line - M. Schwamb, Habilitation thesis, Johannes Gutenberg-Universitat atMainz, 2006.

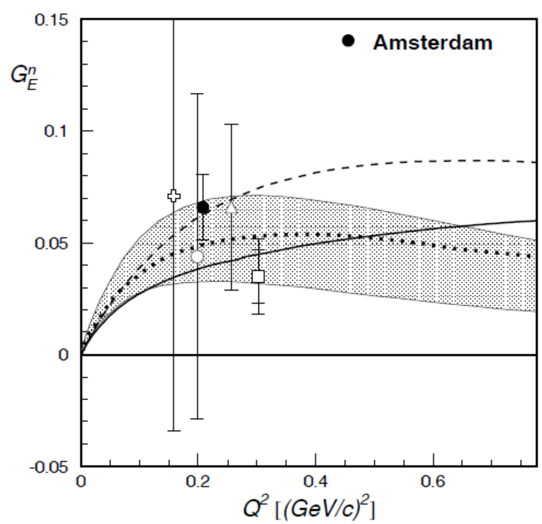
Experiments at NIKHEF

The spin correlation parameter A^V_{ed} was measured for the $^2\vec{H}(\vec{e},e'p)n$ reaction for missing momenta up to 350 MeV/c at a four-momentum transfer squared of 0.21 $(GeV/c)^2$

Phys.Rev.Lett. 88 (2002) 102302

The data give detailed information about the spin structure of the deuteron, and are in good agreement with the predictions of microscopic calculations based on realistic nucleon-nucleon potentials and including various spin dependent reaction mechanism effects. The experiment demonstrates in a most direct manner the effects of the D-state in the deuteron ground-state wave function and shows the importance of isobar configurations for this reaction.





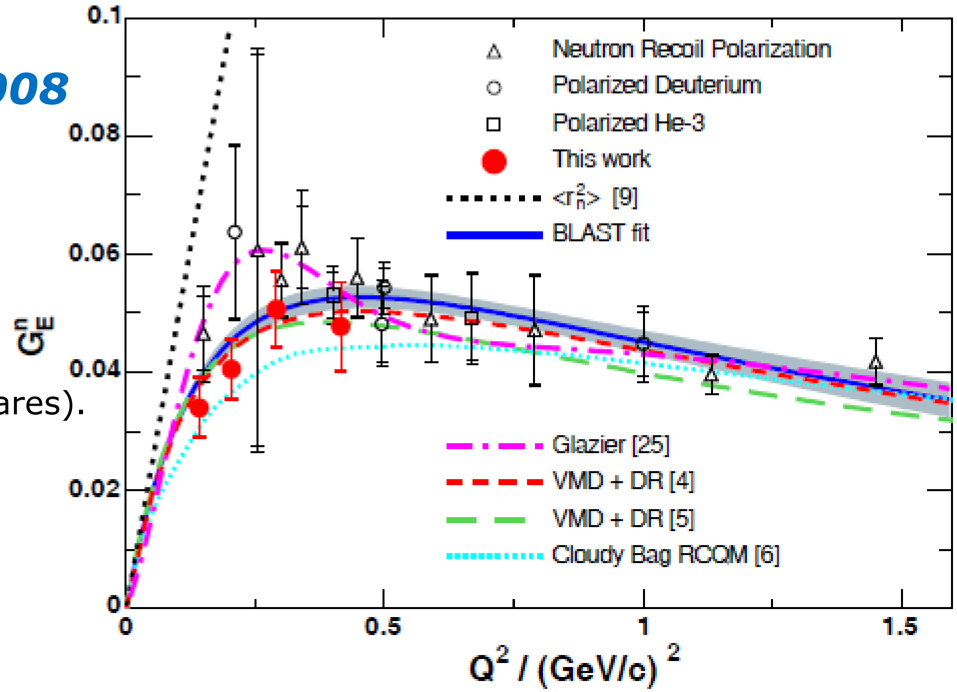
Phys.Rev.Lett. 82 (1999) 4988

The Charge Form Factor of the Neutron from the Reaction $^2\vec{H}(\vec{e},e'n)p$

Experiments with BLAST

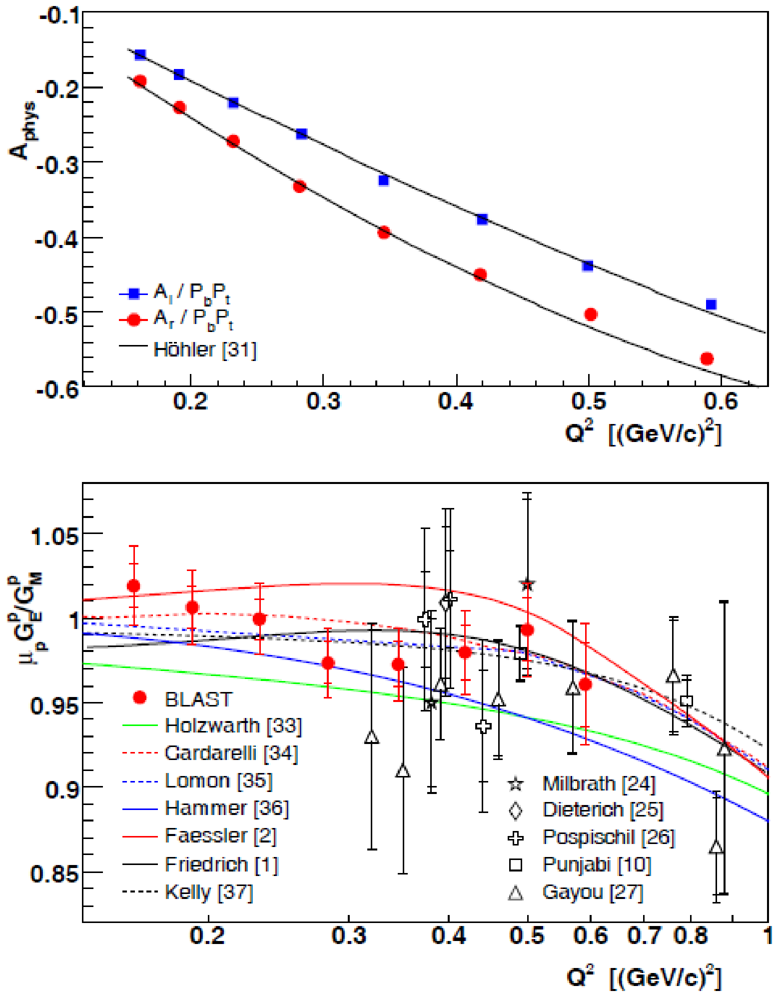
Phys.Rev.Lett.101:042501,2008

World data on G_E^n from double-polarization experiments [8].
The data correspond to neutron recoil polarization experiments with unpolarized ^2H target (open triangles) and experiments with polarized ^2H (open circles; solid red dots=this work) and ^3He targets (open squares).
The “BLAST fit” (blue solid line) is a parameterization of all data displayed based on the sum of two dipoles shown with a one-sigma error band.
The recent parameterization (magenta dash-dotted line) is based on the form introduced in 21. Also shown are recent results based on vector meson dominance and dispersion relations (red short-dashed and green long-dashed lines), and of a light-front cloudy bag model with relativistic constituent quarks

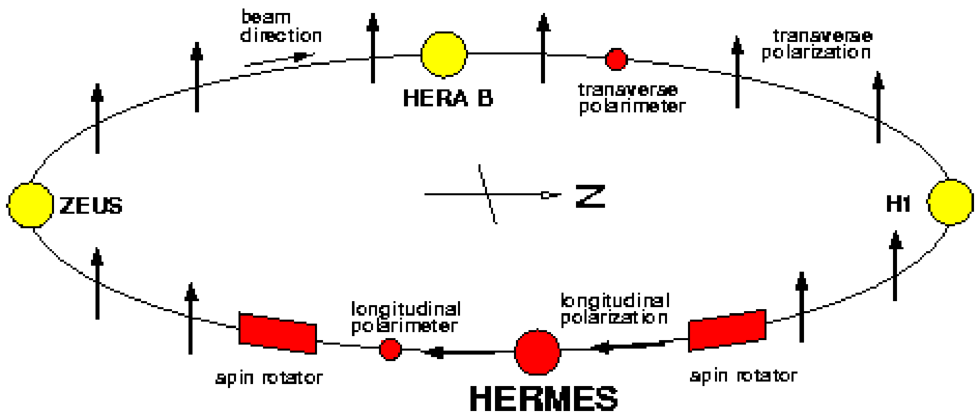


Phys.Rev.Lett.98, 052301 (2007)

Upper panel: Spin-dependent $^{1}\vec{H}(\vec{e}, e'p)$ asymmetry ($P_b\ P_t = 0.537 \pm 0.003$) compared to the expected asymmetries based on the parameterization for the nucleon form factors.
Lower panel: Results of $\mu_p G_{pE}/G_{pM}$ shown with the world polarized data and several models described in the text.



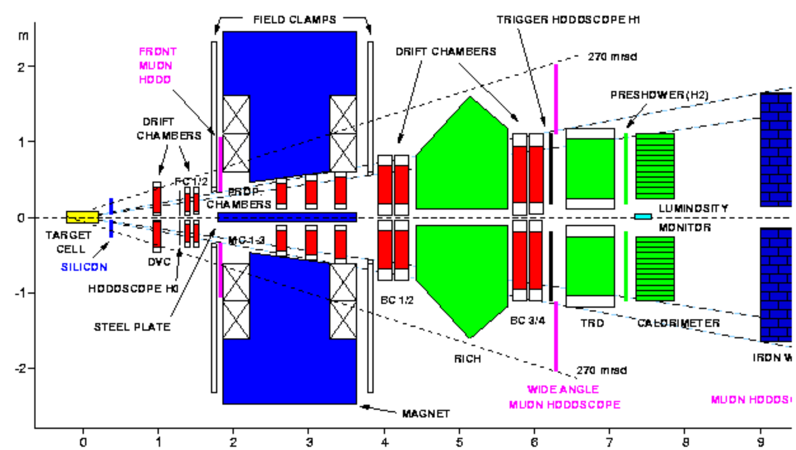
The HERMES experiment at DESY-HERA



HERA $e^{+/-}$ ring:

- 45 mA
- 27.5 GeV
- $P \approx 55$ %

HERMES spectrometer



The experiment's goal was to investigate the quark-gluon structure of matter by examining how a nucleon's constituents affect its spin. HERMES completed its first run between 1995 and 2000, and a second run began in 2001 and ended during the summer of 2007.

nucleon spin structure

$$\langle S^N_z \rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta g + L_g$$

Early calculations suggested $\Delta\Sigma \sim 2/3$
R.Jafef and Manohar Nucl.Phys B 337(1990)509
K.Suzuki and W. Weise Nucl. Phys. A 634(1998)141

HERMES result $\Delta\Sigma$ = 0.347±0.024±0.066

Phys.Rev.D71:012003,2005

HUNDREDS OF SCIENTIFIC PUBLICATIONS

Tuesday 21 October 2014
Plenary Session IV (Chair: Franco Bradamante) - (10:15-12:00)
10:15 Latest Results from HERMES
ROSTOMYAN, Armine

Wednesday 22 October 2014
Parallel-VI: S2 (Chair: Peter Bosted) - (10:30-12:00)
11:45 Multiplicities of Charged Pions and Kaons in Deep-inelastic Scattering byProtons and Deuterons at HERMES and the Strange-quark Distribution in theNucleon
HERMES

