Back angle measurements using P2

Sebastian Baunack

Dominik Becker, Kathrin Gerz, Krishna Kumar, Frank Maas

Mainz University

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Polarized Electron Beams up to 300 MeV MIT, Cambridge,

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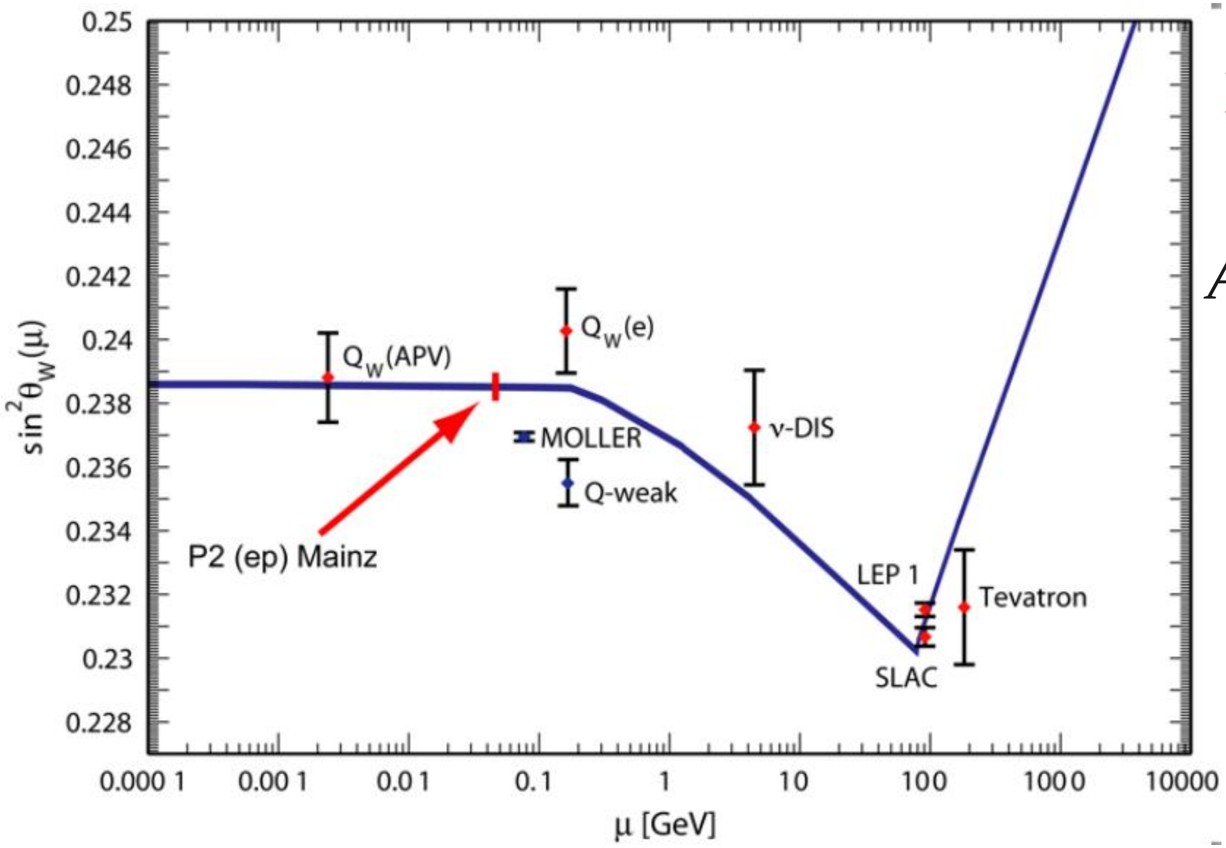
Back angle measurements using P2

- Expected uncertainties in the P2 experiment
- The form factors G_M^s and G_A
- Possible back angle measurements and impact on P2

P2 experiment at MESA



Aim: Measure the
weak charge of the proton:

$$A_{PV} = \frac{-G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W(p) - F(Q^2)\right)$$

Weak mixing angle (tree level)

$$Q_w(p) = 1 - 4\sin^2(\theta_W)$$

Proton structure enters here as "dilution":

$$F(Q^2) = F_{EM}(Q^2) + F_{Axial}(Q^2) + F_{Strange}(Q^2)$$

Proton structure: Parameterized by form factors

$$F_{EM}\left(Q^2\right)=\frac{\varepsilon G_E^p G_E^n+\tau G_M^p G_M^n}{\varepsilon\left(G_E^p\right)^2+\tau\left(G_M^p\right)^2}$$

$$F_{axial}\left(Q^2\right)=\frac{(1-4s_z^2)\sqrt{1-\varepsilon^2}\sqrt{\tau(1+\tau)}G_M^p G_A}{\varepsilon\left(G_E^p\right)^2+\tau\left(G_M^p\right)^2}$$

$$F_{Strange}\left(Q^2\right)=\frac{\varepsilon G_E^p G_E^s+\tau G_M^p G_M^s}{\varepsilon\left(G_E^p\right)^2+\tau\left(G_M^p\right)^2}$$

where $\tau=\frac{Q^2}{4M_p^2}$ and $\varepsilon=\frac{1}{1+2\left(1+\tau\right)\tan^2\frac{\theta}{2}}$

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sufficiently enough known

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suppressed by weak charge

vanishes for $\Theta \longrightarrow 0$

but large uncertainty for G_A

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sufficiently enough known

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suppressed by weak charge
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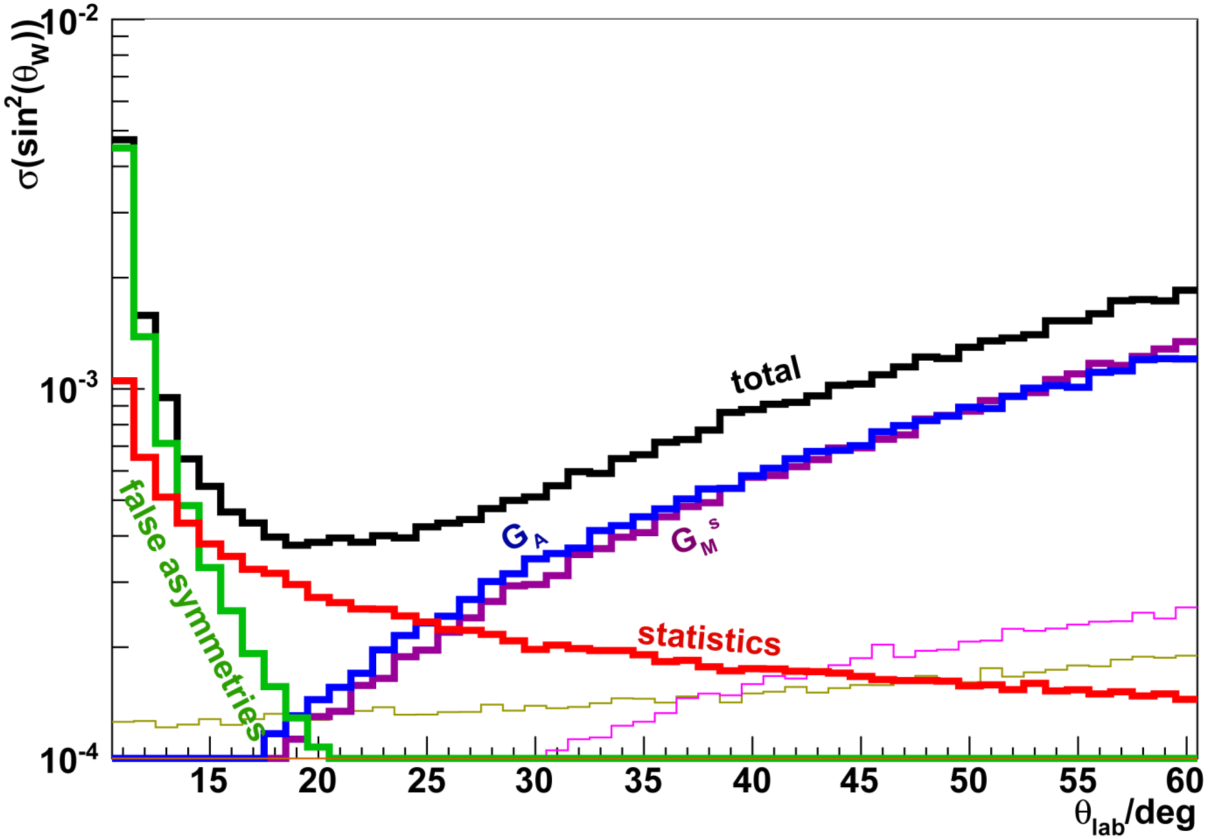
G_E^s sufficiently enough known
but large uncertainty for G_M^s

