Recent results from MAMI

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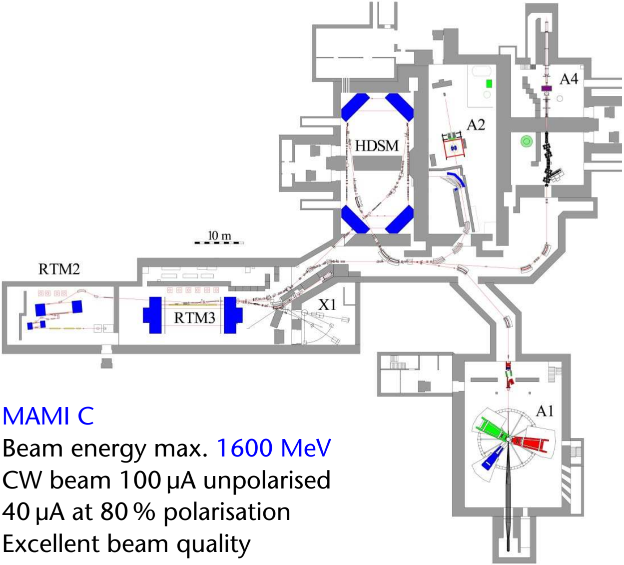
The Mainz Microtron MAMI



MAMI C

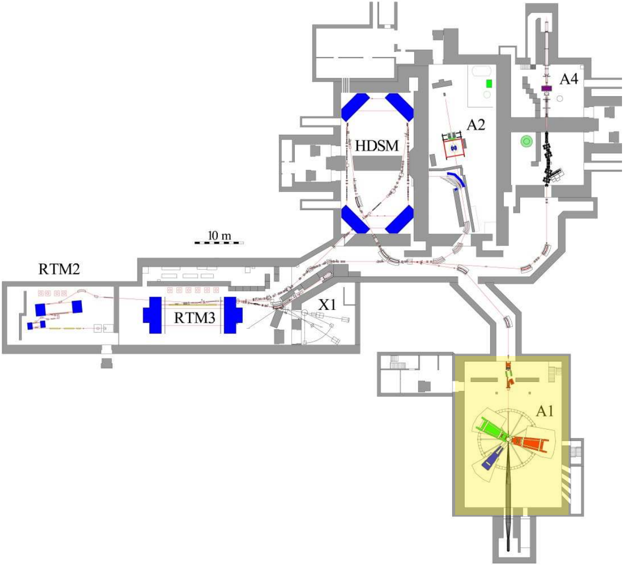
Beam energy max. 1600 MeV

CW beam 100 μA unpolarised

40 μA at 80 % polarisation

Excellent beam quality

A1: Electron scattering



Three-spectrometer setup of the A1 collaboration

Spectrometer A:

$$\begin{aligned}\alpha &> 20^\circ \\ p &< 735\,\text{MeV}/c \\ \Delta\Omega &= 28\,\text{msr} \\ \Delta p/p &= 20\%\end{aligned}$$

Spectrometer B:

$$\begin{aligned}\alpha &> 8^\circ \\ p &< 870\,\text{MeV}/c \\ \Delta\Omega &= 5.6\,\text{msr} \\ \Delta p/p &= 15\%\end{aligned}$$

Spectrometer C:

$$\begin{aligned}\alpha &> 55^\circ \\ p &< 655\,\text{MeV}/c \\ \Delta\Omega &= 28\,\text{msr} \\ \Delta p/p &= 25\%\end{aligned}$$

Nucleon form factors

Elastic electron scattering: Cross section and form factors

Cross section:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \cdot \frac{\epsilon G_E^2(Q^2) + \tau G_M^2(Q^2)}{\epsilon\,(1+\tau)}$$

with:

$$\tau = \frac{Q^2}{4m_p^2}, \qquad \epsilon = \left(1 + 2\,(1+\tau)\tan^2\frac{\theta_e}{2}\right)^{-1}$$

Fourier transform of G_E, G_M → spatial distribution (Breit frame)

Electric and magnetic radius:

$$\langle r_E^2 \rangle = -6\hbar^2 \left.\frac{dG_E}{dQ^2}\right|_{Q^2=0} \qquad \langle r_M^2 \rangle = -6\hbar^2 \left.\frac{d(G_M/\mu)}{dQ^2}\right|_{Q^2=0}$$

Proton form factors: Motivation

Form factors from elastic ep scattering

Two classes of experimental methods:

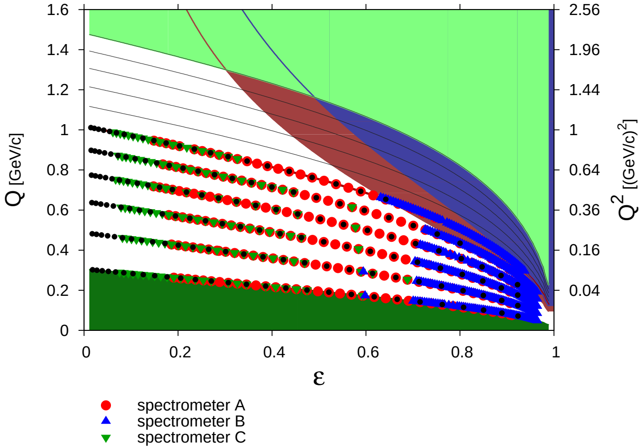
- Unpolarised scattering: "Rosenbluth separation"
  Separated $G_E(Q^2)$ and $G_M(Q^2)$,
  but contribution from two photon exchange (TPE)
- Polarised scattering:
  - polarised electrons scattered from polarised targets
  - polarisation transfer from electron to nucleon

  Only ratio $G_E(Q^2)/G_M(Q^2)$,
  little contribution from two photon exchange (TPE)?

As always in physics: What accuracy can be reached?