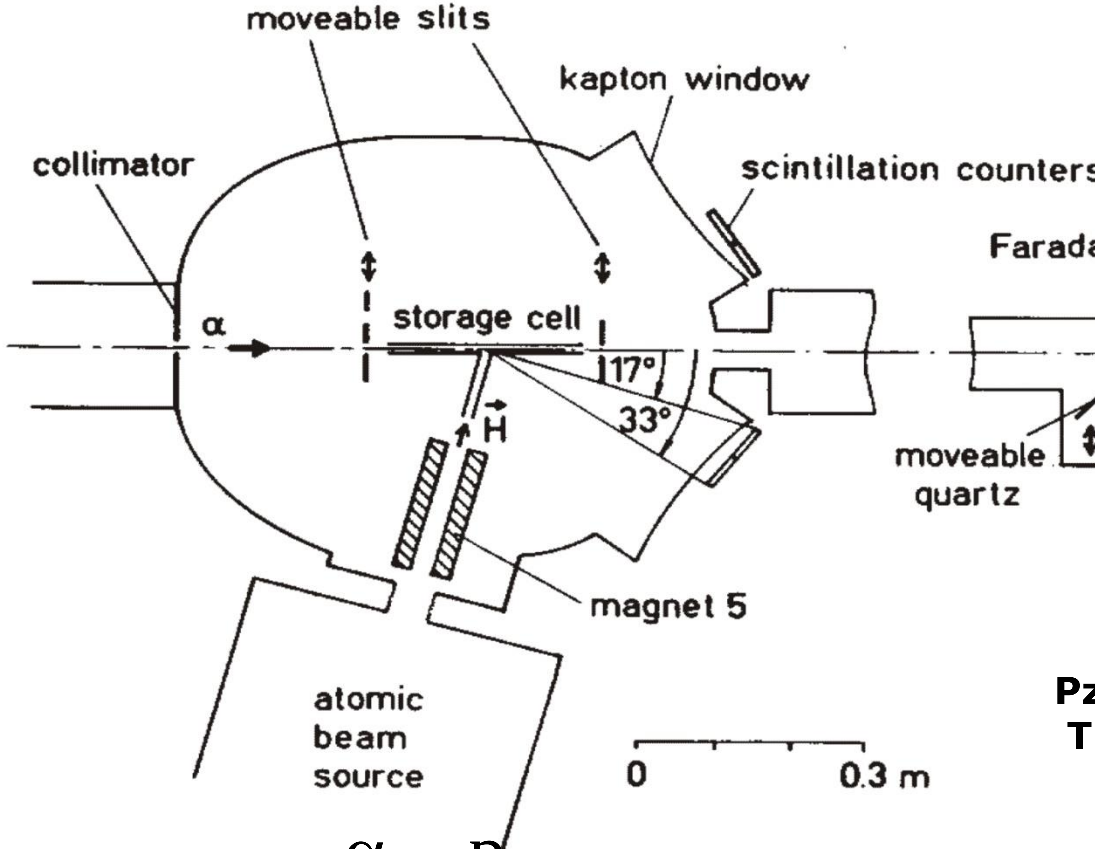
Friday 24 October 2014
Parallel-VII: S3 (Chair: Han-Xin He) - (08:15-10:15)
08:45 Transverse Target Single-spin Asymmetry in Inclusive Electroproduction of Charged Pions and Kaons
HERMES

Parallel-VII: S4 (Chair: Dieter Mueller) - (08:15-10:15)
08:45 DVCS at HERMES
HERMES

First use of polarized target in ion ring TSR

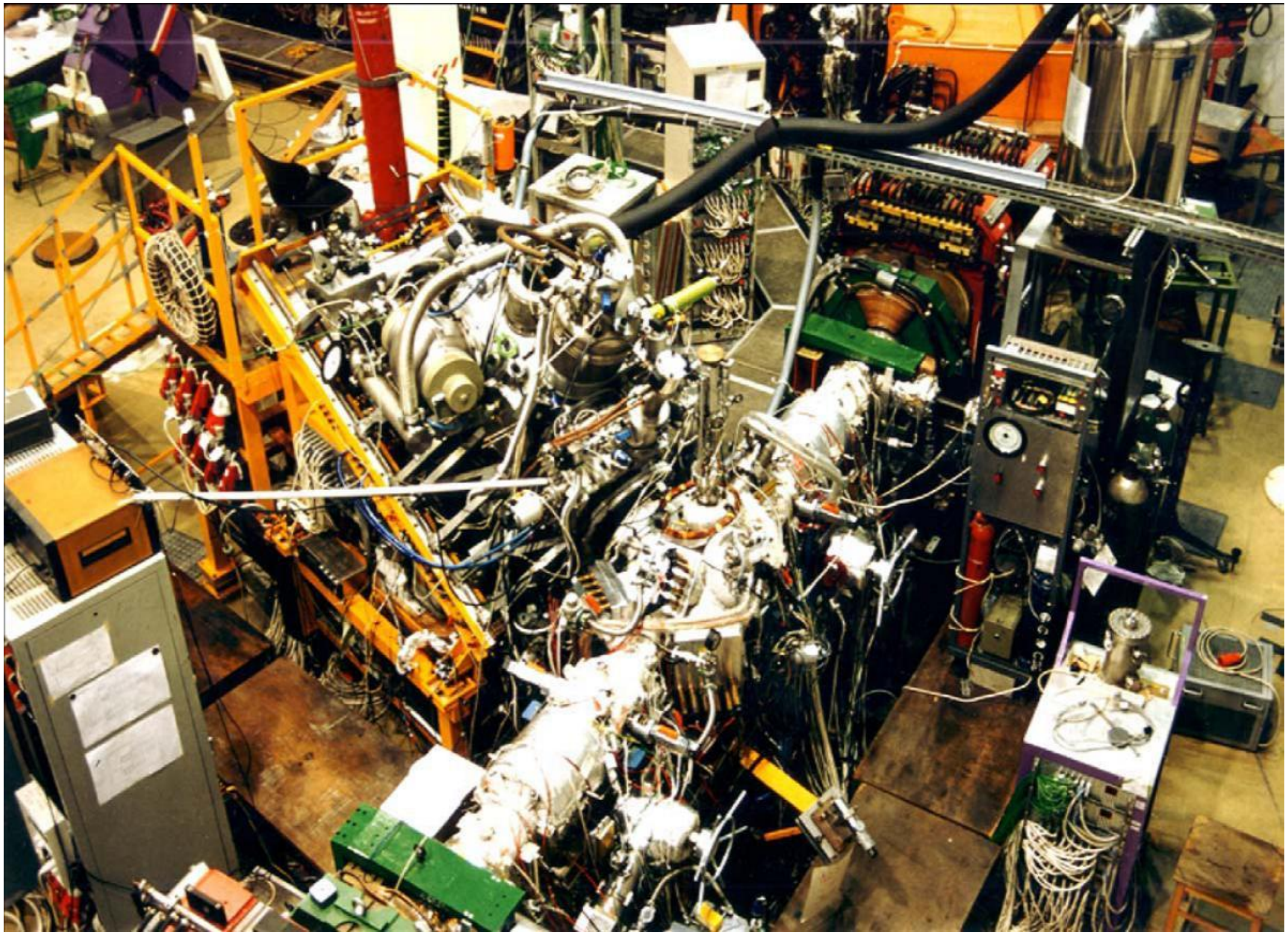
Elastic scattering
E=34.5 МэВ

NIM A322(1992)13



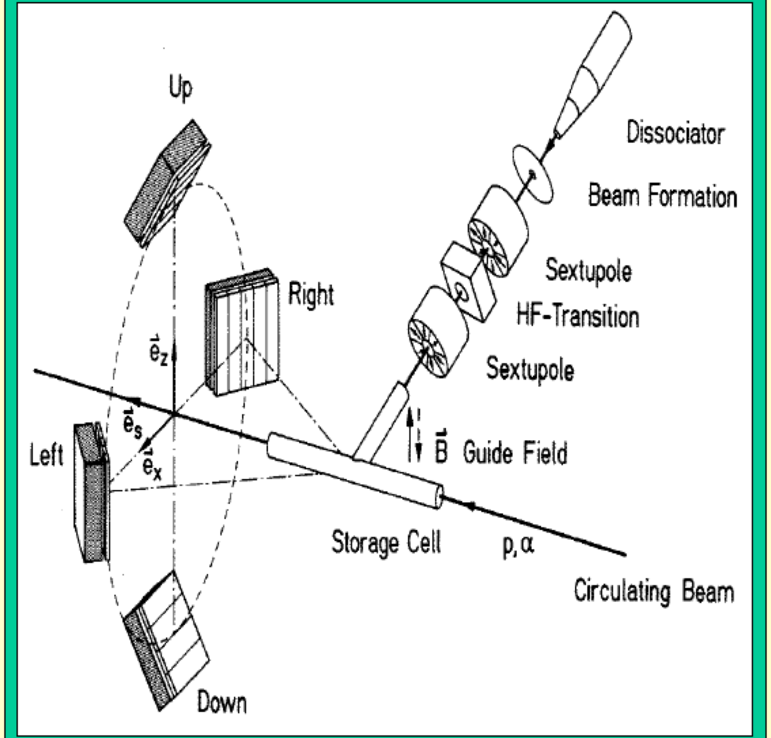
Pz = 0.42 +- 0.04
T =(2.6 +- 0.2)10^{13}at/cм^{2}

$\alpha - p$

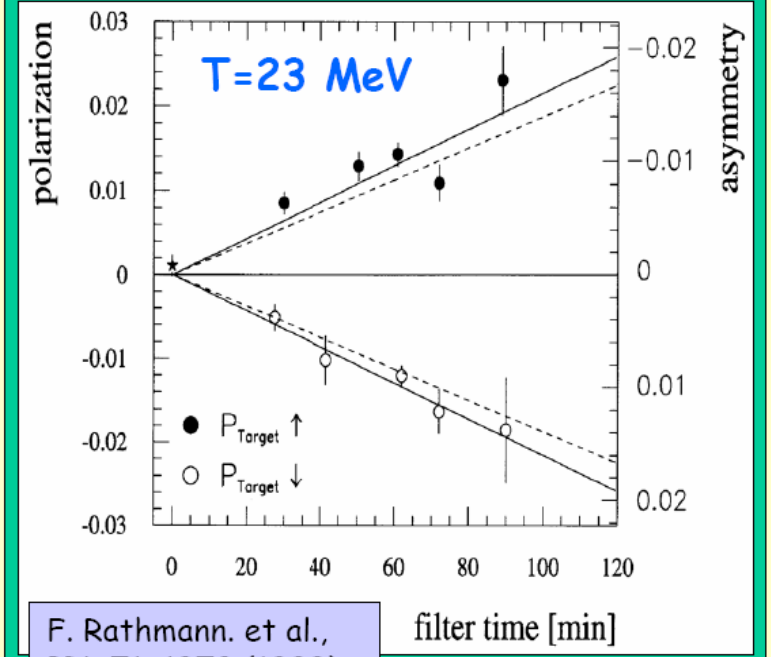


Experimental Results from Filter Test

Experimental Setup



Results



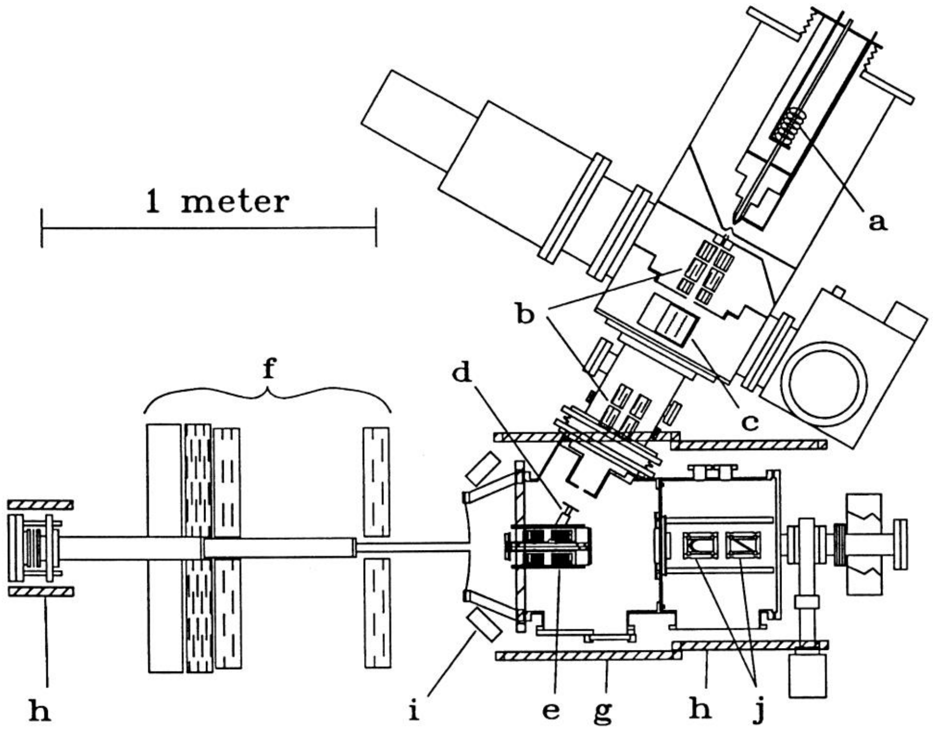
F. Rathmann. et al.,
PRL 71, 1379 (1993)