where $\tau=\dfrac{Q^2}{4M_p^2}$ and $\varepsilon=\dfrac{1}{1+2\left(1+\tau\right)\tan^2\dfrac{\theta}{2}}$

Precision of P2: Monte-Carlo-Studies



Proposed experimental conditions:

- Beam energy: 200 MeV
- Beam current: 150 µA
- Polarization: 85% ± 0.5%

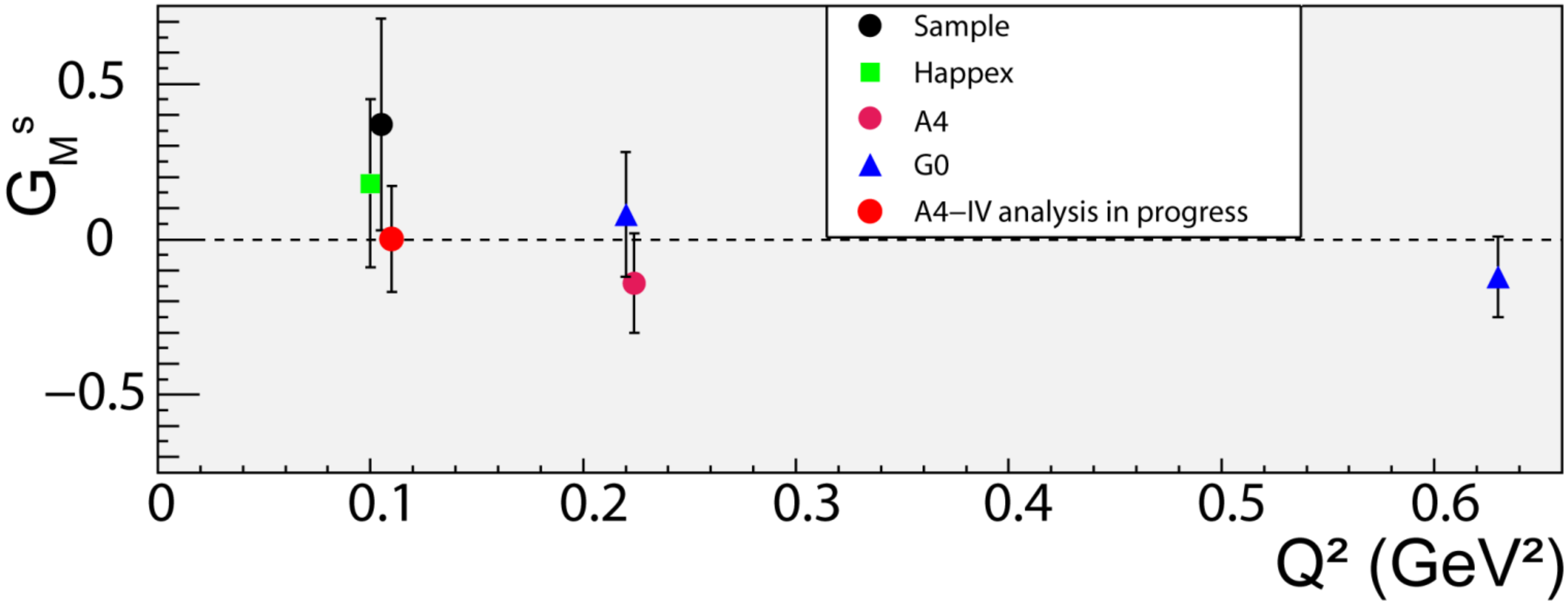
$$\theta_{lab} = 20° \pm 10°$$

$$\Delta\phi = 2\pi$$

- Target: 60 cm liquid hydrogen
- Measuring time: 10000 h

Q^2	0.0029 GeV^2
A_{phys}	-20.25 ppb
ΔA_{tot}	0.34 ppb (1.7 %)
ΔA_{stat}	0.25 ppb
ΔA_{sys}	0.19 ppb (0.9%)
Rate	0.44 10^{12} Hz
$\Delta\sin^2\theta_{W\ stat}$	2.8 10^{-4}
$\Delta\sin^2\theta_{W\ tot}$	3.6 10^{-4} (0.15 %)