Proton form factor: Measured settings

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \cdot \frac{\epsilon G_E^2(Q^2) + \tau G_M^2(Q^2)}{\epsilon\,(1+\tau)}$$

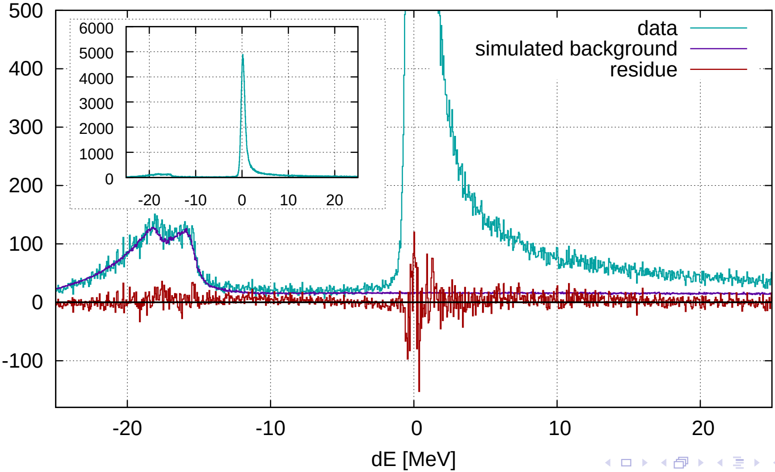


- ~1400 settings
- $> 10^9$ events

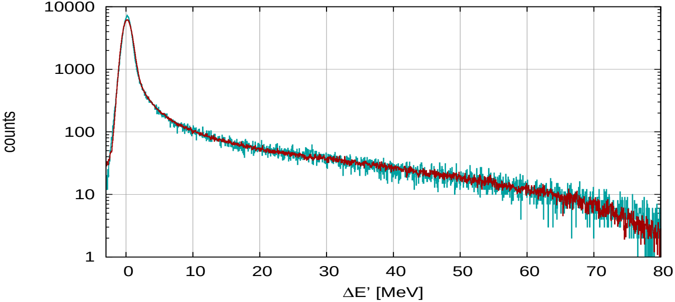
Background subtraction

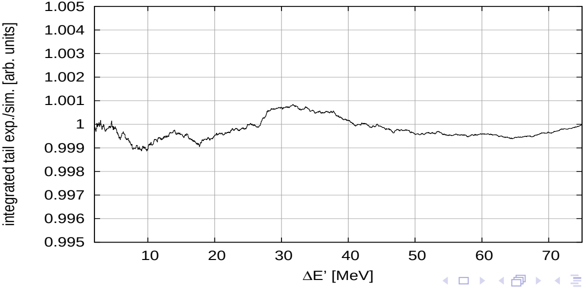
Simulation:

- Background from elastic and quasi-elastic scattering at target walls
- Model for energy loss and small angle scattering
- Input: momentum-, angular-, vertex resolution

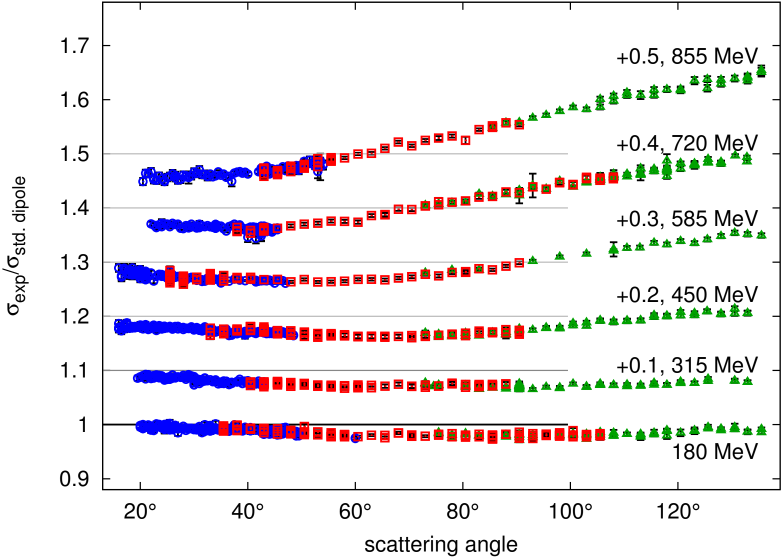


Description of the radiative tail





Cross sections / standard dipole



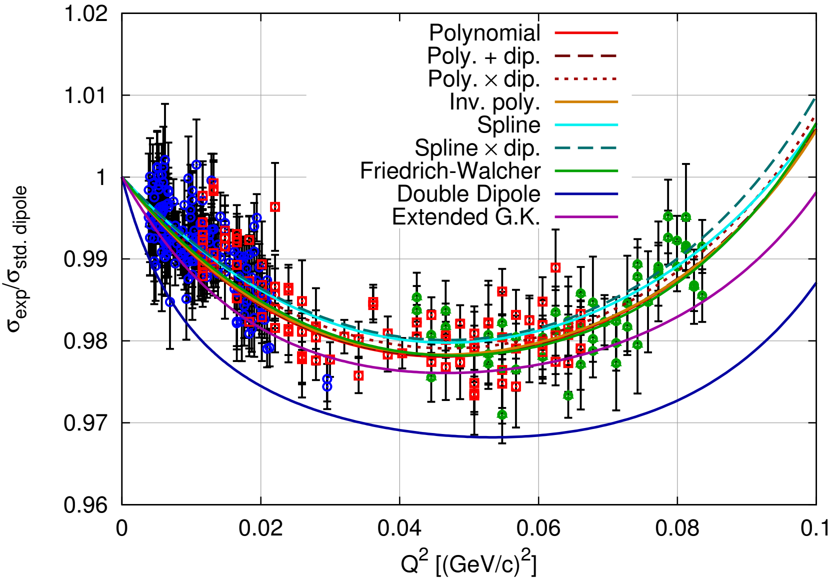
Extraction of form factors

1. Traditionally: Rosenbluth separation at constant Q^2
2. "Super-Rosenbluth Separation":
   fit of form factor models directly to the cross sections
   - Feasible due to fast computers
   - All data at all Q^2 and ϵ values contribute to the fit
     no projection to constant Q^2 $\Rightarrow$ no limit of kinematics
   - Easy fixing of normalisation
   - Model dependence?

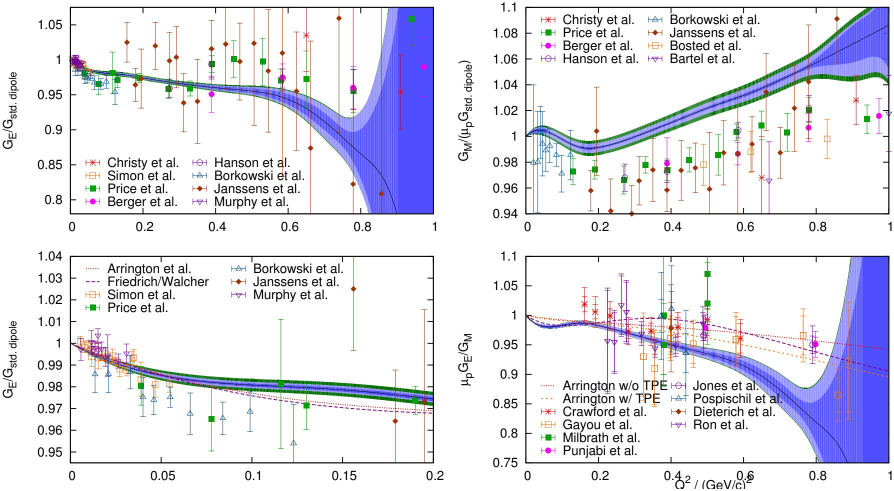
For extraction of radii: Need a fit anyway!