Low energy pp scattering

$\sigma_1 < 0 \Rightarrow \sigma_{tot+} < \sigma_{tot-}$

Expectation	
Target	Beam
↑	↑
↓	↓

IUCF Cooler Storage Ring



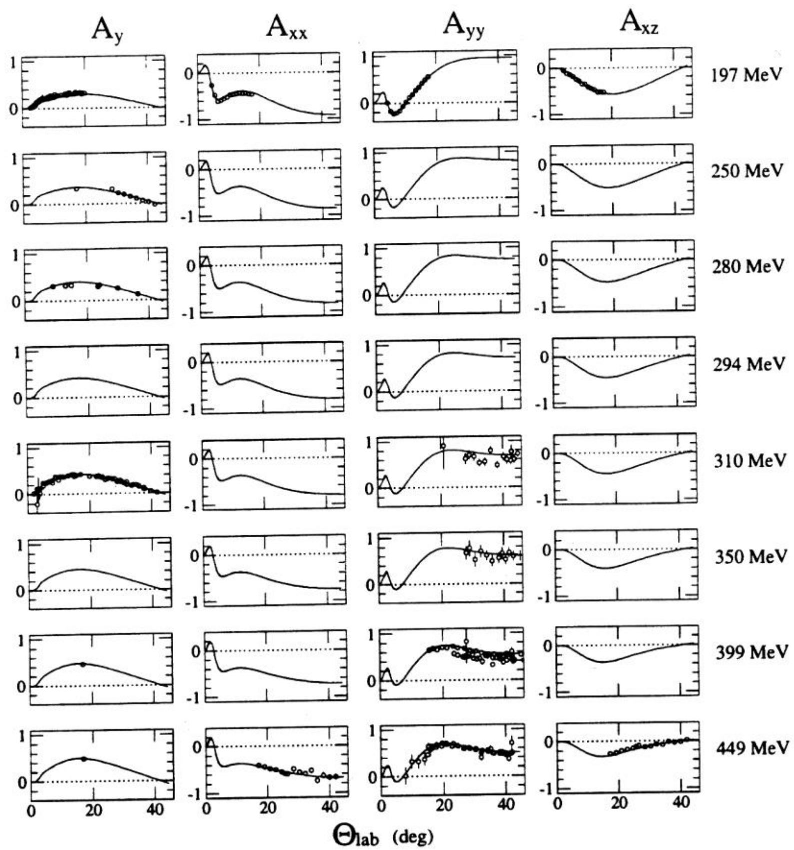
The PINTEX group has been studying proton-proton and proton-deuteron scattering and reactions between 100 and 500 MeV at the Indiana University Cyclotron Facility (IUCF). The PINTEX program ended in August 2002

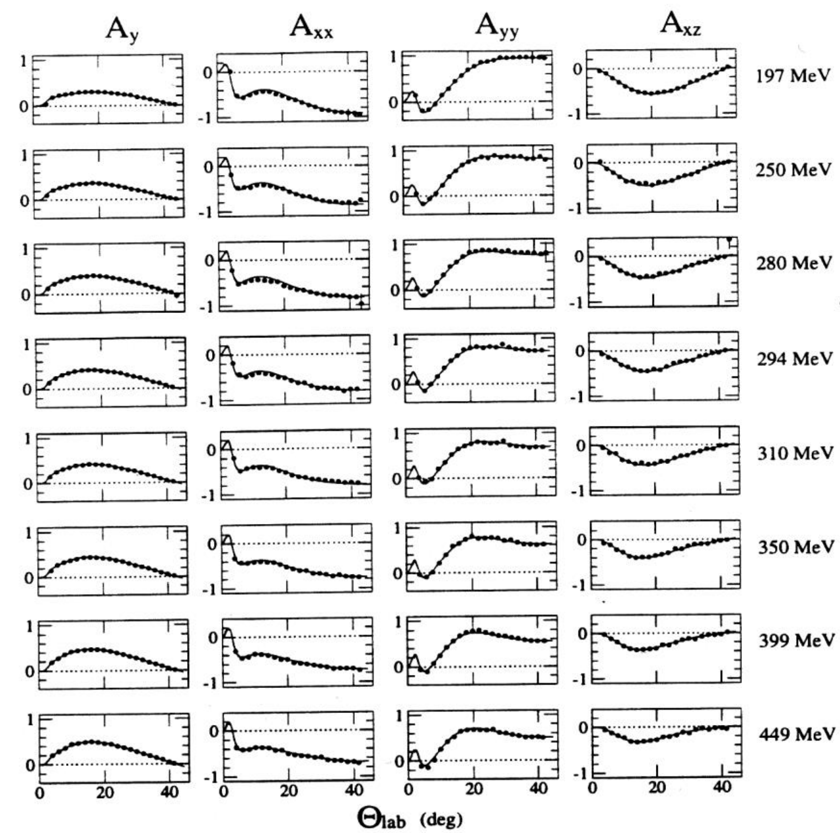
e – silicon strip detector
f – forward detector
i – scintillators

10-30 mkA/min
I = 100 – 400 mkA
T = $2*10^{13}$at/cm^2
L =$4.5*10^{28}$ s^{-1} cm^{-2}

Beam – target polarization
++, +-, -+, --

Analyzing power and spin correlation coefficients as function of energy and angle





All previously existing data between 175 MeV and 475 MeV from the SAID data base

B.v.Przewoski et al. Phys. Rev. C 58, 1897-1912 (1998)

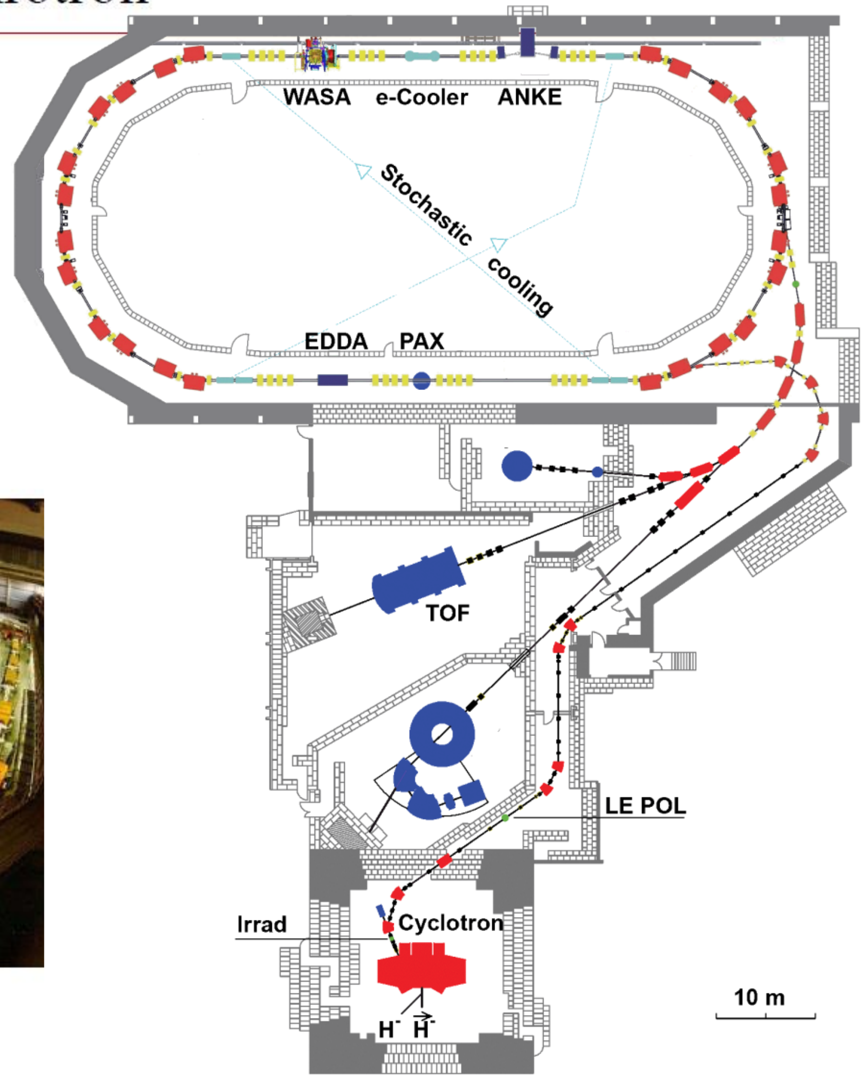
The curves are the SM97 phase shift analysis

COSY – COoler SYnchrotron

$$p,\ \vec{p},\ d,\ \vec{d}$$

with momenta up to 3.7 GeV/c

- **internal experiments** – with the circulating beam
- **external experiments** – with the extracted beam



First $\vec{d}\vec{p}$ commissioning @ ANKE – Jan/Feb 2007

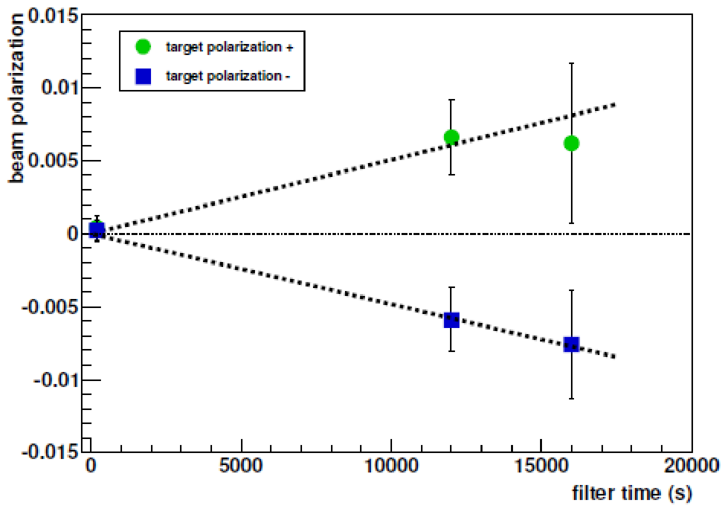
The ABS was built for the purpose of extending the physics program of ANKE from unpolarized and single-polarized investigations with stored beams towards double-polarized experiments, thus facilitating nuclear reaction studies

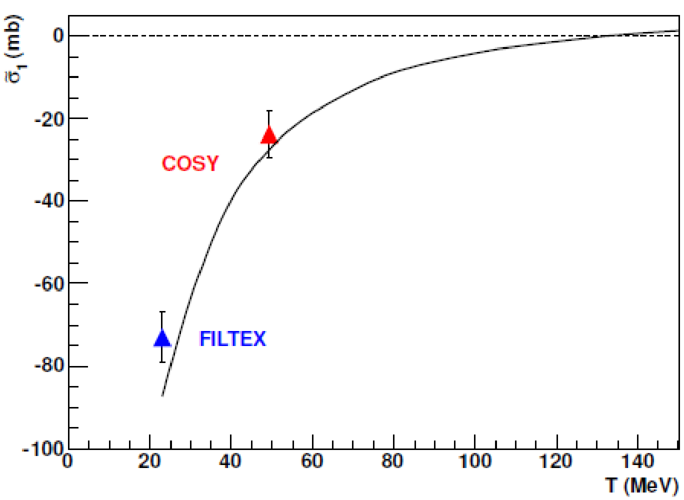
involving $\vec{p}\vec{p}$, $\vec{p}\vec{d}$, $\vec{d}\vec{p}$ and $\vec{d}\vec{d}$ initial states.

In 2011 the ***PAX Collaboration*** has performed a successful spin-filtering test using protons at Tp = 49.3MeV at the COSY ring, which confirms that spin filtering is a viable method to polarize a stored beam and that the present interpretation of the mechanism in terms of the proton-proton interaction is correct.

A linear fit allows to determine dP/dt = (4.8 +- 0.8) 10^{-7} s $^{-1}$.

EPJ Web of Conferences 66,11039 (2014)





Monday 20 October 2014
Parallel-I: S5 (Chair: Xiaomei Li) - (13:30-15:15)
14:50 Initial Research of np Scattering with Polarized Deuterium Target at ANKE/COSY
GOU, Boxing

Parallel-II: S8 (Chair: Krishna Kumar) - (15:30-17:30)
16:50 Test of Time-Reversal Invariance at COSY (TRIC)
EVERSHEIM, Dieter

Thursday 23 October 2014
Plenary Session VI (Chair: Hans Stroeher) - (10:30-12:00)
11:00 Spin Physics at COSY - Recent Results and Future Plans
KACHARAVA, Andro

Friday 24 October 2014
Parallel-VII: S10 (Chair: Don Crabb) - (08:15-10:15)
09:55 The H and D Polarized Target for Spin-filtering Measurements at COSY.
CIULLO, Giuseppe

Polarized target for polarimetry of the circulated beam

Polarimetry of the electron beam

Application of internal gas target for beam polarization measurement in the electron storage ring. AIP Conf. Proc. No.570(2001) p.892

Moller polarimeter for VEPP-3 storage ring based on internal polarized gas jet target. NIM A 536(2005)338.