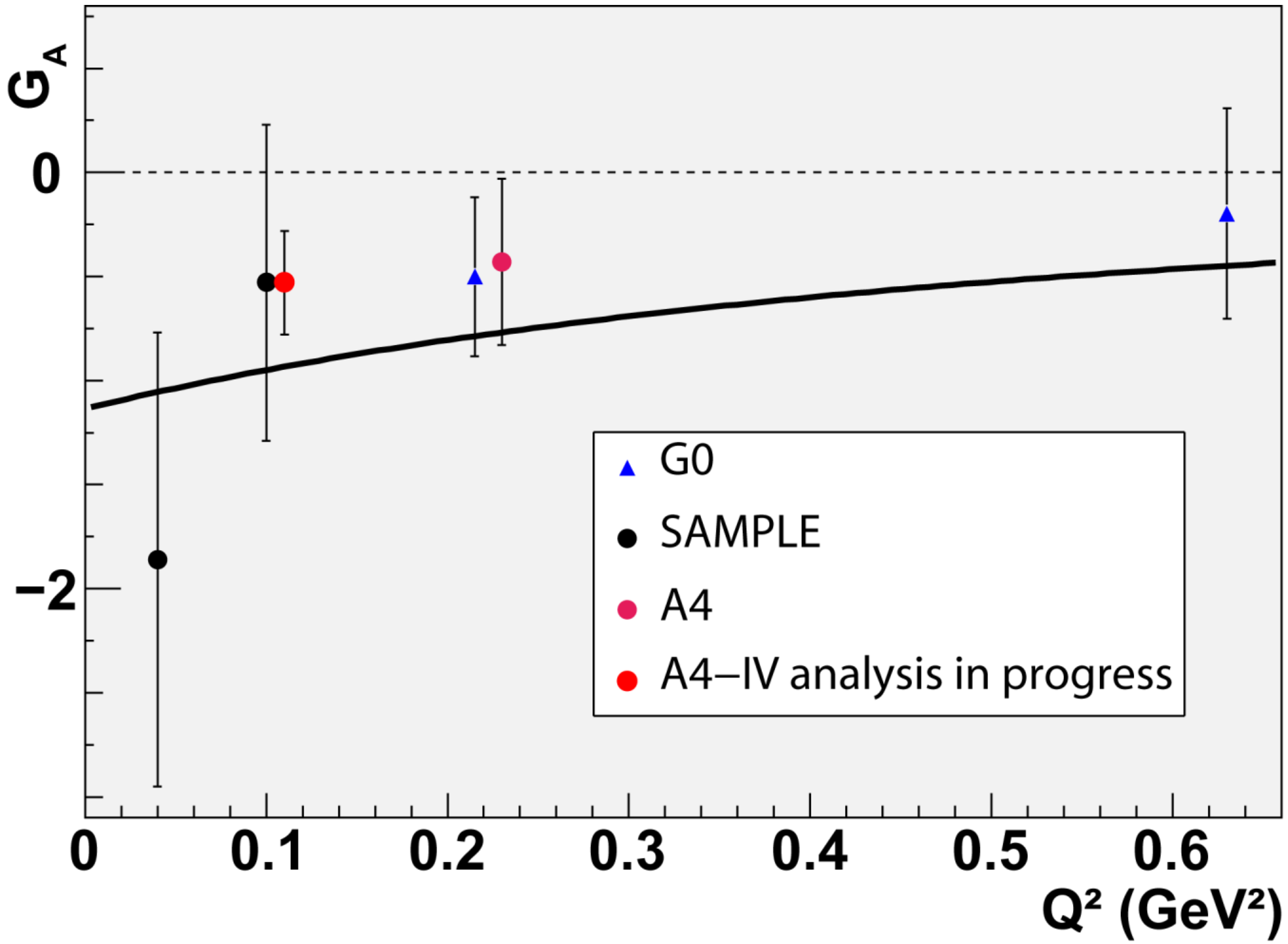
Experimental data for G_M^s



SAMPLE: D. T. Spayde *et al*., Phys.Rev.Lett. 84 (2000) 1106-1109
Happex: A. Acha *et al*., Phys.Rev.Lett. 98 (2007) 032301
G0: D. S. Armstrong *et al.*, Phys.Rev.Lett. 95 (2005) 092001
D. Androic *et al.*, Phys.Rev.Lett. 95 (2010) 092001
A4: F. E. Maas *et al*., Phys.Rev.Lett. 93 (2004) 022002
S. Baunack *et al*., Phys.Rev.Lett. 102 (2009) 151803

A4-IV: about 800 hours hydrogen data on tape, analysis in progress

Experimental data for G_A



SAMPLE: T. M. Ito *et al*., Phys.Rev.Lett. 92 (2004) 102003
G0: D. S. Armstrong *et al.*, Phys.Rev.Lett. 95 (2005) 092001
D. Androic *et al.*, Phys.Rev.Lett. 95 (2005) 092001
A4: Paper in progress

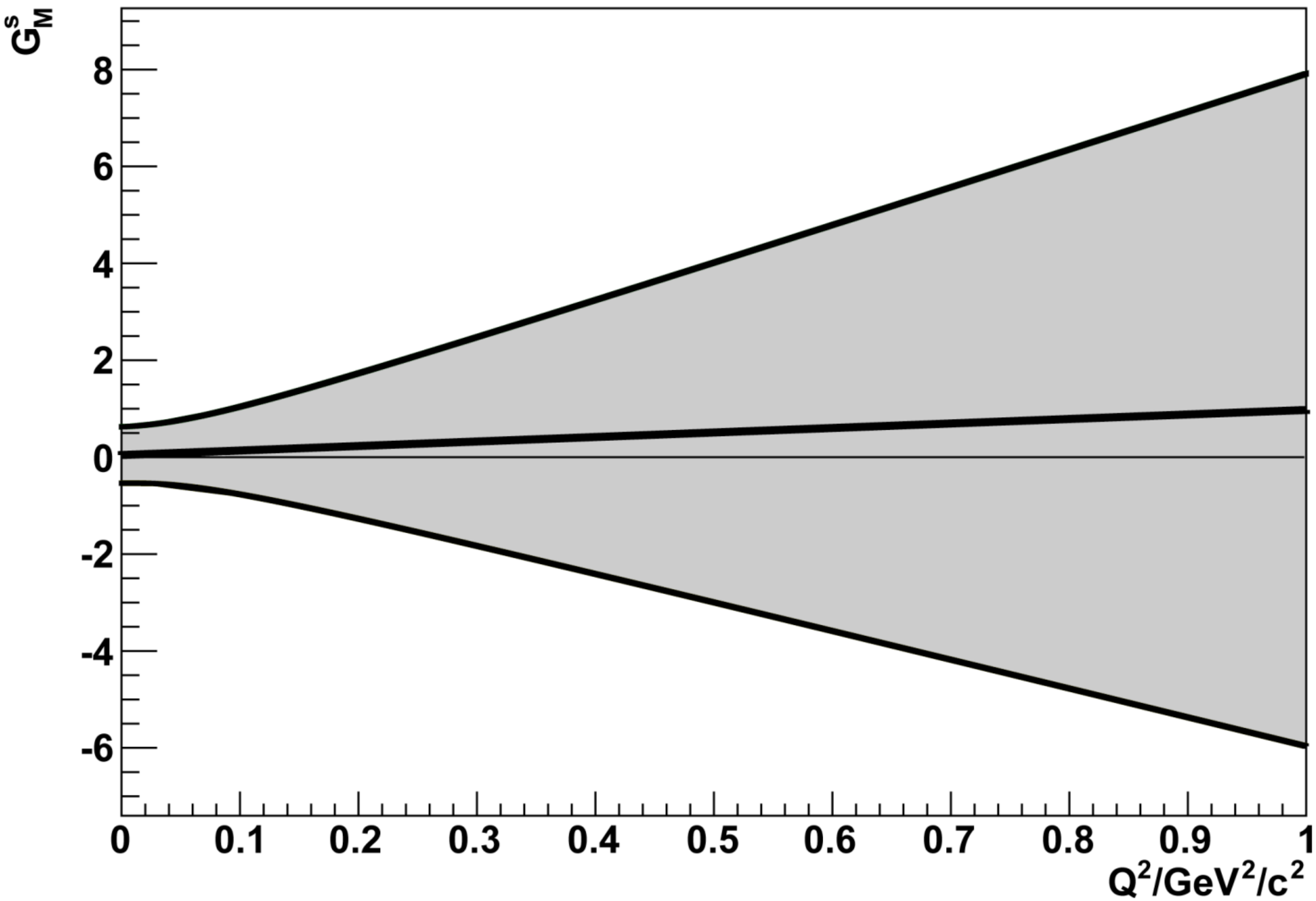
A4-IV: about 700 hours deuterium data on tape

G_M^s : Presently used parameterization for P2 studies

Fit to experimental data (valid up to Q^2=0.3 GeV²), taken from:
P. Wang, D. B. Leinweber, A. W. Thomas and R. D. Young, Phys. Rev. C **79**, 065202 (2009)

$$G_M^s(Q^2) = 0.044 + 0.93\,Q^2 \pm \sqrt{0.34 - 7.02\,Q^2 + 47.8\,Q^4}$$

with Q^2 in GeV²



- Quite large uncertainty
- At low Q^2: $\Delta G_M^S \approx 0.6$
- For P2 studies: Assume improvement in the uncertainty by factor 4

