Parity-violating electron scattering and strangeness form factors of the nucleon

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A4 Collaboration

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Outline

- Strangeness matrix elements from neutral current observables

- Parity-violating (PV) electron scattering

  – The A4 Experiment at MAMI

- Backward angle results

Strangeness matrix elements

- Why quark operator matrix elements?

Short distance degrees of freedom: QCD quarks and gluons ⟷ ??? Long distance: hadrons

- Why the strange quark in the nucleon?

Flavour decomposition → valence sector ⟹ constituent quarks: effective d.o.f.?

→ sea quarks

- Candidates?

$\langle N | \bar{s}s | N \rangle$ πN-Σ-term

$\langle N | \bar{s}\gamma^{\mu}\gamma_{5}s | N \rangle$ DIS (Δs)

$\langle N | \bar{s}\gamma^{\mu}s | N \rangle$ PV electron scattering

Flavour vector form factors

Nucleon EM current:

$$\left\langle J_\gamma^\mu \right\rangle = \sum_{f=u,d,s} Q_f \left\langle \mathrm{N}\right| \bar{f}\gamma^\mu f \left|\mathrm{N}\right\rangle$$

$$= \bar{\mathrm{N}}(p') \left[\gamma^\mu F_1(q^2) + i\frac{\sigma^{\mu\nu}q_\nu}{2M} F_2(q^2) \right] \mathrm{N}(p)$$

Definition of flavour vector form factors:

$$\left\langle \mathrm{N}\right| \bar{f}\gamma^\mu f \left|\mathrm{N}\right\rangle \equiv \bar{\mathrm{N}}(p') \left[\gamma^\mu F_1^f(q^2) + i\frac{\sigma^{\mu\nu}q_\nu}{2M} F_2^f(q^2) \right] \mathrm{N}(p)$$

$$F_{1,2}(q^2) = \sum_{f=u,d.s} Q_f F_{1,2}^f(q^2)$$

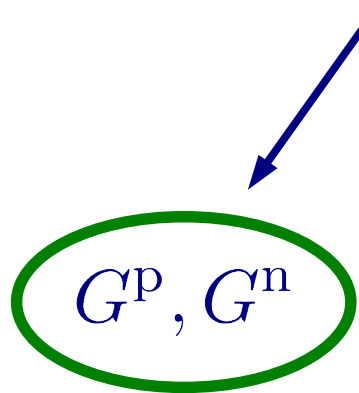$$G_{E,M}(q^2) = \sum_{f=u,d.s} Q_f G_{E,M}^f(q^2)$$

Sachs form factors:

$$G_E^{(f)} \equiv F_1^{(f)} - \tau F_2^{(f)}$$
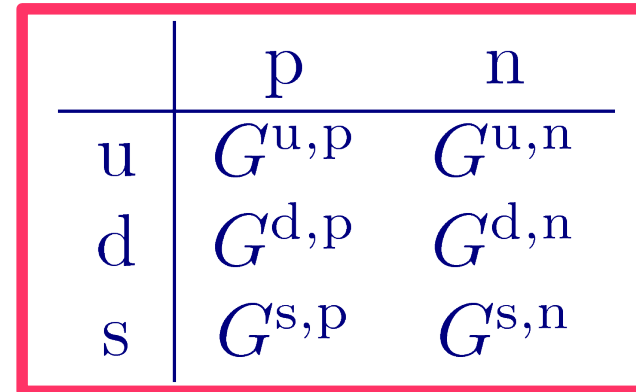
$$G_M^{(f)} \equiv F_1^{(f)} + F_2^{(f)}$$

$$(\tau = -q^2/4M^2)$$

Flavour form factors

EM form factors: <u>4 measurements</u>, <u>12 unknowns</u>:

$$G^{\mathrm{p}}, G^{\mathrm{n}}$$

	p	n
u	$G^{\mathrm{u,p}}$	$G^{\mathrm{u,n}}$
d	$G^{\mathrm{d,p}}$	$G^{\mathrm{d,n}}$
s	$G^{\mathrm{s,p}}$	$G^{\mathrm{s,n}}$

Charge symmetry:

$$G^{\mathrm{u,p}} = G^{\mathrm{d,n}} \equiv G^{\mathrm{u}}$$
$$G^{\mathrm{d,p}} = G^{\mathrm{u,n}} \equiv G^{\mathrm{d}}$$
$$G^{\mathrm{s,p}} = G^{\mathrm{s,n}} \equiv G^{\mathrm{s}}$$

$\Longrightarrow$ <u>6 unknowns!</u>

Nucleon neutral current

$$\langle J_Z^\mu \rangle = \bar{N}(p')\left[\gamma^\mu \tilde{F}_1(q^2) + i\frac{\sigma^{\mu\nu}q_\nu}{2M}\tilde{F}_2(q^2) + \gamma^\mu\gamma_5 G_A(q^2)\right]N(p)$$

$$= \langle V_Z^\mu \rangle + \langle A_Z^\mu \rangle$$

$$\langle V_Z^\mu \rangle = \sum_{f=u,d,s} Q_f^w \langle N|\,\bar{f}\gamma^\mu f\,|N\rangle$$

$$\langle J_\gamma^\mu \rangle = \sum_{f=u,d,s} Q_f \langle N|\,\bar{f}\gamma^\mu f\,|N\rangle$$

universal

$$\tilde{G}_{E,M}(q^2) = \sum_{f=u,d.s} Q_f^w \boxed{G_{E,M}^f(q^2)}$$

$$G_{E,M}(q^2) = \sum_{f=u,d.s} Q_f \boxed{G_{E,M}^f(q^2)}$$

are the same

$\Longrightarrow$ two missing constraints: in principle solved!