Polarimetry of the proton beam

Measurement of the analyzing power A_N in pp elastic scattering in the CNI region with a polarized atomic hydrogen gas jet target. Phys. Lett. B 638 (2006) 450

Absolute polarimetry at RHIC AIPConf.Proc.980:370-379,2008

Møller Polarimeter for VEPP-3 based on Internal Polarized Gas Jet Target

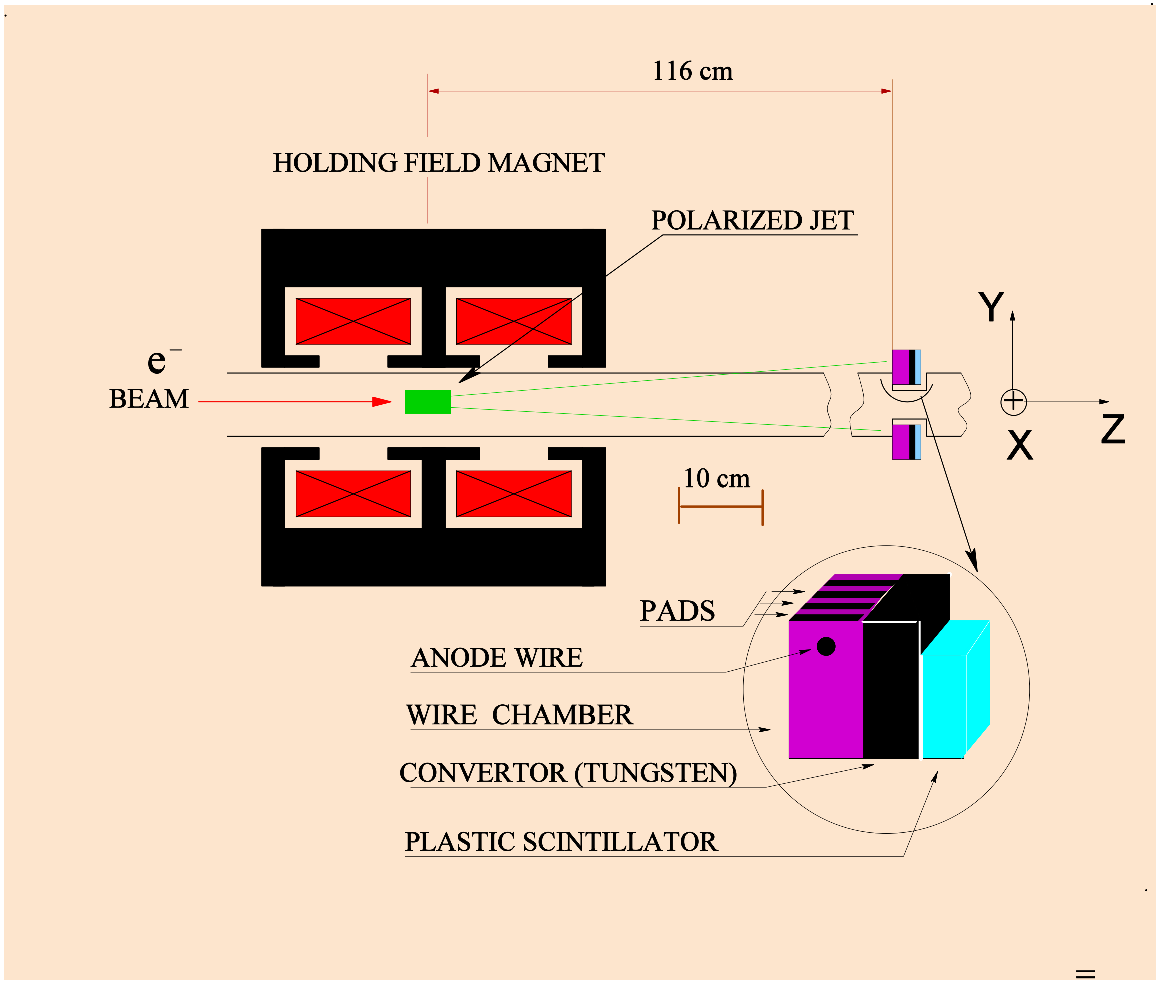
$$A = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} = A_g \zeta_B \zeta_T$$

ζ_B is Beam Polarization

ζ_T is Target Polarization

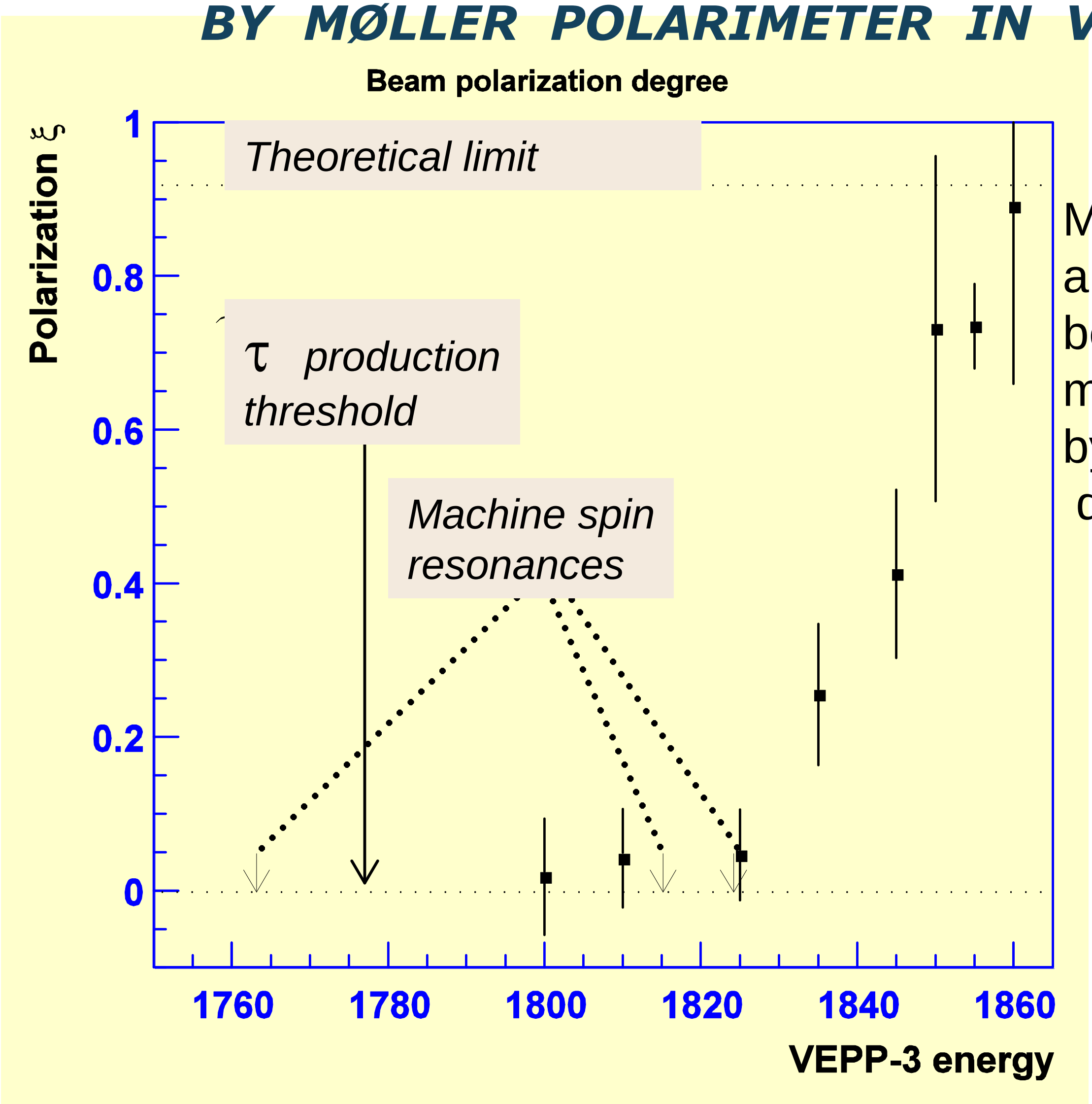
$\zeta_T \approx 100\%$

$A_g \approx 0.09 \quad (A_g^{max} = 1/9)$



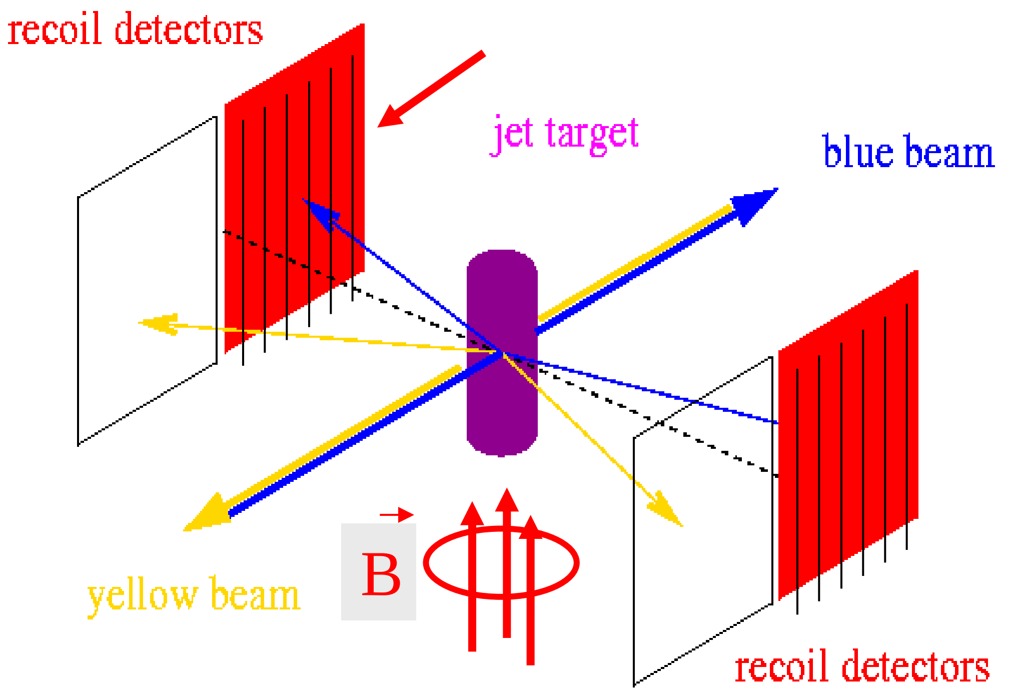
RESULTS OF THE BEAM POLARIZATION MEASUREMENT BY MØLLER POLARIMETER IN VEPP-3 VS. ENERGY

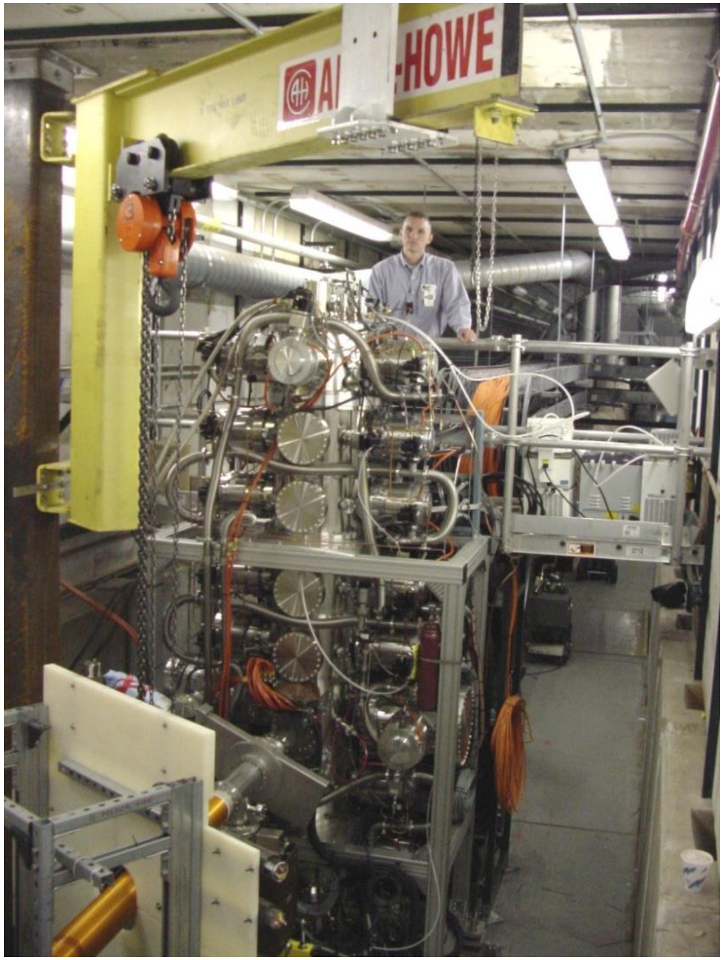
NIM A 536(2005)338



Measurement helped to choose a scenario to get a polarized beams at VEPP-4 for precision measurement of τ lepton mass by the method of resonance depolarization