G_A : Presently used parameterization for P2 studies

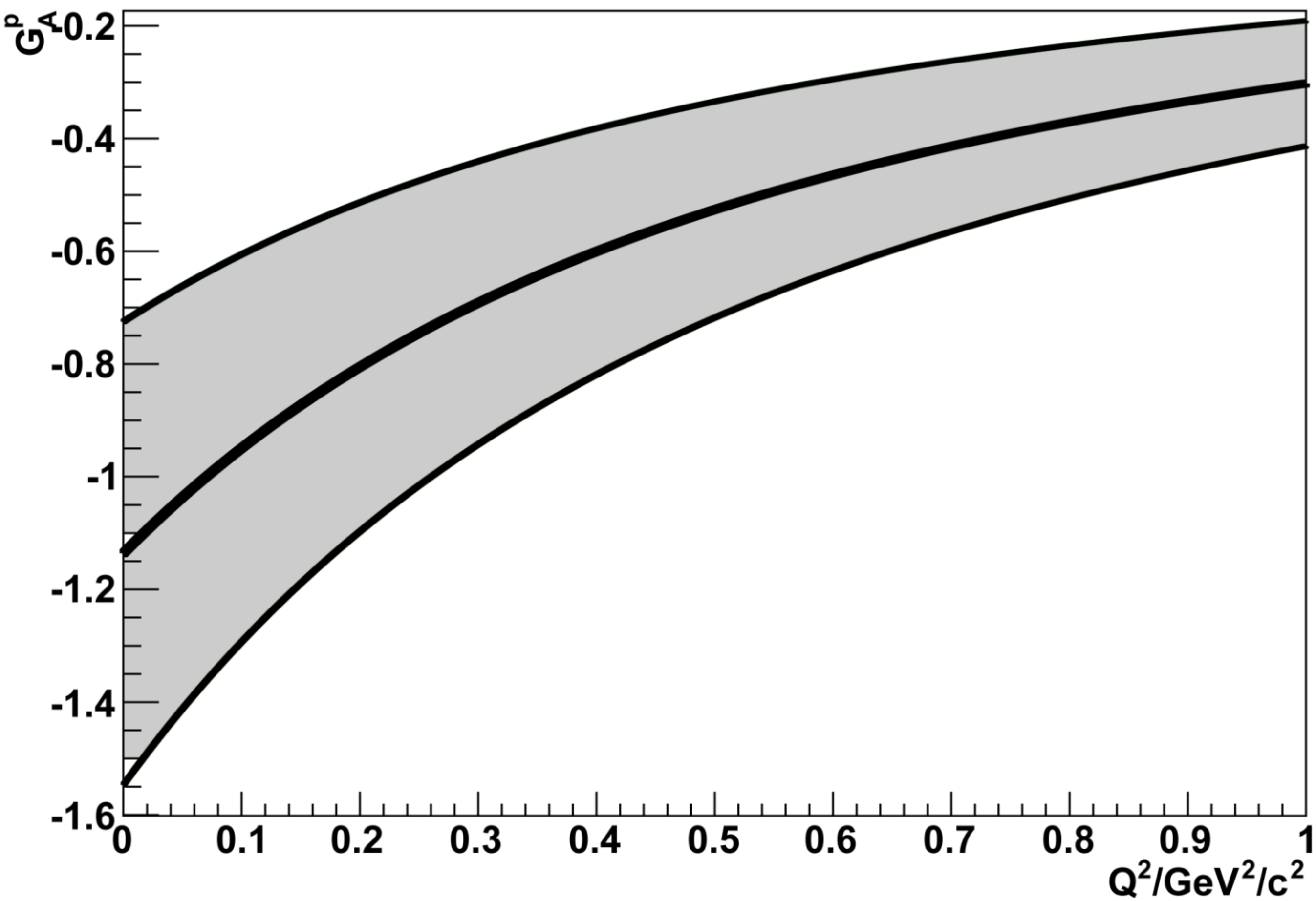
$$G_A(Q^2{=}0) = -\,1.136 \pm 0.411$$

$$G_A^D(Q^2) = \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$ with M_A = (1.032 ± 0.036) GeV

$$G_A = G_A(Q^2 = 0) \cdot G_A^D(Q^2)$$

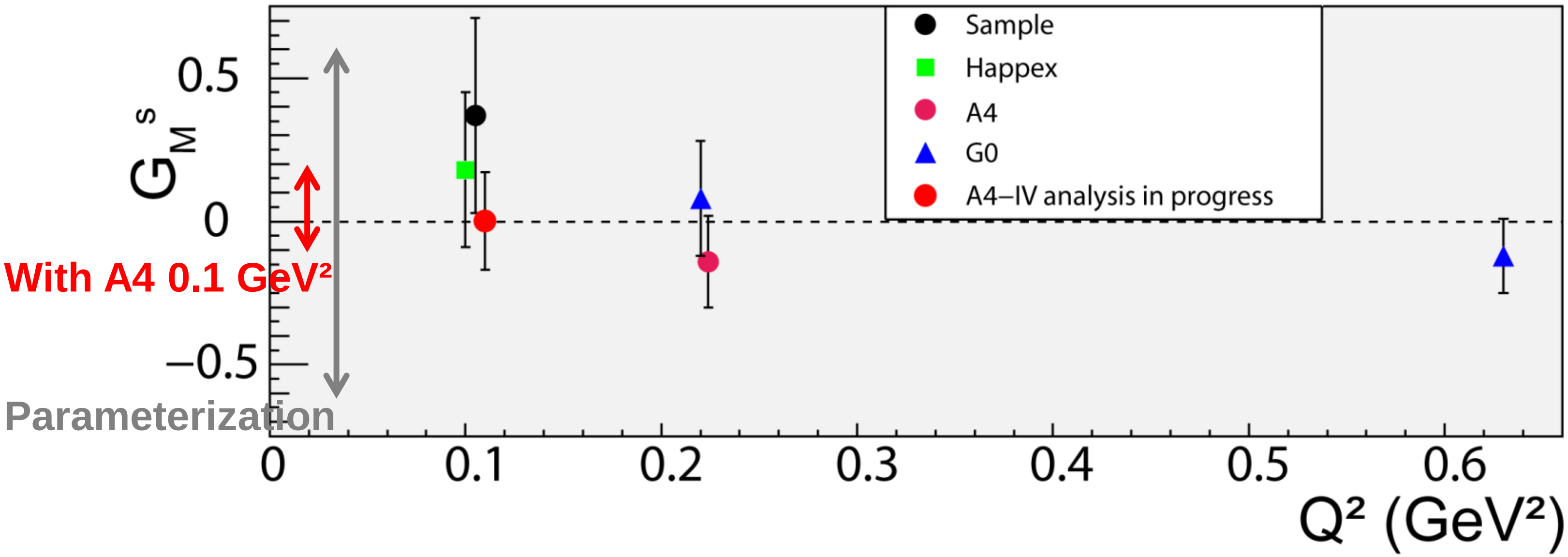
taken from:
M. Musolf *et al.*, Phys. Rept. **239** (1994)