Classical Rosenbluth: Extracted G_E and G_M highly correlated
$\Rightarrow$ Error propagation very involved

Cross sections: 180 MeV



Form factor results



Jan C. Bernauer *et al.*, “High-precision determination of the electric and magnetic form factors of the proton”, PRL 105 (2010) 242001, arXiv:1007.5076

Radii of the proton from electron scattering

MAMI result with Coulomb correction (McKinley and Feshbach):

$$\begin{aligned}\langle r_E^2\rangle^{1/2} &= 0.879 \pm 0.005_{\mathrm{stat.}} \pm 0.004_{\mathrm{syst.}} \pm 0.002_{\mathrm{mod.}} \pm 0.004_{\mathrm{grp}}\ \mathrm{fm}\\ \langle r_M^2\rangle^{1/2} &= 0.777 \pm 0.013_{\mathrm{stat.}} \pm 0.009_{\mathrm{syst.}} \pm 0.005_{\mathrm{mod.}} \pm 0.002_{\mathrm{grp}}\ \mathrm{fm}\end{aligned}$$

PRL 105 (2010) 242001

MAMI result with TPE correction (Borisyuk and Kobushkin):

$$\begin{aligned}\langle r_E^2\rangle^{1/2} &= 0.876 \pm 0.005_{\mathrm{stat.}} \pm 0.004_{\mathrm{syst.}} \pm 0.002_{\mathrm{mod.}} \pm 0.004_{\mathrm{grp}}\ \mathrm{fm}\\ \langle r_M^2\rangle^{1/2} &= 0.803 \pm 0.013_{\mathrm{stat.}} \pm 0.009_{\mathrm{syst.}} \pm 0.005_{\mathrm{mod.}} \pm 0.002_{\mathrm{grp}}\ \mathrm{fm}\end{aligned}$$

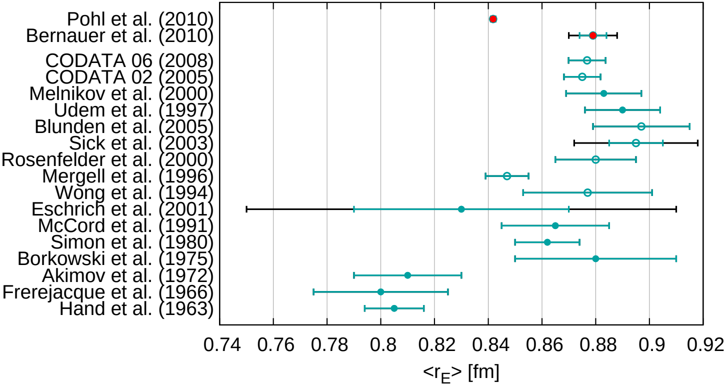
PRL 107 (2011) 119102

Magnetic radius from hyperfine splitting in hydrogen:

$$\langle r_M^2\rangle^{1/2} = 0.778(29)\ \mathrm{fm}$$

A. V. Volotka, V. M. Shabaev, G. Plunien, G. Soff: EPJ D 33 (2005) 23

Overview of different proton charge radius results



Filled circles: results from new measurements

Hollow circles: reanalysis of existing data

→ Talks by: S. Dubnicka (thursday)
I. Sick (friday)

Electric form factor of the neutron

Problem:

- No free neutron target available
- G_E^n small compared to G_M^n
  Rosenbluth separation gives large errors:

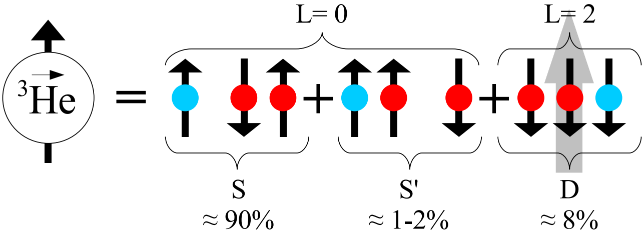
$$\frac{d\sigma}{d\Omega} \propto aG_E^2(Q^2) + bG_M^2(Q^2)$$

Solution:

Double polarisation experiments on ^{2}H or ^{3}He

- $^2\mathrm{H}(\vec{e}, e'\vec{n})$
- $^3\vec{\mathrm{He}}(\vec{e}, e'n)$

Double polarisation experiments on ^{3}He



Beam target asymmetry:

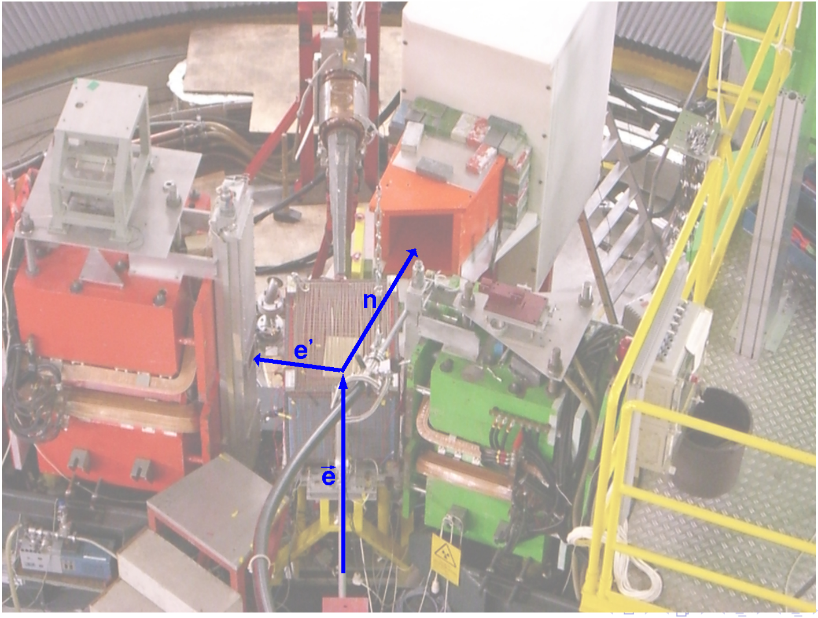
$$A = \frac{N(\uparrow\uparrow) - N(\uparrow\downarrow)}{N(\uparrow\uparrow) + N(\uparrow\downarrow)}$$

$$= \mathcal{P}_e \mathcal{P}_n \frac{a G_E^n G_M^n \sin\theta + b {G_M^n}^2 \cos\theta}{c {G_E^n}^2 + d {G_M^n}^2}$$