H-jet polarimeter setup at IP12



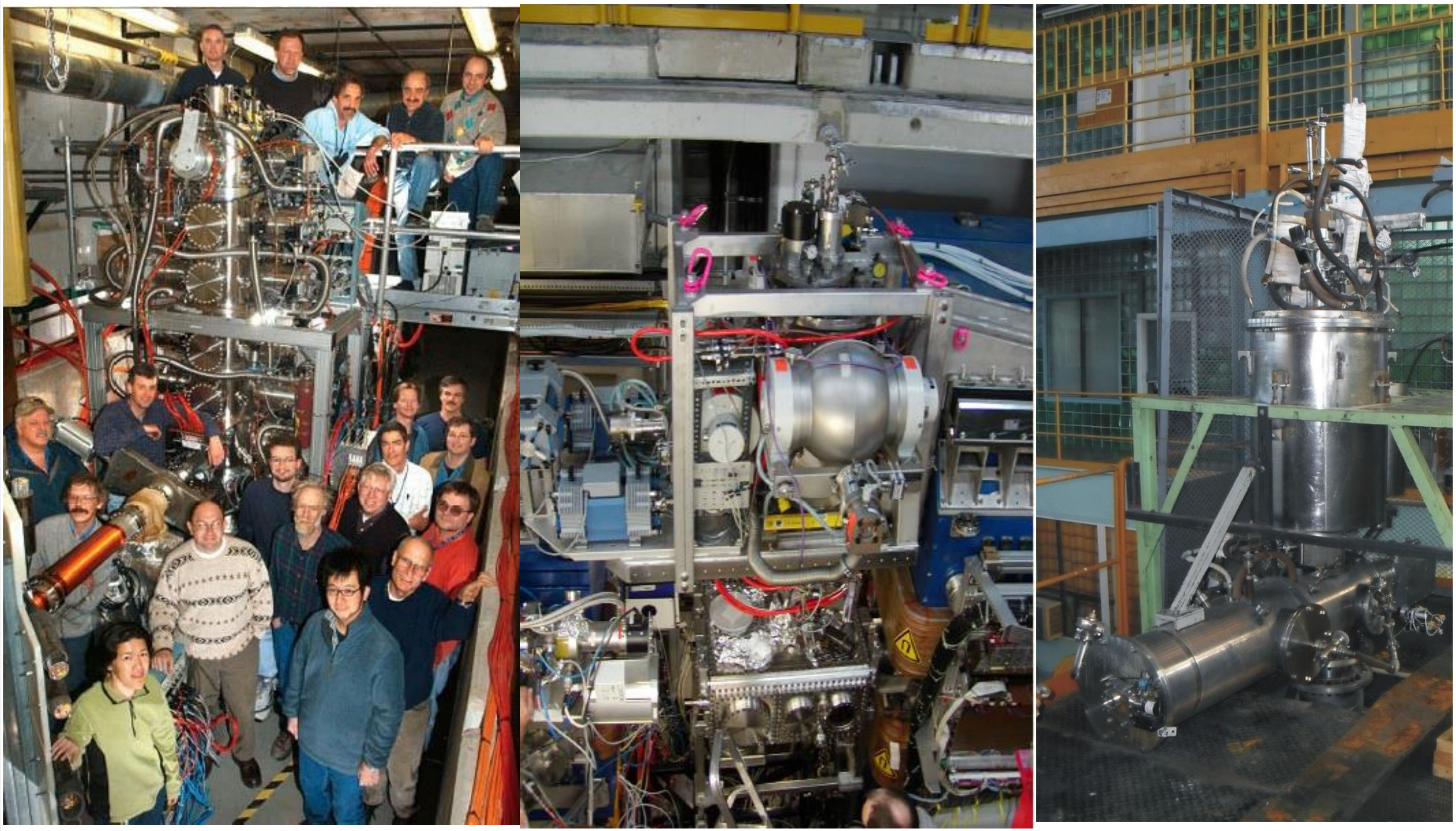


Polarized H-jet target - $1.3 \cdot 10^{12}$ at/cm^2.
Polarization ~ 93%.

Event rate ; ~6Hz (0.7~5MeV)

Parallel-I: S9 (Chair: Andreas Lehrach) - (13:30-15:15)
14:20 RHIC Proton Polarimetry Current Status and Future Plans. Speaker: Yousef Makdisi (BNL)

Right now the experiments with polarized targets are in progress in three centers: BNL (RHIC), Juelich (COSY) and Novosibirsk (VEPP-3)



The tagging system of almost-real photons at VEPP-3 *CREATED and TESTED*

:: New possibilities

- **complete kinematic reconstruction that permits to make a reliable rejection of the background process**

- **to extend the measurements to higher photon energy *up to 1.5 GeV* (photodisintegration of $\vec{d}$, photoproduction of mesons on $\vec{d}$)**

- **to determine the linear polarization of the photon, thus enabling the another kind of experiments: measurements of *Σ-asymmetry, double-polarization experiments* (for example, interaction of polarized photon with a polarized neutron of $\vec{d}$).**

A little bit of history of polarized beams

Apparently Wrede , Phipps and Taylor were the first who got a polarized atomic hydrogen beam.

E. Wrede, ***Zs. F. Physik*** **41** (1927) 569

Friedburg and Paul suggested to apply a focusing magnet which provides more intensive atomic beam.

H. Friedburg, W. Paul, ***Naturwiss*** **37** (1950) 20***; Naturwiss*** **38** (1951) 159

Kantrowitz and Grey suggested to use a supersonic nozzle with purpose to obtain more directed beam.

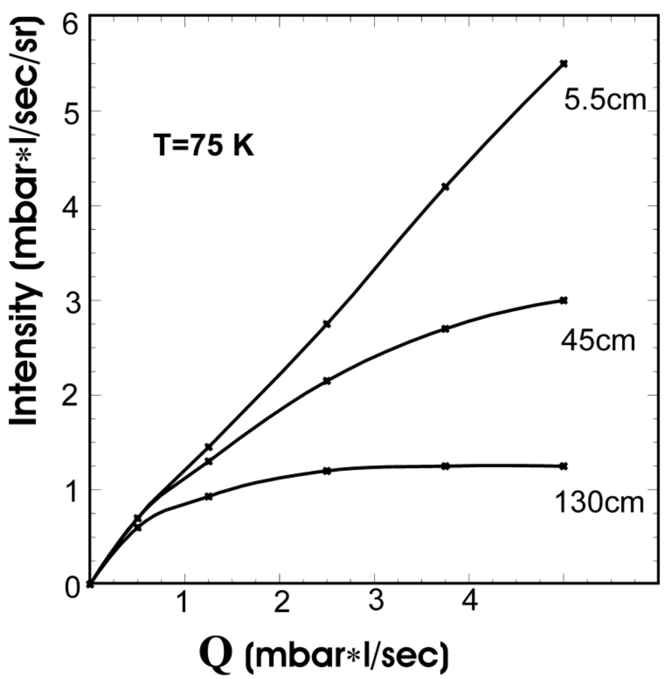
A. Kantrowitz, J. Grey, ***Rev. Sci. Instr.*** **22** (1951) 328

Clausnitzer et al. first got a polarized proton beam using an ABS with quadrupole focusing magnets.

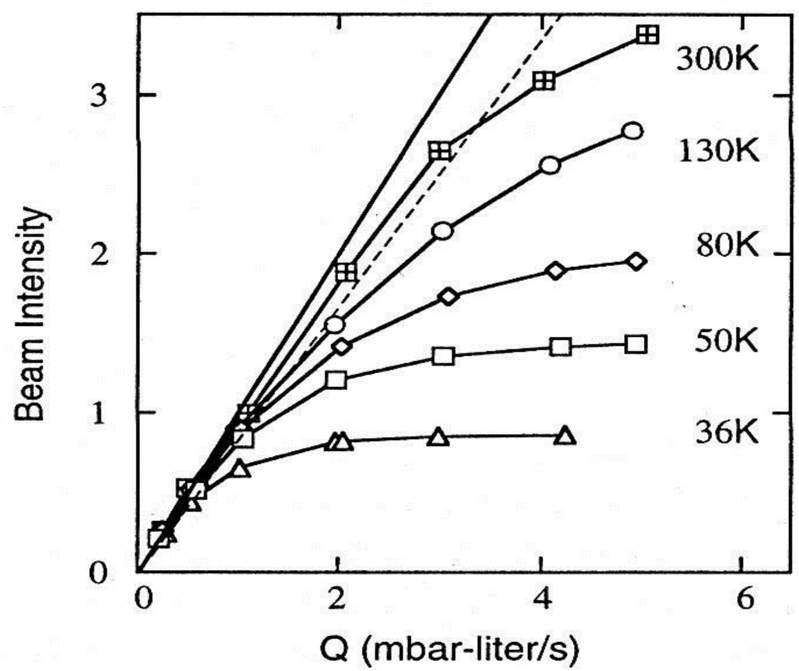
G. Clausnitzer, R. Fleischman, H. Shopper, ***Zs. F. Physik*** **144** (1956) 336

ABS	$\Omega_{geom.}$ (sr) = $\pi r^2_{mag.}/l^2_{n\text{-}mag.}$	$\Omega_{mag.}$ (sr) = $\pi\mu B/kT_{nozzle}$	$\Omega_{av.}$ = $\Omega_{g.}\Omega_{m.}/(\Omega_{g.}+\Omega_{m.})$	Intensity H / D at/sec
Wisconsin ABS NIMA336(1993)410	$2.86{*}10^{-2}$	$3.74{*}10^{-2}$	$1.62{*}10^{-2}$	$8.6{*}10^{16}$ total H $6.7{*}10^{16}$ d 10mm H
FILTEX ABS NIMA343(1994)334	$2.38{*}10^{-2}$	$2.95{*}10^{-2}$	$1.31{*}10^{-2}$	$8.1{*}10^{16}$ d 10mm H
HERMES ABS NIMA496(2003)277	$1.73{*}10^{-2}$	$3.16{*}10^{-2}$	$1.12{*}10^{-2}$	$6.6{*}10^{16}$ d 10mm H $5.0{*}10^{16}$ D
ETH ABS (NIKHEF) el. mag. NIMA378(1996)40	$2.5{*}10^{-2}$	$3.31{*}10^{-2}$	$1.42{*}10^{-2}$	$2.6{*}10^{16}$ d 12mm H $1.6{*}10^{16}$ D
ETH ABS (NIKHEF) p. mag. NIMA455(2000)769	$2.29{*}10^{-2}$	$5.1{*}10^{-2}$	$1.58{*}10^{-2}$	$7.6{*}10^{16}$ max H $6.4{*}10^{16}$ d 12mm H $4.5{*}10^{16}$ D
Cryogenic ABS NIMA495(2002)8	$4.3{*}10^{-2}$	$5.3{*}10^{-2}$	$2.37{*}10^{-2}$	$7.9{*}10^{16}$ total H $8.2{*}10^{16}$ D
RHIC ABS NIMA536(2005)248 NIMA556(2006)1	$2.36{*}10^{-2}$	$5.48{*}10^{-2}$	$1.65{*}10^{-2}$	$12.4{*}10^{16}$ total H
ANKE ABS NIMA721(2013)83	$3.14{*}10^{-2}$	$5.8{*}10^{-2}$	$2.04{*}10^{-2}$	$7.5{*}10^{16}$ d 10mm H $3.9{*}10^{16}$ D

FILTEX 1991



T.Wise et al. NIMA 336(1993) 410



For parallel molecular beam with a σ - scattering cross section

Q(x) = Q(0)/[1+α*x*Q(0)] α = σ*Δv/v[2] **Δv** – velosity spread in the beam

for **α*x*Q(0) >> 1, Q(x) ~ (α*x)$^{-1}$** intensity doesn't depend on **Q(0)**

***For tipical ABS condition** Q(150 cm) ~ 2-5*10^{17} at/cm^2*

Hard limit for the intensity of ABS

Laser driven spin exchange polarized H and D targets

IUCF LDT Q= $1.0*10^{18}$ at/s P_{eff} = 0.09+-0.01 was measured at experiment
MIT LDT Q= $1.1*10^{18}$ at/s P = 0.247

Optically pump Polarized ^{3}He targets

Target thickness $1.5*10^{14}$ at/cm^2 . Polarization P=0.46±0.02

In 1995 an optically pumped polarized 3He target was installed at HERA.