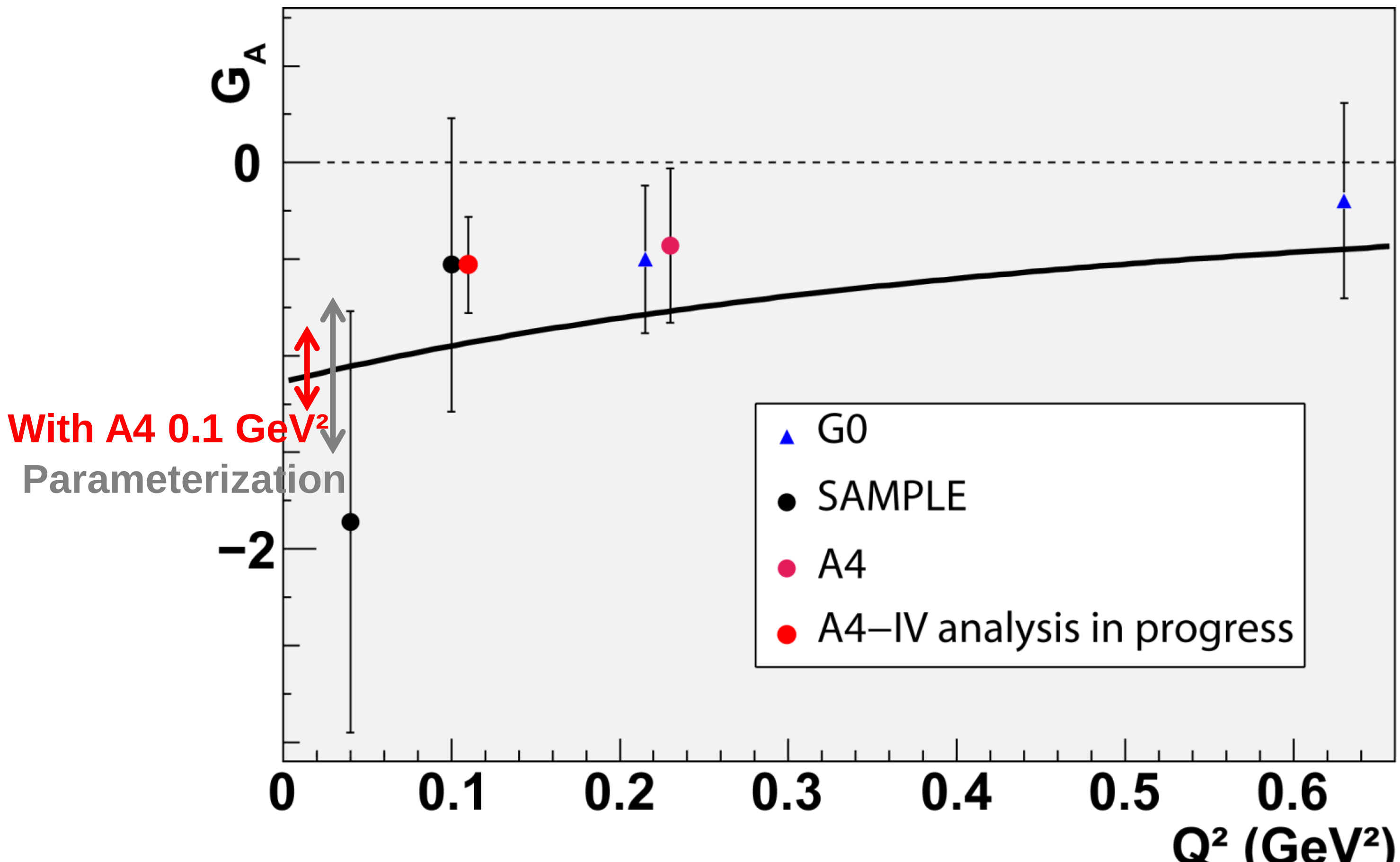
g_A, Δs, anapole moment, ...



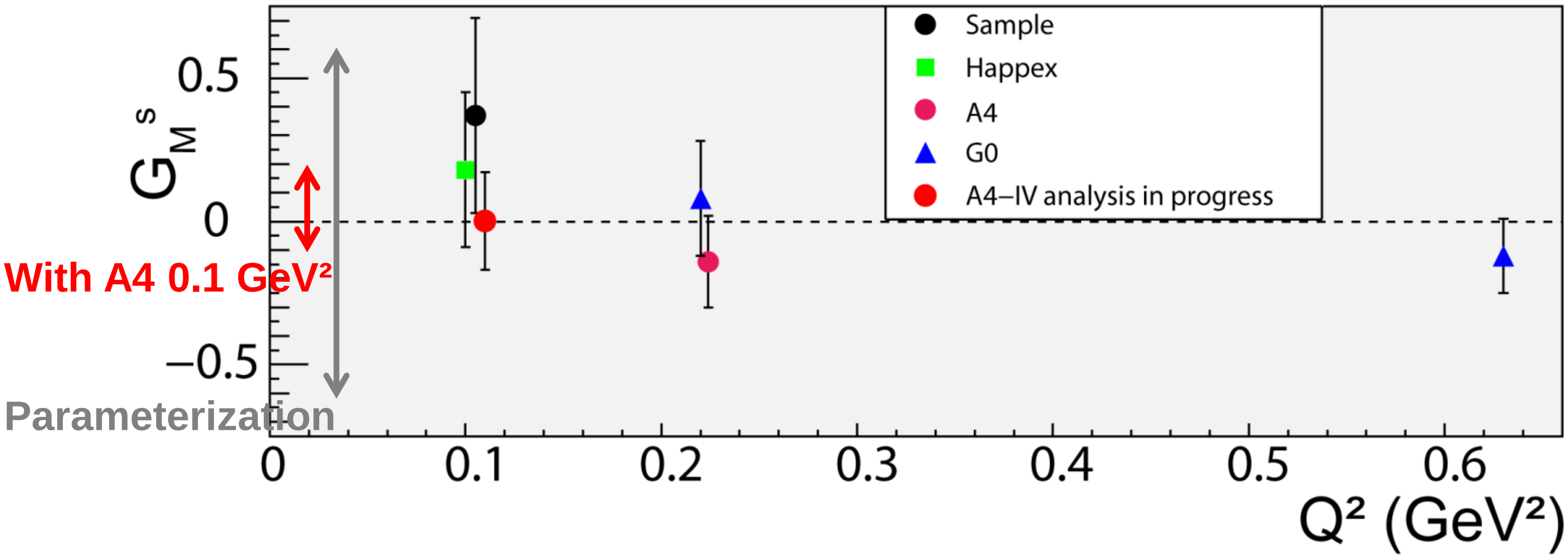
- Uncertainty calculated using Gaussian error propagation
- At low Q^2: $\Delta G_A \approx 0.4$
- For P2 studies: Assume improvement in the uncertainty by factor 2