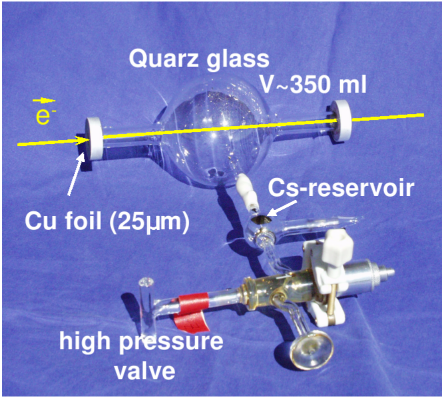
Ratio of asymmetries:

$$\frac{A(\theta = 90^\circ)}{A(\theta = 0^\circ)} = \frac{A_\perp}{A_\parallel} = \frac{a}{b} \frac{G_E^n}{G_M^n}$$

2008 measurement: G_E^n at $Q^2 \approx 1.5\,(\mathrm{GeV}/c)^2$



Polarised ^{3}He target



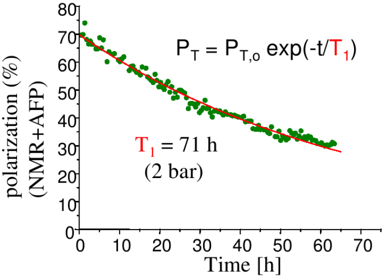
Change of the target cell
every 12 hours

J. Krimmer et al., NIM 611 (2009) 18

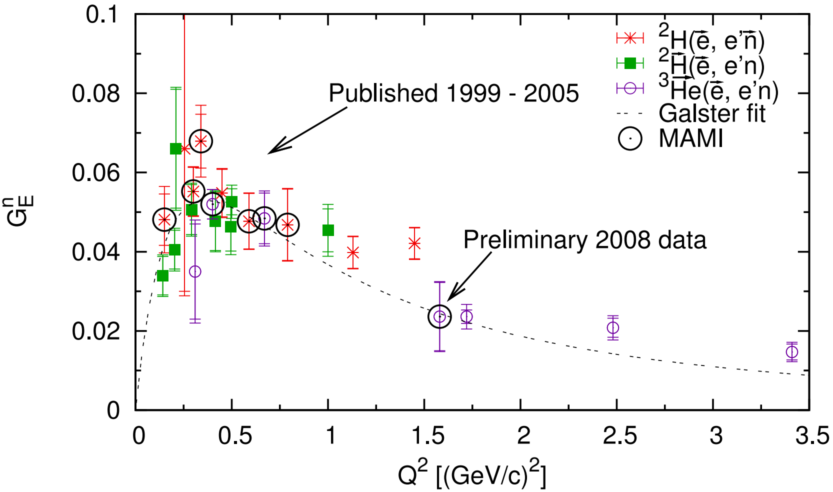
Relaxation due to

- surfaces
- pressure (5 bar)
- field gradients
- electron beam

$\rightarrow T_1 \sim 45$ h

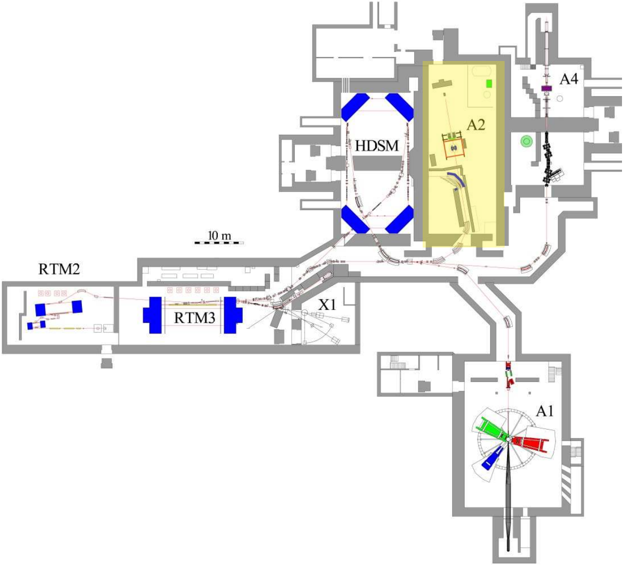


G_E^n from double polarisation experiments

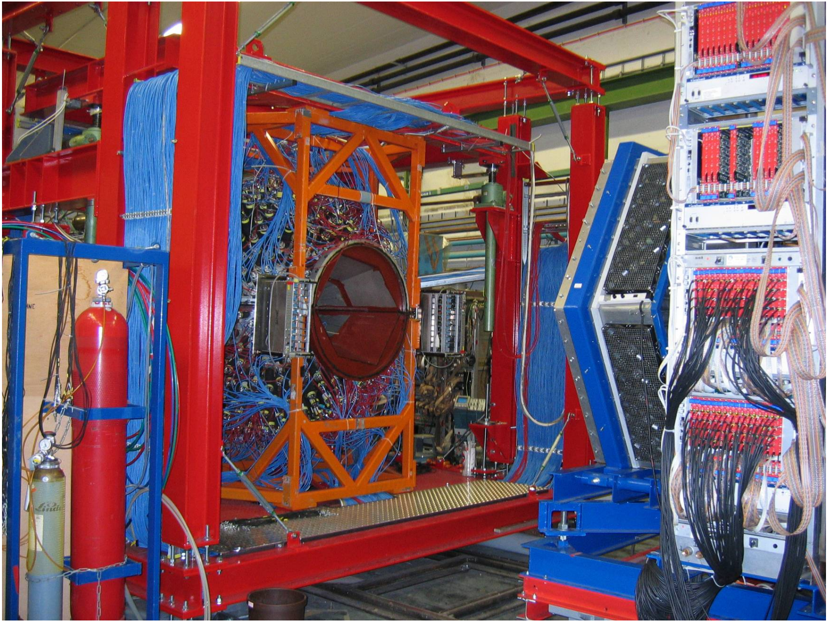


S. Schlimme: PhD thesis, Mainz (2011)

A2: Real photon experiments

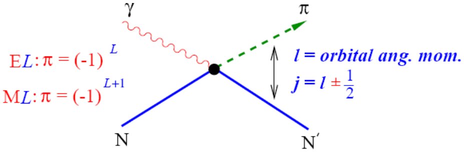


A2: Crystal Ball / TAPS



π^0 photoproduction near threshold

Test of LETs



Close to threshold only s and p waves contribute:

$l = 0$	E_{0+}	s wave
$l = 1$	M_{1+}, M_{1-}, E_{1+}	p waves

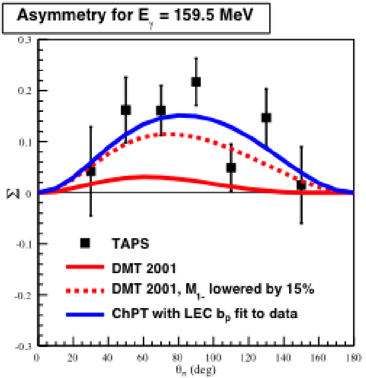
so that

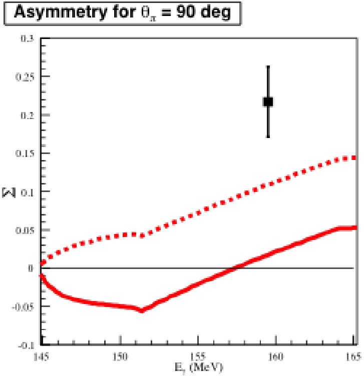
$$\frac{d\sigma}{d\Omega}(k, \theta) = \frac{q}{k}[A + B\cos\theta + C\cos^2\theta]$$

where A, B, and C are functions of E_{0+}, M_{1+}, M_{1-}, and E_{1+}

π^0 photoproduction near threshold

Previous data





A. Schmidt et al., PRL 87 (2001) 232501

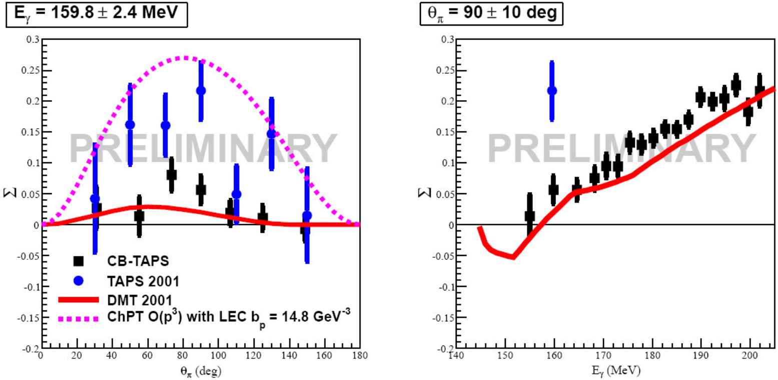
S. Kamalov et al., PR C 64 (2001) 032201

V. Bernard et al., EPJ A 11 (2001) 209

Discrepancy with DMT prediction?

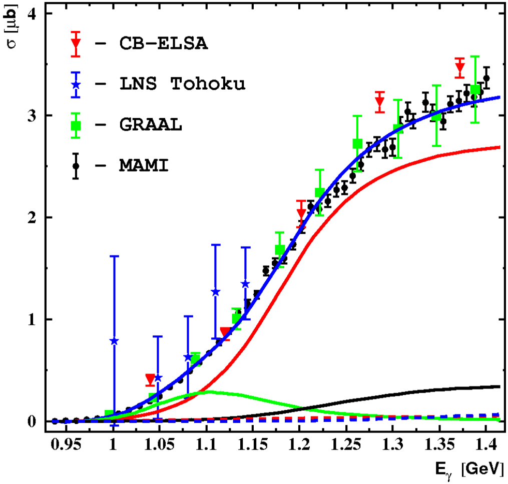
π^0 photoproduction near threshold

CB/TAPS 2008 data



- CB/TAPS 2008: Much better statistics
- Subtraction of target window contributions
- Energy dependence of Σ
- New fit of multipoles under way, publication in preparation

$\gamma p \to \pi^0 \eta p$ cross section



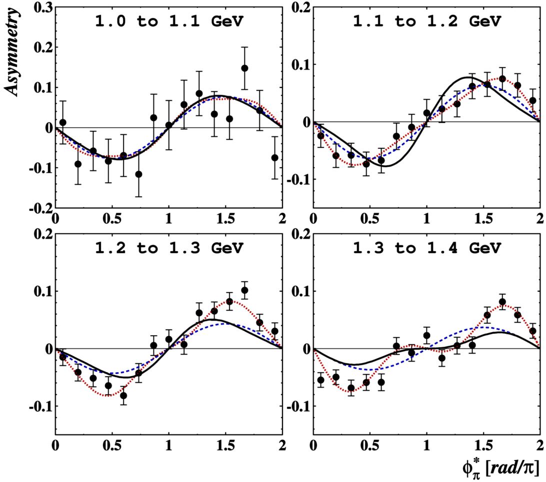
- Blue line: best fit with
  $D_{33}(1700)$,
  $P_{33}(1600)$,
  $P_{31}(1750)$,
  $F_{35}(1905)$,
  and Born terms
- Partial contributions:

Red line:	$D_{33}(1700)$
Green line:	$P_{33}(1600)$
Black line:	$P_{31}(1750)$
Dashed red line:	$F_{35}(1905)$
Dashed blue line:	Born terms

⇒ Dominated by $D_{33}(1700)$

V. Kashevarov et al., EPJ A 42 (2009) 141
A. Fix et al., EPJ A 36 (2008) 61

$\gamma p \rightarrow \pi^0 \eta p$ beam helicity asymmetry



Dotted red line:

Fourier fit (3 terms)

Dashed blue line:

$D_{33}(1700)$ only

Black line:

Isobar model, 6 resonances (A. Fix et al.)

Phys. Lett. B 693 (2010) 551

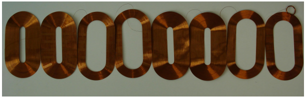
More spin observables will be measured (T and F, pol. beam and pol. target)

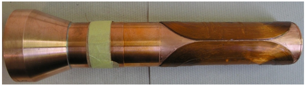
Polarized frozen spin target for Crystal Ball

Frozen spin target in operation since beginning of 2010

^{3}He-^{4}He dilution refrigerator (Mainz / JINR Dubna)
Material: Butanol, polarisation $> 90\,\%$
$\sim$ 1000 hours relaxation time & low He consumption
Running with transverse polarised target!