Friday 24 October 2014
Parallel-VIII: S10 (Chair: Seonho Choi) - (10:30-12:00)
11:25 Overview of Polarized ^{3}He Gas Targets
CHEN, Jian-ping

Great interest to the
Nucleon Electromagnetic Form Factors

Tuesday 21 October 2014
08:00 - 10:00 Plenary Session III
08:30 Nucleon Electromagnetic Form Factors
CATES, Gordon

Parallel-III: S4 (Chair: Nicole D'Hose) - (13:30-15:15)
13:30 Nucleon Form Factors
BRISCOE, Bill

Parallel-IV: S4 (Chair: Barbara Pasquini) - (15:30-17:30)
15:30 Nucleon Form Factors: An Incisive Window into Quark-Gluon Dynamics
CLOET, Ian

PHYSICAL REVIEW VOLUME 102, NUMBER 3 MAY 1, 1956

Elastic Scattering of 188-Mev Electrons from the Proton and the Alpha Particle*†‡§‖¶

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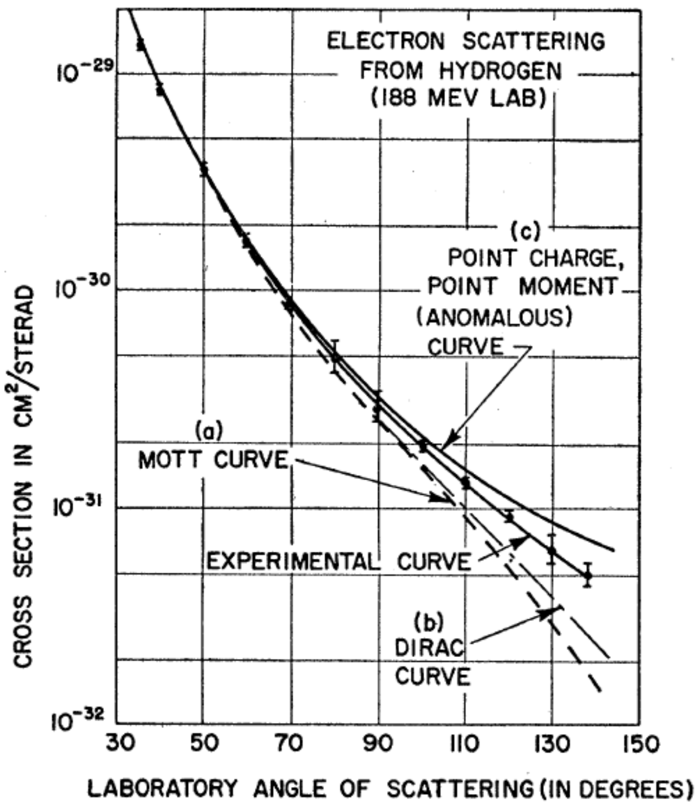
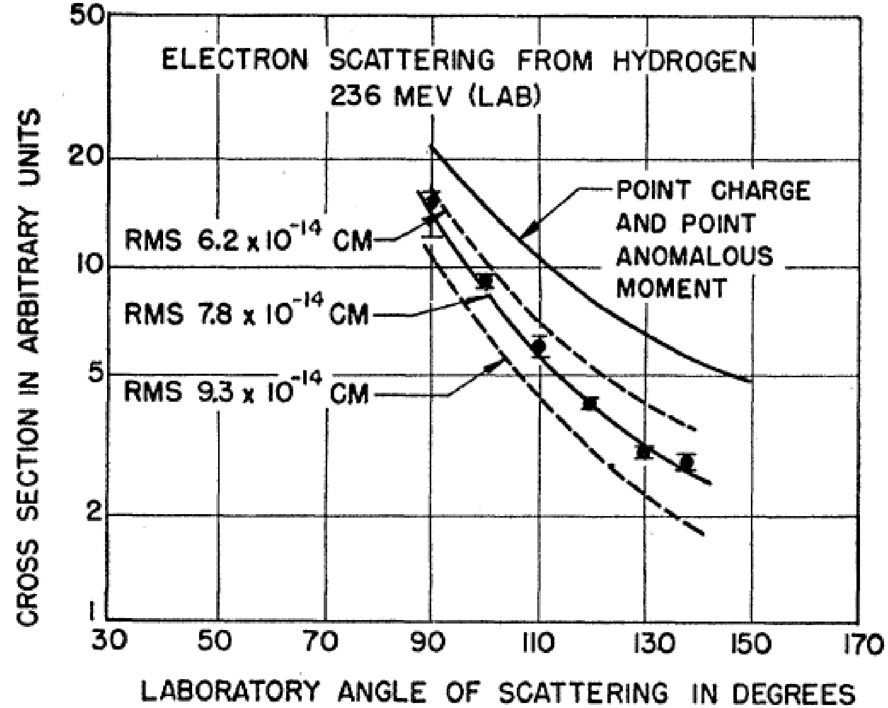
(Received January 25, 1956)





Nobel prize 1961

for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons

Unpolarized and polarized elastic *ep* scattering

The first such measurements were reported in 1956 by Robert Hofstadter.

It was found that both the electric and magnetic form factors are well described by the so-called dipole formula


Robert Hofstadter

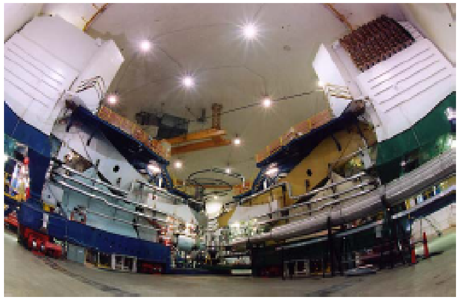
$$G_E(Q^2) = \left(1 + \frac{Q^2}{0.71\ \mathrm{GeV}^2}\right)^{-2}, \quad G_M(Q^2) = \mu\, G_E(Q^2),$$

implying a ratio of $\mu\, G_E/G_M \approx 1$, where $\mu \approx 2.79$ is the proton magnetic moment.

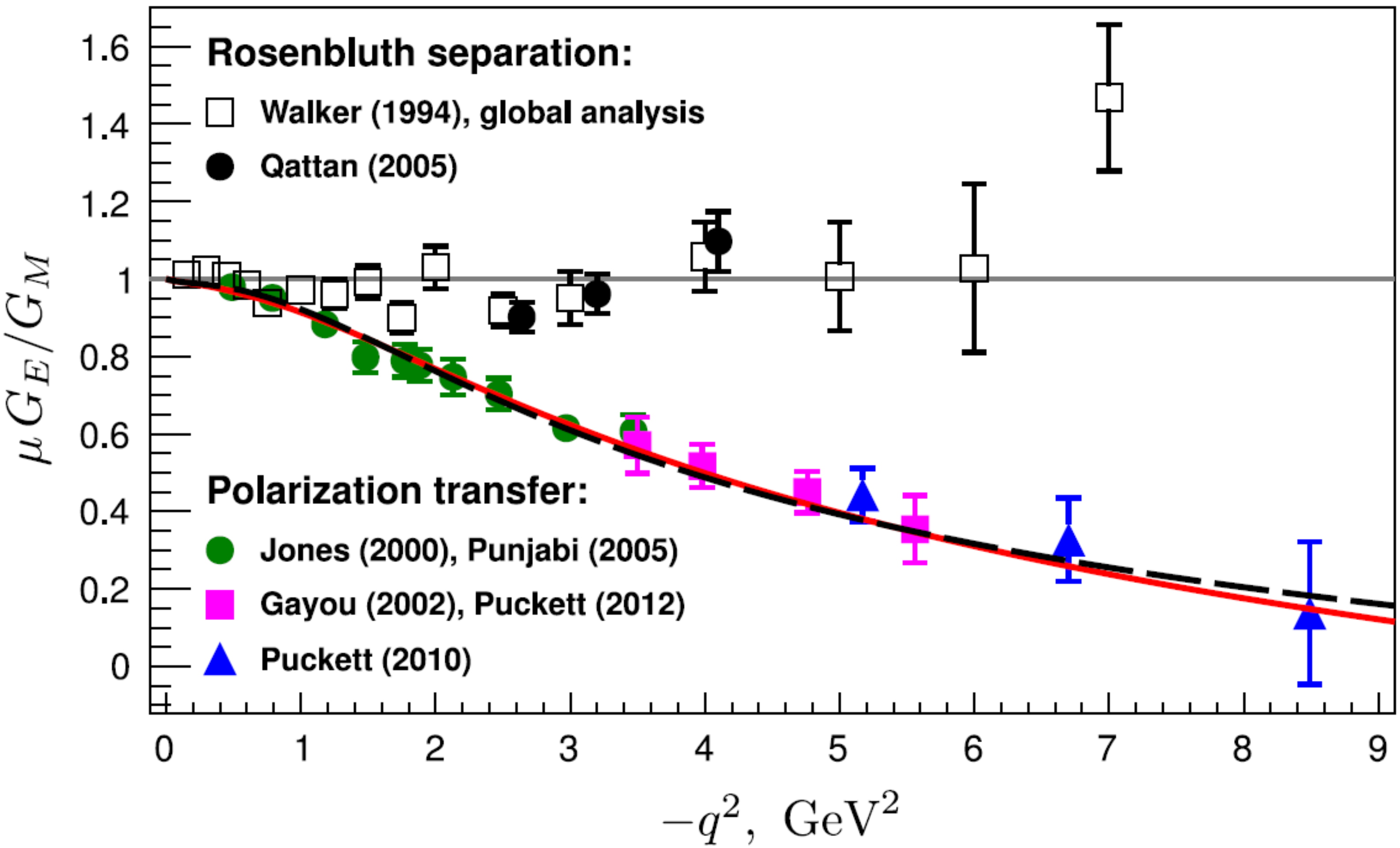
The form factors also can be measured in polarization transfer experiments using $(\vec{e}, e'\vec{p})$ scattering.

In such a case the ratio P_t/P_l of transverse P_t and longitudinal P_l recoil proton polarizations is directly proportional to G_E/G_M:

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{E+E'}{2M}\tan\frac{\theta}{2}$$


Jefferson Lab, Hall A

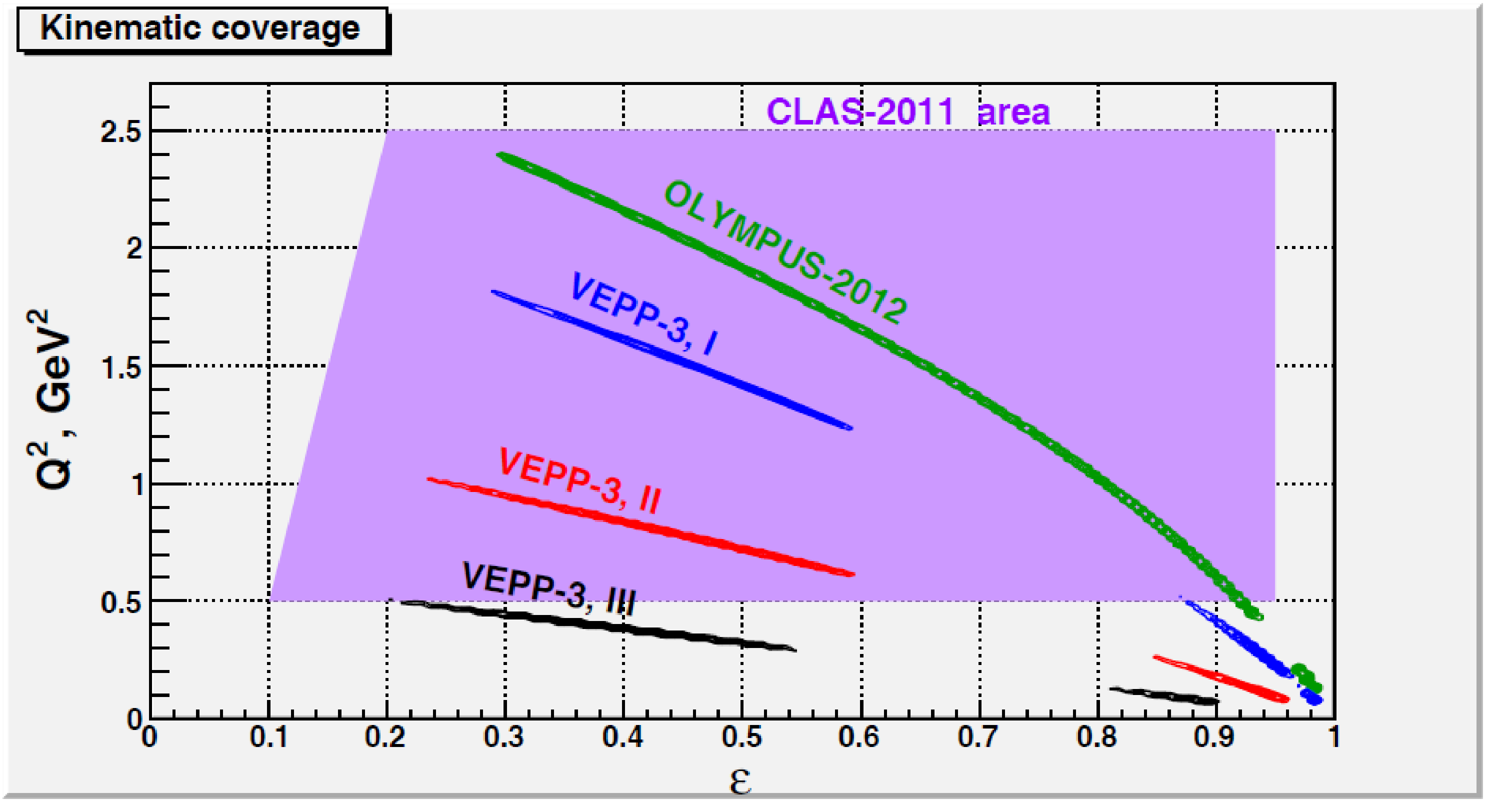
A series of precise measurements of the ratio G_E/G_M for a wide range of Q^2 was carried out recently at Jefferson Lab (USA).