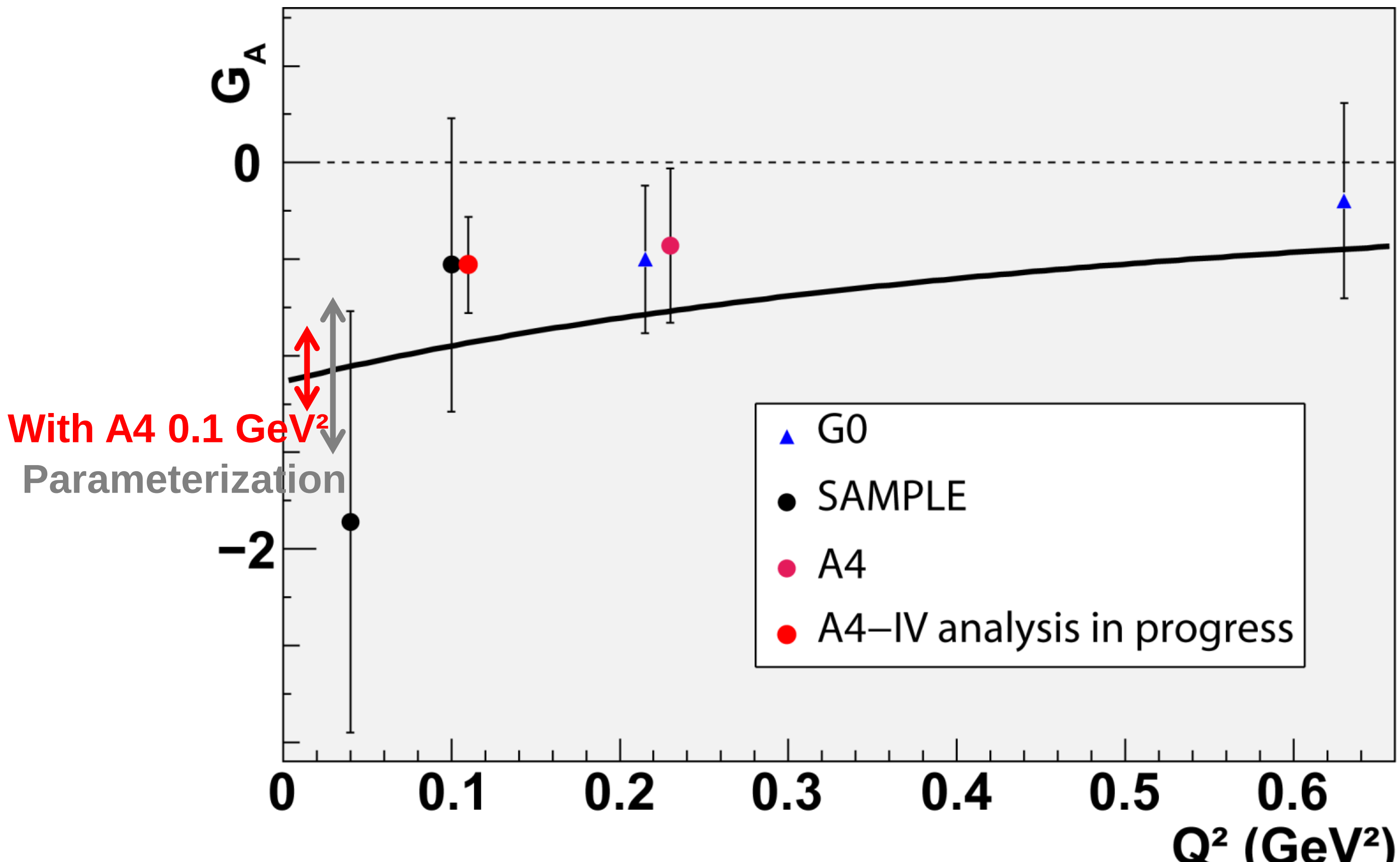
Present situation





Present situation



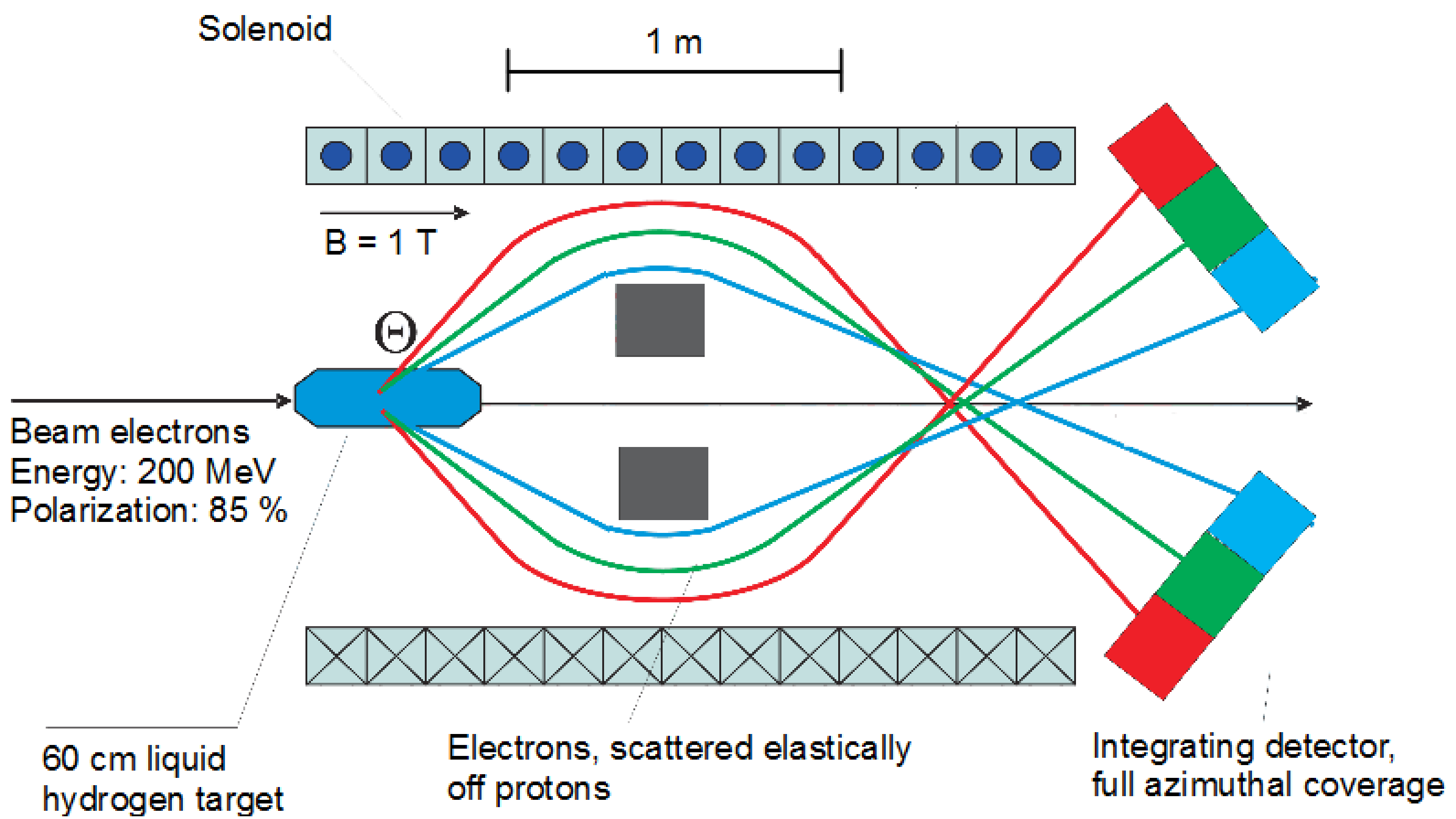


Can we do better?