Now: D-Butanol, $P = 75\,\%$, $t_R \sim 1300\,\mathrm{h}$ (Bochum)





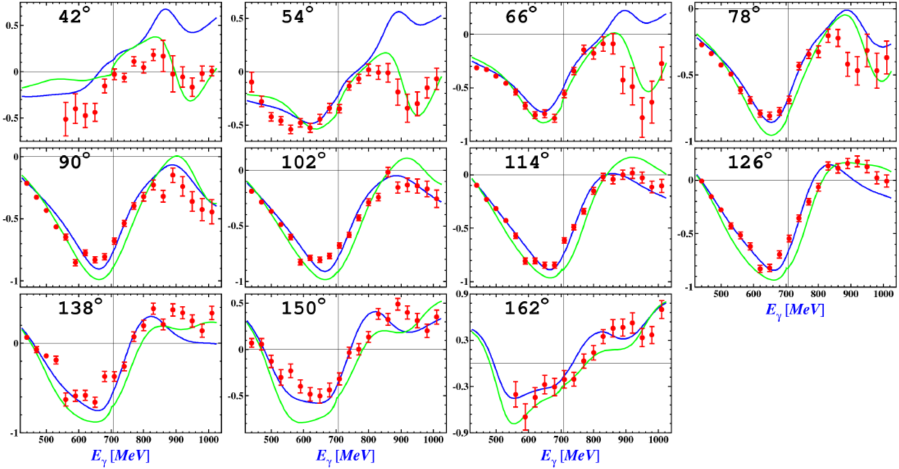
First measurement of transverse spin observable F in $\gamma\vec{p} \rightarrow \pi^0 p$

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{unpol}} \Big[1 - P_\gamma^{\text{lin}} \Sigma(\theta)\cos(2\phi) \\ + P_x \left[-P_\gamma^{\text{lin}} H(\theta)\sin(2\phi) + P_\gamma^{\text{circ}} F(\theta)\right] \\ + P_y \left[-T(\theta) + P_\gamma^{\text{lin}} P(\theta)\cos(2\phi)\right] \\ + P_z \left[-P_\gamma^{\text{lin}} G(\theta)\sin(2\phi) + P_\gamma^{\text{circ}} E(\theta)\right]\Big]$$

- T asymmetry: transverse polarised target
- F asymmetry: circular polarised photons, transverse polarised target
- Need to separate contribution from ^{12}C, ^{16}O (Butanol), and $^{3/4}$He