Rosenbluth separation:
Walker (1994), global analysis
Qattan (2005)
Polarization transfer:
Jones (2000), Punjabi (2005)
Gayou (2002), Puckett (2012)
Puckett (2010)
$\mu G_E/G_M$
$-q^2$, GeV^2
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9

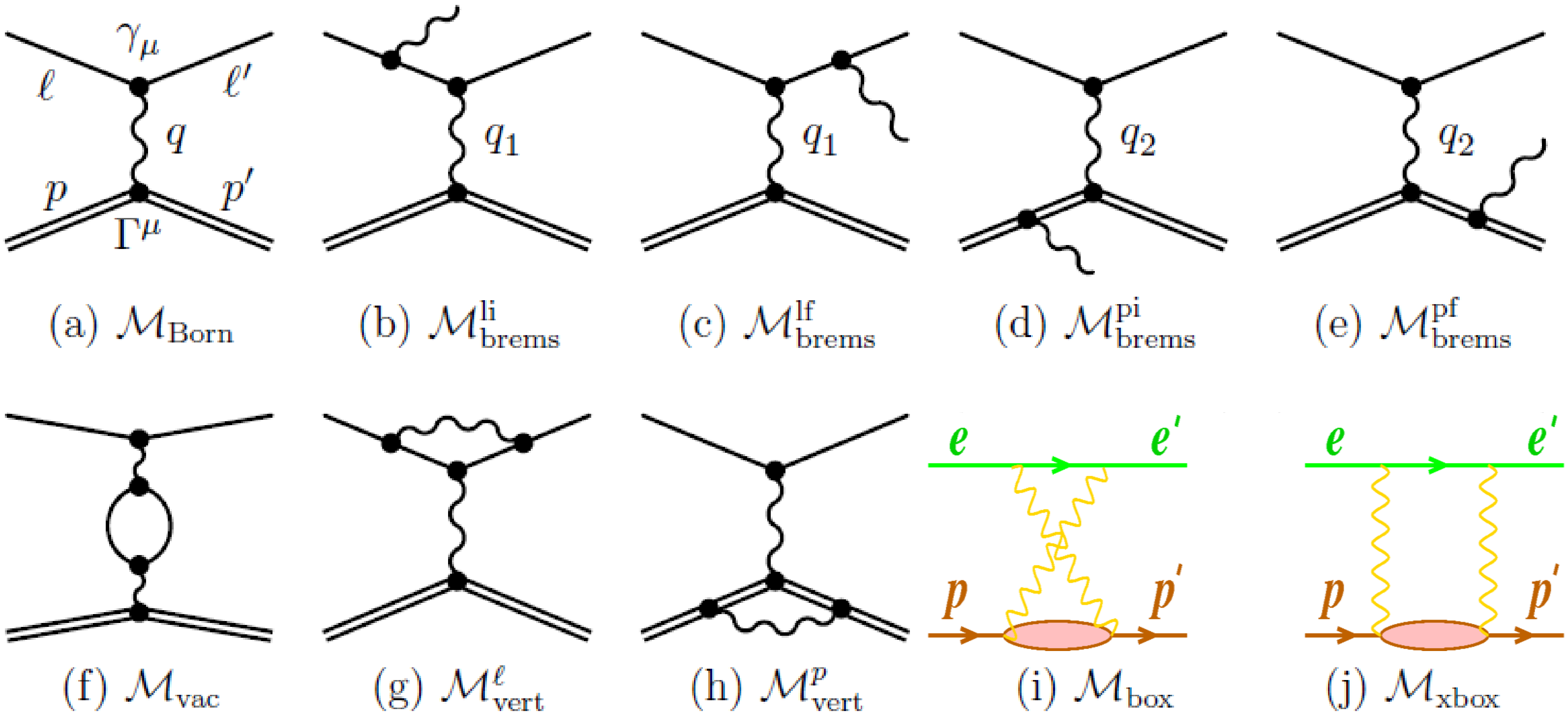
Three experiment to measure two-photon exchange contribution

VEPP-3 (E_{beam} = 1.6, 1, 0.6 GeV)
CLAS@Jlab (E_{beam} = 0.5 - 4 GeV)
OLYMPUS@DESY (E_{beam} = 2 GeV)



$$\varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1}$$

Feynman diagrams representing the elastic scattering of charged leptons on protons in the leading and next-to-leading orders.



The experiment's goal was to measure the ratio of the elastic ***e⁺p*** and ***e⁻p*** scattering cross section in several kinematic regions

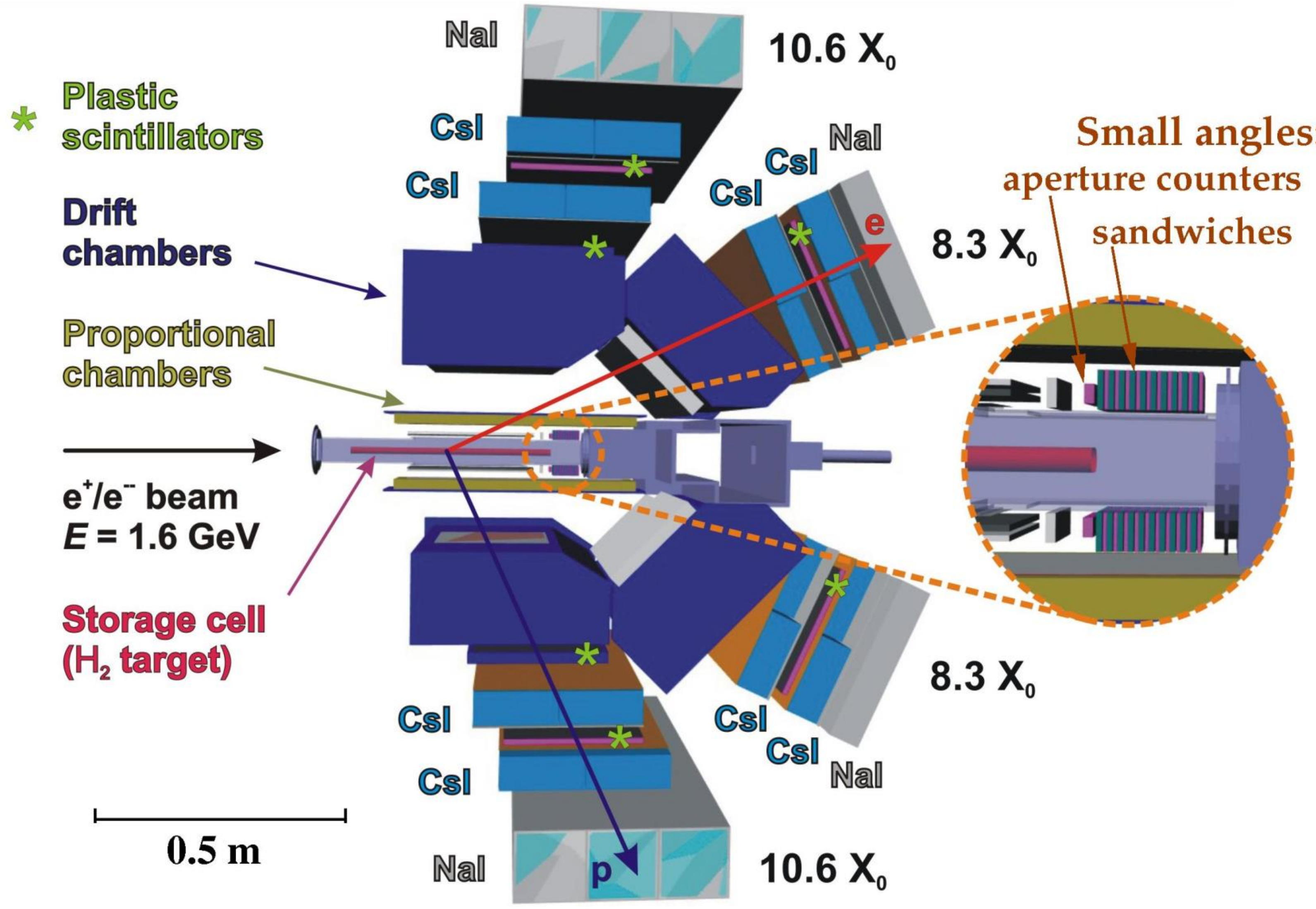
$$R=\sigma(e^+p)/\,\sigma(e^-p)$$

After applying the *standart radiative* corrections the ratio R becomes

$$R_{2\gamma}=\frac{1-\delta_{2\gamma}}{1+\delta_{2\gamma}} \quad \text{where} \quad \delta_{2\gamma}=\frac{2\mathrm{Re}\,(M^{+}_{Born}M^{hard}_{2\gamma})}{|M_{Born}|^2}$$

The events of elastic scattering for ***e+*** or ***e⁻*** *were collected under very similar experimental conditions*. Therefore factors such as the acceptances of the detectors, detection efficiencies, target thickness and beam current integrals could be kept almost the same for the electron–proton and positron–proton scattering.

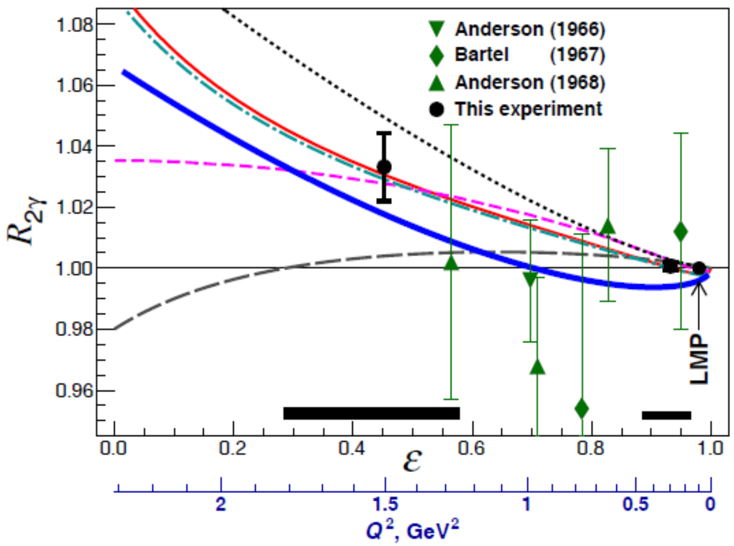
Precise measurements of $\delta_{2\gamma}$ at several kinematic points allow to *test the available theoretical* calculations and help to understand whether the hard TPE effects explain the observed discrepancy between the two methods for measuring the ratio G_E/G_M.