Back angle measurements

<u>Sketch of P2 main experiment:</u>

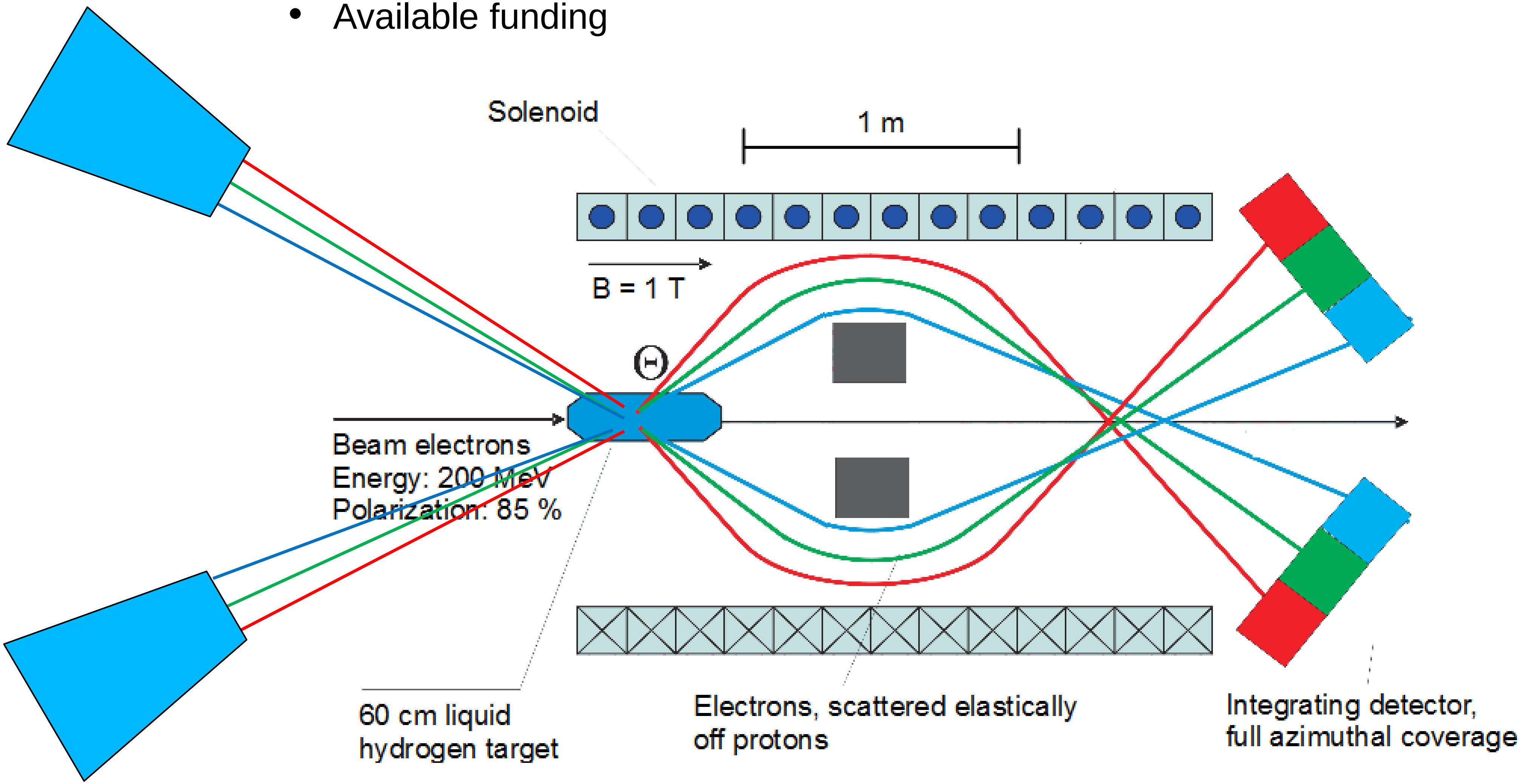
- Liquid hydrogen target
- Elastic ep-scattering $10° \leq \Theta \leq 30°$
- Measurement time: T=10.000 h
- Luminosity $L = 2.5 \cdot 10^{39} \frac{1}{s \cdot cm^2}$



Back angle measurements

Maybe in parallel a back angle measurement possible?
Depends on

- Available space
- Available man power
- Available funding



Benefits compared to the A4 (E=210 MeV) back angle measurement

Imagine to place an A4-like detector ($\Delta\Omega$=0.63 sr, 140° ≤ Θ ≤ 150°) into the P2 setup:
$A_{PV} \approx 7.5$ ppm

	A4 experiment	**P2 back angle experiment**
Integrated luminosity	$1.5\cdot10^5$ fb^{-1} ΔA_{stat} = 0.60 ppm	$8.7\cdot10^7$ fb^{-1} ΔA_{stat}= 0.03 ppm
HC correlated false asymmetries	ΔA_{HC} = 0.25 ppm	ΔA_{HC} = 0.0001 ppm
Polarimetry	ΔP = 4% ΔA_{Pol} = 0.41 ppm	ΔP = 0.5% ΔA_{Pol} = 0.04 ppm
Uncertainty in the measured asymmetry	**ΔA_{tot} = 0.80 ppm (10.6 %)**	**ΔA_{tot} = 0.05 ppm (0.7 %)**

Such a measurement could yield a less than 1% determination of A_{PV} at backward angle !

Possible back angle measurements

- **Option A:**
  Back angle measurement on hydrogen parallel to P2 main experiment

  Advantage: - Very precise determination of A_{PV}
  Disadvantages: - Gives only a linear combination of G_M^s and G_A
  - Momentum transfer Q^2=0.1 GeV^2 does not match the main experiment's $Q^2 \approx 0.0029\ GeV^2$

- **Option B:**
  Dedicated back angle measurements on hydrogen and deuterium with lower beam energy E = 150 MeV

  Advantage: - Separate determination of G_M^s and G_A with better matching Q^2
  - Back angle setup alone requires less space in ExHall 4

  Disadvantage: - Requires additional beam time, assume here 1000h each

Option A: Back angle measurement on hydrogen parallel to the P2 main experiment

Conditions:

- Beam energy: E = 200 MeV, Q^2=0.1 GeV^2
- Beam current: I=150 µA, Target length 60 cm
- Measurement time: T=10.000 h
- Acceptance: 140° ≤ Θ ≤ 150°, 0 ≤ ϕ ≤ 2π
- Parity violating asymmetry: A_{PV} ≈ 7.5 ppm

Backward, H2 only: Form factor input $F_{EM} = 0.558 \pm 0.010$

Can measure linear combination: $F_{Strange} + F_{Axial} = 0.398 \cdot \left(G_M^s + 0.442 \cdot G_A\right)$

With precision: $\Delta(F_{Strange} + F_{Axial}) = 0.011$

P2: $F_{Strange} + F_{Axial} = 0.0040 \cdot \left(G_M^s + 0.691 \cdot G_A\right)$

With Precision: $\Delta(F_{Strange} + F_{Axial}) = 0.00076$

Option A: Backward, H2 parallel to P2 main experiment

- Scale down the measured linear combination to the P2 forward condition:

$$F_{Strange} + F_{Axial} = 0.0040 \cdot \left(G_M^s + 0.442 \cdot G_A\right) \pm 0.00011$$

- But Q² not the same, must be extrapolated, and linear combination does not match exactly: Assume an additional uncertainty of the same size 0.00011:

$$\Delta(F_{Strange} + F_{Axial}) = 0.00016$$ From backward measurement, H2 only

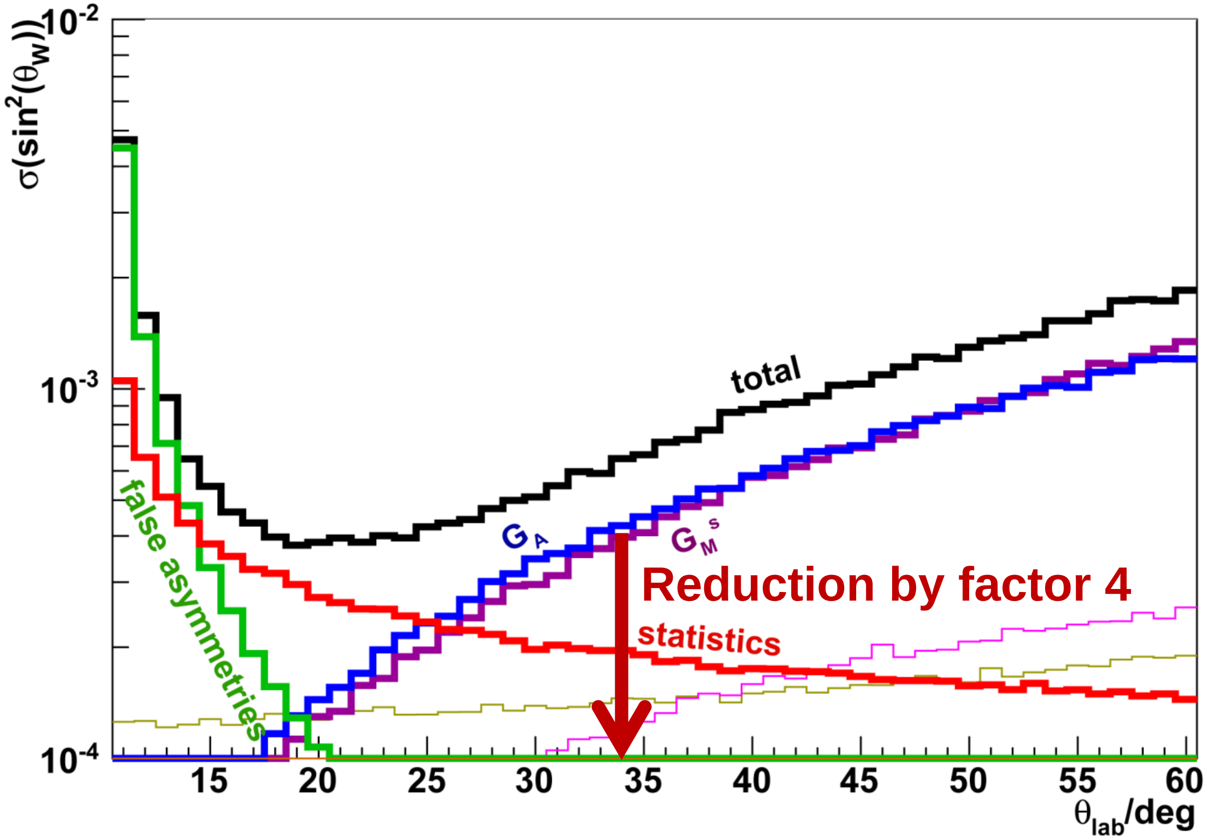
$$\Delta(F_{Strange} + F_{Axial}) = 0.00076$$ P2 input without back angle measurement

→ **Improvement by factor 4**

Uncertainty in $\Delta\sin^2\Theta_W$ drops from $\Delta\sin^2(\theta_W) = 3.6 \cdot 10^{-4}$ **to** $\Delta\sin^2(\theta_W) = 3.1 \cdot 10^{-4}$

Option A: Backward, H2 parallel to P2 main experiment

- Also, the P2 main experiment might go to larger scattering angles



Option B: Dedicated back angle measurements on hydrogen and deuterium

Conditions:

- Beam energy: E = 150 MeV, Q^2=0.06 GeV^2
- Beam current: I=150 μA, Target length 60 cm
- Measurement time: T=1.000 h for each target
- Acceptance: 140° ≤ Θ ≤ 150°, 0 ≤ ϕ ≤ 2π
- Targets: Hydrogen and deuterium

Backward, H2: Form factor input $$F_{EM} = 0.500 \pm 0.007$$

Can measure linear combination: $$F_{Strange} + F_{Axial} = 0.323 \cdot \left(G_M^s + 0.565 \cdot G_A\right)$$

With precision: $$\Delta(F_{Strange} + F_{Axial}) = 0.015$$

Backward, D2: Form factor input $$F_{EM} = 0.745 \pm 0.005$$

Can measure linear combination: $$F_{Strange} + F_{Axial} = 0.105 \cdot \left(G_M^s + 2.902 \cdot G_A\right)$$

With precision: $$\Delta(F_{Strange} + F_{Axial}) = 0.013$$

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Also an improvement in the uncertainty by factor 4

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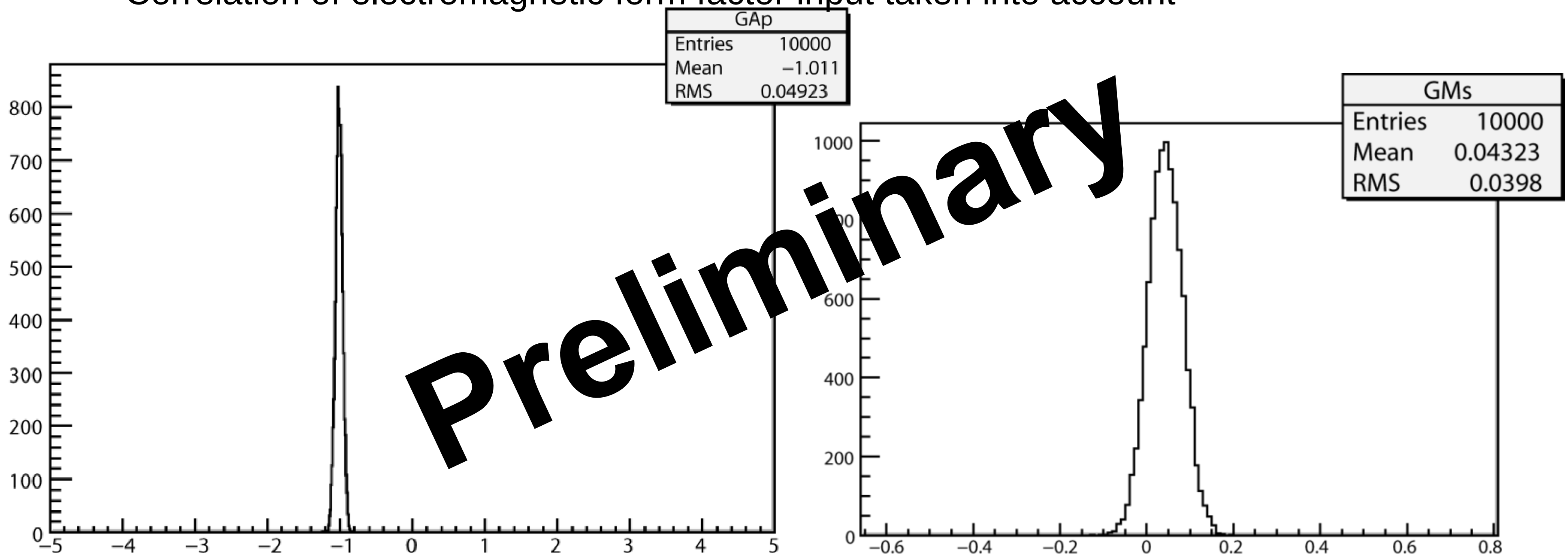
Summary

- P2 measures the weak mixing angle and nucleon form factor input is needed
- G_A and G_M^s make non-negligible contributions to the uncertainty and limit the the central scattering angle to values below 25°
- A back angle measurement on hydrogen parallel to P2 main experiment:
  - \+ Can lower the error contribution by factor 4
  - \+ No additional run time required
  - \- Q^2 and linear combinations do not match
  - \- Setup needs more space in experimental hall
- A dedicated measurement on H_2 and D_2 at lower beam energy E=150 MeV
  - \+ Can lower the error contribution by factor 4
  - \+ Q^2 matches better and a separate determination of G_M^s and G_A is possible
  - \- Requires additional beam time

Separate Determination of G_A and G_M^s at Q^2=0.06 GeV^2

- Numerical determination of precision
- Choose randomly EM form factors and asymmetries according to their uncertainties and calculate G_A and G_M^s
- Correlation of electromagnetic form factor input taken into account



$\Delta G_A = 0.05$ $\Delta G_M^s = 0.04$