$\vec{\gamma}\vec{p} \rightarrow \pi^0 p$ preliminary results

Transverse target asymmetry T

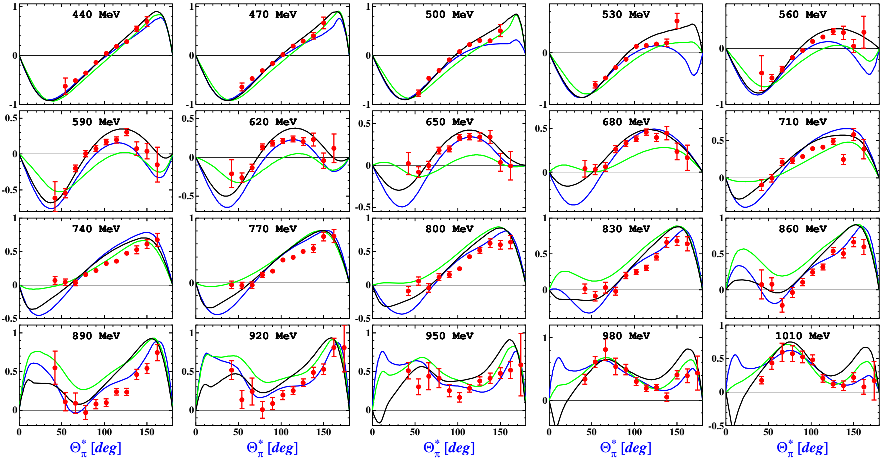


Blue line – MAID 2007

Green line – SAID

$\vec{\gamma}\vec{p} \to \pi^0 p$ preliminary results

Double polarisation observable F

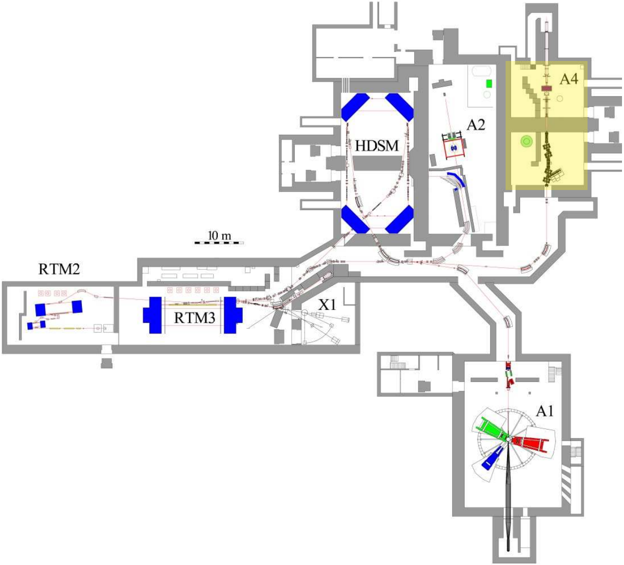


Blue line – MAID 2007

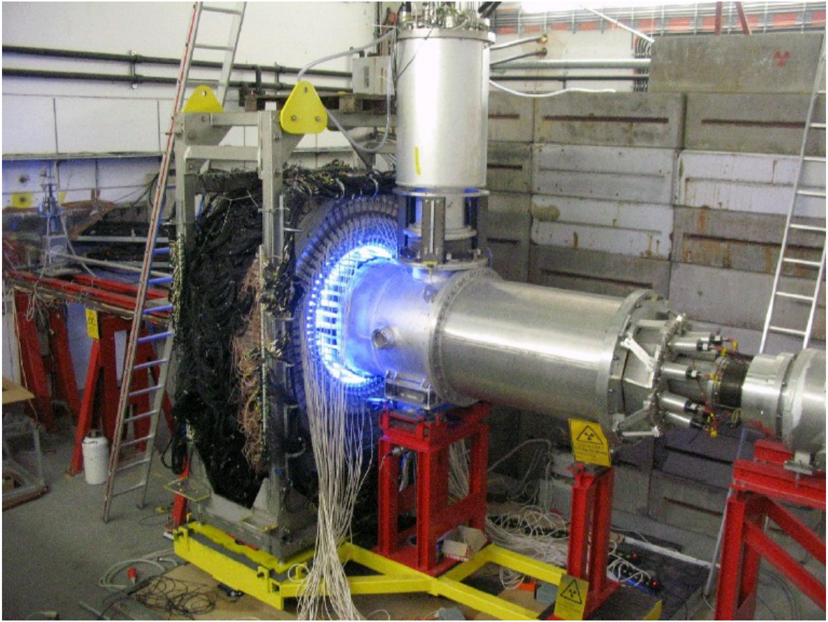
Green line – SAID

Black line – BG 2010-02

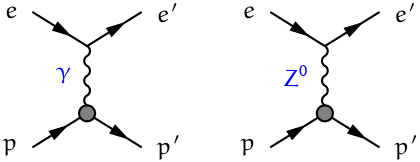
A4: Strangeness in the nucleon



A4: Lead flouride calorimeter



Parity violation asymmetry



$$\sigma \propto \left| \frac{j_{\gamma,\mu}\langle J^{\mu}_{\gamma}\rangle}{q^2} + \frac{j_{Z,\mu}\langle J^{\mu}_{Z}\rangle}{M_Z^2} \right|^2$$

$$A_{RL} = A_0 + A_S \quad \text{with} \quad A_S = a\rho'_{eq}\frac{\epsilon G_E^p G_E^s + \tau G_M^p G_M^s}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}$$

$$A_{RL} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx 10^{-5}$$

- $A_0 = A_V + A_A$: can be calculated in Standard Model
- A_{RL}: can be measured

⇒ Strangeness contribution A_S can be determined in experiment

Measurement of strangeness form factors

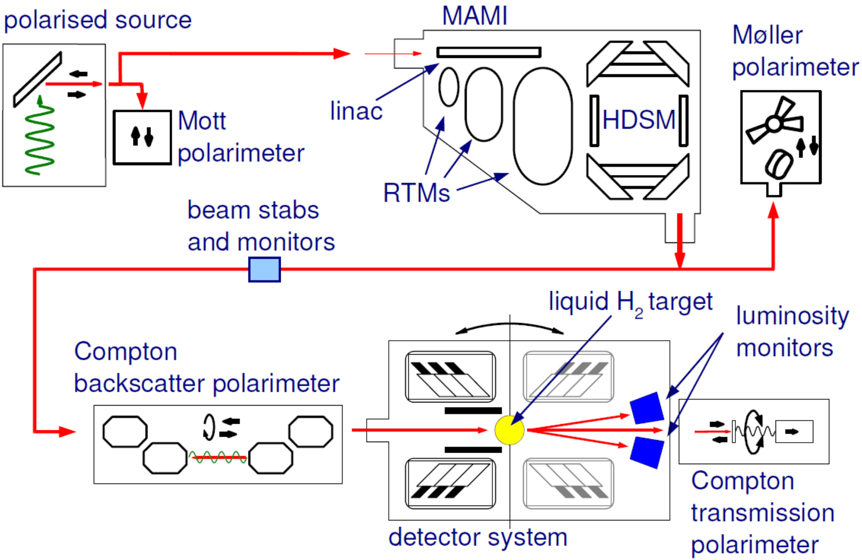
Three quantities to be measured:

- G_E^s, G_M^s: strangeness contribution
- G_A: (isoscalar) axial form factor, large electroweak corrections

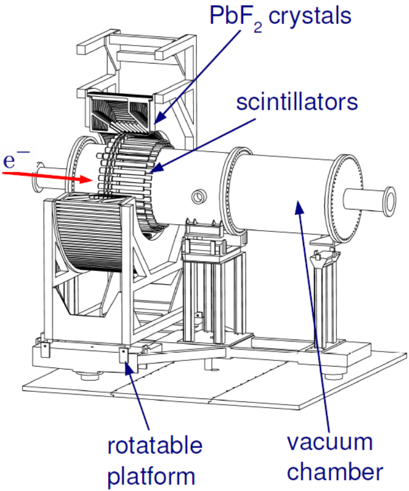
For one specific four-momentum transfer Q^2:
at least *three* measurements

Scattering experiment	sensitive to
$e + p$ elastic, forward angle	G_E^s and G_M^s
$e + p$ elastic, backward angle	G_M^s and G_A
$e + d$ quasi-elastic, backward angle	G_M^s and G_A
$e + {}^4$He elastic, forward angle	G_E^s

Setup of the A4 experiment



A4: Lead flouride calorimeter



PbF_2 calorimeter:

- pure Cherenkov radiator
- count rate: 100 MHz
- acceptance: 0.6 sr

  (30° to 40° or 140° to 150°)
- 1022 crystals in 7 rings
- fully absorbing

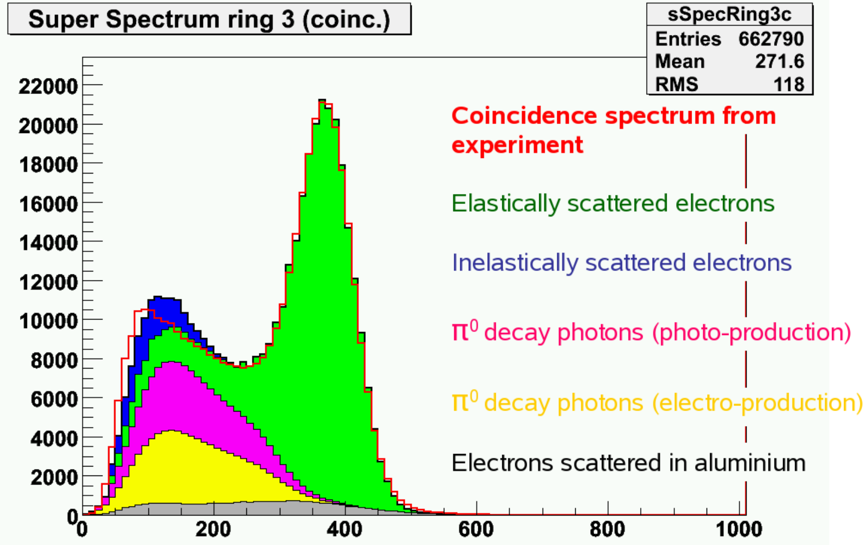
Electron tagger (backward):