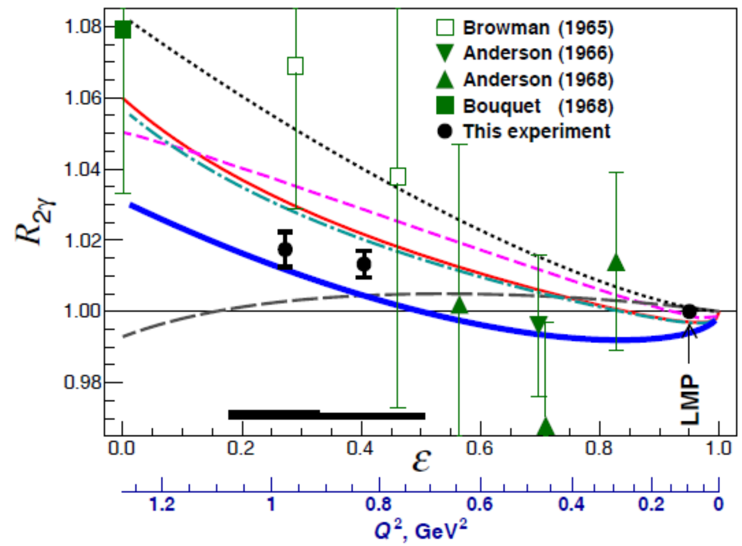
Plastic scintillators
Drift chambers
Proportional chambers
e+/e- beam
E = 1.6 GeV
Storage cell
(H2 target)
NaI
CsI
CsI
NaI
CsI
CsI
10.6 X0
8.3 X0
8.3 X0
10.6 X0
e
p
CsI
CsI
CsI
CsI
NaI
NaI
Small angles:
aperture counters
sandwiches
0.5 m

Results of the Novosibirsk TPE experiment

Run-I (2009):
$E_{\text{beam}} = 1.594$ GeV



Run-II (2011–2012):
$E_{\text{beam}} = 0.998$ GeV



Theoretical predictions:

⋯⋯	*I. A. Qattan, et al.,*	Phys. Rev. C **84** (2011) 054317	:Parametrization
——	*P. G. Blunden, et al.,*	Phys. Rev. C **72** (2005) 034612	:hadronic TPE calculation
–·–·–	*D. Borisyuk and A. Kobushkin,*	Phys. Rev. C **78** (2008) 025208	:dispersion relations
– – –	*E. Tomasi-Gustafsson, et al.,*	Phys. Atom. Nucl. **76** (2013) 937	:“analytical model”
– – –	*J. Arrington and I. Sick,*	Phys. Rev. C **70** (2004) 028203	:Coulomb corrections
——	*J. C. Bernauer, et al.,*	Phys. Rev. C **90** (2014) 015206	:Global *ep* data fit

- *LMP – Luminosity Monitoring Point – set to* $R_{2\gamma} = 1$;
- *error bars are statistical errors, black bands show* ε*-bin width and systematic uncertainties;*
- *the standard radiative corrections are taken into account (according to arXiv:1401.2959).*

M. MOTEABBED *et al.* PHYSICAL REVIEW C **88, 025210 (2013)**

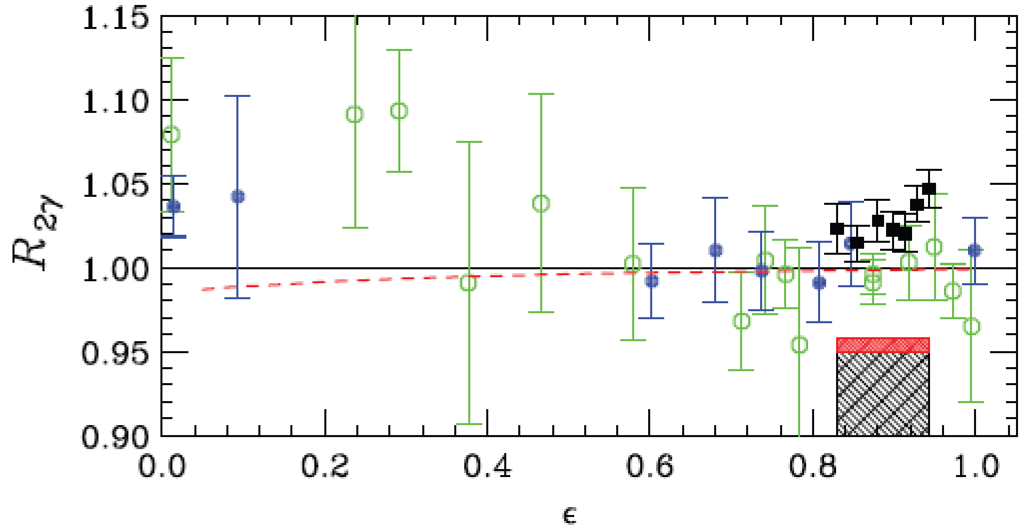


FIG. 13. (Color online) Ratio *R2γ overlaid on the world data.*
Black filled squares are from this experiment at *Q2 = 0.206 GeV2*
and have had radiative corrections applied, filled circles (blue online)
are previousworld data at similar*Q2, and hollowpoints (green online)*
are the rest of the previous world data with *Q2 < 2 GeV2 [29].*
The **densely shaded band (red online) indicates the point-to-point** systematic uncertainty (1*σ) and the* ***black shaded band represents the*** **scale-type systematic uncertainty (due to relative luminosity)** on the present data. The dashed curve (red online) is the BMT calculation [51] at *Q2 = 0.2 GeV2.*

TABLE I. Different contributions to the systematic uncertainty of $R_{2\gamma}$ (in %).

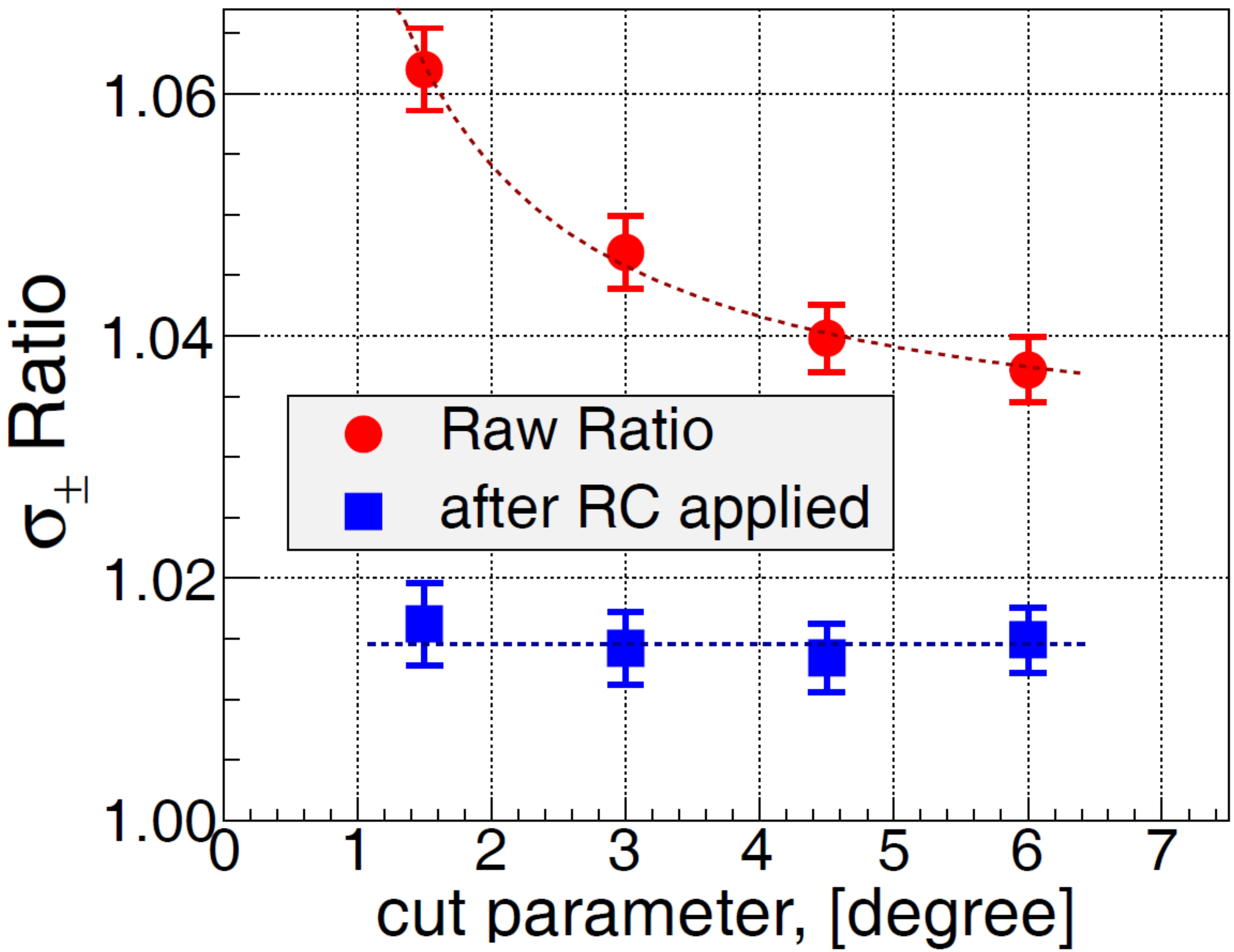
	Run-I		Run-II	
Kinematics	#1	#2	#3	#4
Variations of beam energy	0.027	0.018	0.017	0.017
Variations of beam position	0.162	0.172	0.040	0.056
Variations of detection efficiency	0.085	0.085	0.061	0.061
Background subtraction	0.140	0.001	0.070	0.050
Accuracy of the cut parameters	0.224	0.050	0.166	0.069
Radiative corrections	0.090	0.050	0.130	0.040
Total uncertainty $\Delta R_{2\gamma}^{syst}$	0.33	0.21	0.23	0.13

TABLE II. Experimental results for the ratio $R_{2\gamma}$.

	Run-I			Run-II		
Kinematics	#1	#2	LNP	#3	#4	LNP
E_{beam}, GeV	1.594	1.594	1.594	0.998	0.998	0.998
$\varepsilon_{\min}$	0.29	0.89	0.96	0.18	0.33	0.88
$\varepsilon_{\max}$	0.58	0.97	0.99	0.33	0.51	0.97
$\langle\varepsilon\rangle$	0.452	0.932	0.980	0.272	0.404	0.931
$\langle Q^2\rangle$, GeV^2	1.51	0.298	0.097	0.976	0.830	0.128
$\langle\theta_e\rangle$	66.2°	20.8°	11.4°	91.3°	75.4°	21.4°
$R_{2\gamma}$	1.0332	1.0007	1	1.0174	1.0133	1
$\Delta R_{2\gamma}^{\text{stat}}$	±0.0112	±0.0012	—	±0.0049	±0.0037	—
$\Delta R_{2\gamma}^{\text{syst}}$	±0.0033	±0.0021	—	±0.0023	±0.0013	—

TABLE III. Comparison of the experimental results with several theoretical predictions.

	$R_{2\gamma}$ at LMP		$\chi^2/n_{\text{d.f.}}$		
Prediction	Run-I	Run-II	Run-I	Run-II	Total
Bernauer, et al. [31]	0.997	0.995	1.04	1.25	1.15
Borisyuk & Kobushkin [28]	0.999	0.999	0.27	6.92	3.60
Blunden, et al. [26, 27]	0.999	0.999	0.28	8.76	4.52
Tomasi-Gustafsson, et al. [29]	1.001	0.999	3.70	7.30	5.50
Arrington & Sick [25]	1.001	1.002	0.87	15.16	8.02
Qattan, et al. [30]	1.002	1.006	1.17	40.17	20.67



$$\pi - \Delta < |\phi_e - \phi_p| < \pi + \Delta \text{ and } |\theta_p - \theta_p^*| < \Delta,$$

Two experiments have come up with two wildly different values for the proton's radius.

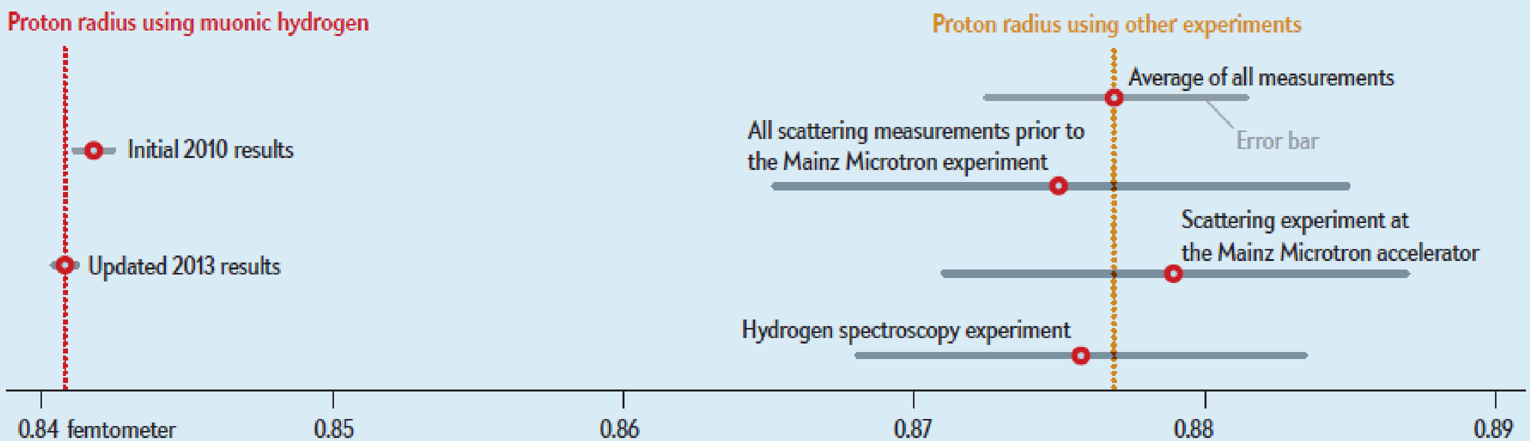
What's going on?

By Jan C. Bernauer and Randolf Pohl

RESULTS

The Incompatible Measurements

The size of the proton should stay the same no matter how one measures it. Laboratories have deduced the proton radius from scattering experiments [*see box on opposite page*] and by measuring the energy levels of hydrogen atoms in spectroscopy experiments. These results were all consistent to within the experimental error. But in 2010 a measurement of the energy levels of so-called muonic hydrogen [*see box on page 38*] found a significantly lower proton radius. Attempts to explain the anomaly have so far failed.



SOURCE: RANDOLF POHL