- 72 plastic scintillators

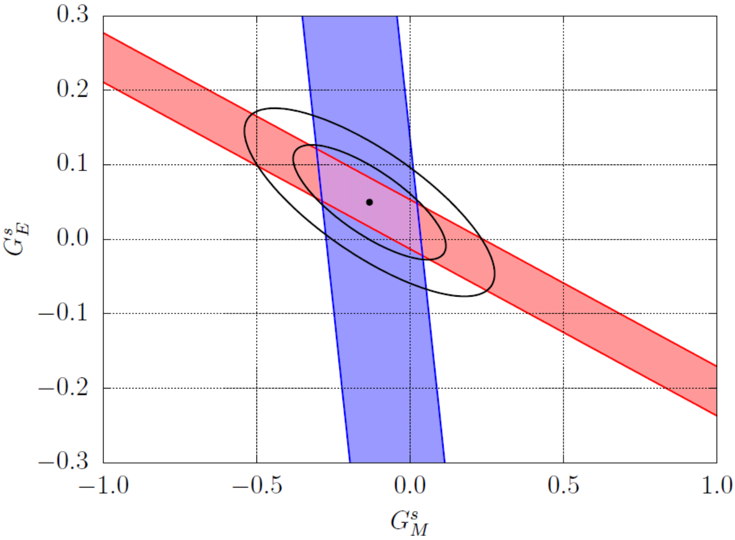
A4: Energy spectrum

Comparison with Monte Carlo simulation

Backward angle (315 MeV)



A4: Strangeness form factor at $Q^2 = 0.23\,(\mathrm{GeV}/c)^2$

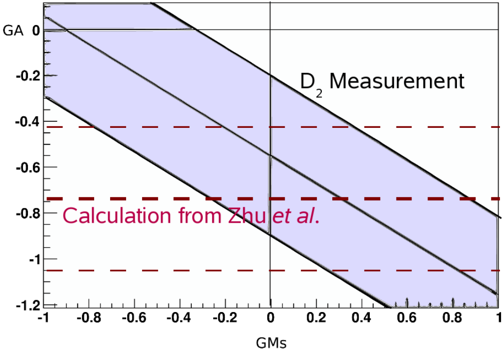


$$
\begin{aligned}
G_E^s &= 0.050 \pm 0.042 (\pm 0.038_{\mathrm{exp}} \pm 0.019_{\mathrm{FF}}) \\
G_M^s &= -0.14 \quad \pm 0.16 \quad (\pm 0.11_{\mathrm{exp}} \quad \pm 0.11_{\mathrm{FF}} \quad)
\end{aligned}
$$

A4: Measurement under backward angle (D_2)

Asymmetry in quasi-elastic ed scattering:

$A = (-20.76 \pm 0.96_{\text{stat}} \pm 0.76_{\text{syst}})$ ppm
(preliminary, but including all corrections)



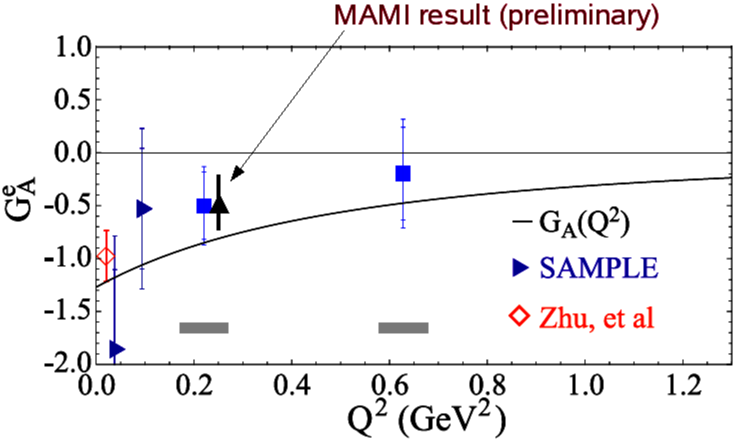
Preliminary result:

$G_A + 0.61\, G_M^s = -0.55 \pm 0.35$

Experiment:	$G_A = -0.47 \pm 0.31$
Zhu et al.:	$G_A = -0.77 \pm 0.35$

A4: Axial form factor (H_2 / D_2)

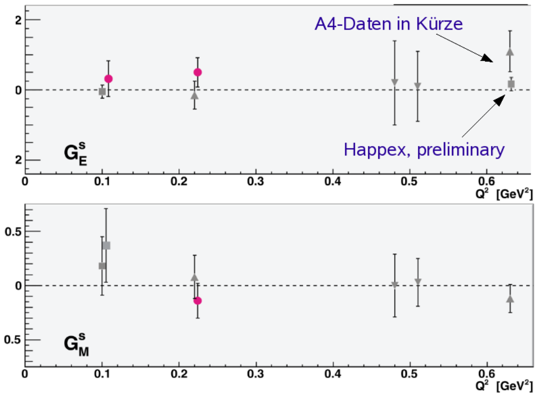
Comparison with G0 results:



Phys.Rev.Lett. 104 (2010) 012001

Strangeness form factors: World data

(At least two measurements at same Q^2)



A4 measurements:

H_2, $Q^2 = 0.23\,(\mathrm{GeV/c})^2$ forward
H_2, $Q^2 = 0.11\,(\mathrm{GeV/c})^2$ backward
H_2, $Q^2 = 0.23\,(\mathrm{GeV/c})^2$ backward
D_2, $Q^2 = 0.23\,(\mathrm{GeV/c})^2$ backward
H_2, $Q^2 = 0.62\,(\mathrm{GeV/c})^2$ forward

Summary

A1: Electron scattering

- High precision electron proton scattering data from MAMI
  Q^2 range from 0.003 to 1 $(\mathrm{GeV}/c)^2$
- Data point for G_E^n with polarised ^{3}He at $Q^2 \approx 1.5\,(\mathrm{GeV}/c)^2$

A2: Real photon experiments

- New data for π^0 threshold photoproduction
  Photon asymmetry Σ consistent with DMT model
- $\gamma p \rightarrow \pi^0 \eta p$, dominated by $D_{33}(1700)$
- First measurement of transverse spin observable F in $\gamma \vec{p} \rightarrow \pi^0 p$

A4: Strangeness in the nucleon

- Separated strangeness form factors G_E^s and G_M^s at $Q^2 = 0.23, (\mathrm{GeV}/c)^2$
- Axial form factor G_A