PV electron scattering

EW cross section:
$$\sigma \propto \left| \frac{j_{\gamma,\mu} \langle J_\gamma^\mu \rangle}{q^2} + \frac{j_{Z,\mu} \langle J_Z^\mu \rangle}{M_Z^2} \right|^2 \qquad j_{Z,\mu} = a_\mu + v_\mu$$

PV Asymmetry:
$$A_{\mathrm{RL}} = \frac{\sigma_{\mathrm{R}} - \sigma_{\mathrm{L}}}{\sigma_{\mathrm{R}} + \sigma_{\mathrm{L}}} \qquad q^2 \ll M_Z^2$$

$$= \frac{q^2}{M_Z^2} \frac{2 j_{\gamma,\mu} \langle J_\gamma^\mu \rangle (a_\mu \langle V_Z^\mu \rangle + v_\mu \langle A_Z^\mu \rangle)}{|j_{\gamma,\mu} \langle J_\gamma^\mu \rangle|^2} \sim 10^{-5}$$

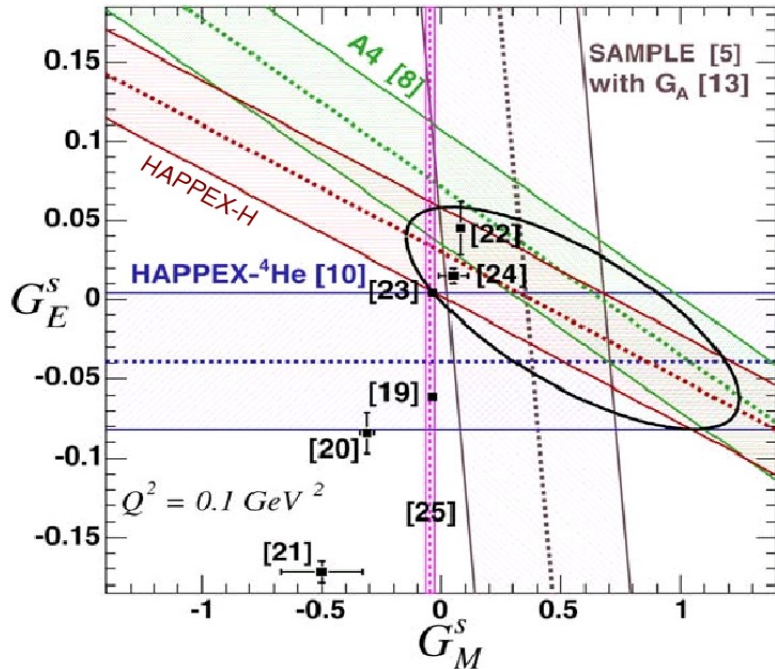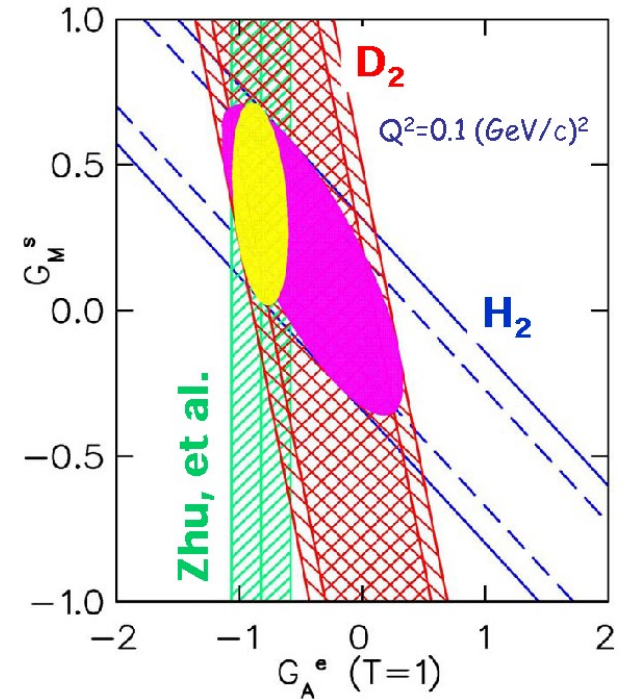**Dependence on FFs:**

$$A_{\mathrm{RL}} = \underbrace{A_{\mathrm{V}} + A_{\mathrm{A}}}_{= A_0} + A_{\mathrm{S}} \begin{cases} A_{\mathrm{V}} &= -a\rho'_{eq} \left[(1 - 4\hat{\kappa}'_{eq}\hat{s}_Z^2) - \frac{\epsilon G_E^{\mathrm{p}} G_E^{\mathrm{n}} + \tau G_M^{\mathrm{p}} G_M^{\mathrm{n}}}{\epsilon (G_E^{\mathrm{p}})^2 + \tau (G_M^{\mathrm{p}})^2} \right] \\[2em] A_{\mathrm{A}} &= a \frac{(1 - 4\hat{s}_Z^2)\sqrt{1-\epsilon^2}\sqrt{\tau(1+\tau)} G_M^{\mathrm{p}} \tilde{G}_A^{\mathrm{p}}}{\epsilon (G_E^{\mathrm{p}})^2 + \tau (G_M^{\mathrm{p}})^2} \\[2em] A_{\mathrm{S}} &= a\rho'_{eq} \frac{\epsilon G_E^{\mathrm{p}} G_E^{\mathrm{s}} + \tau G_M^{\mathrm{p}} G_M^{\mathrm{s}}}{\epsilon (G_E^{\mathrm{p}})^2 + \tau (G_M^{\mathrm{p}})^2} \end{cases}$$

$$a = -G_F q^2 / 4\pi\alpha\sqrt{2}, \quad \tau = -q^2/4M_{\mathrm{p}}^2, \quad \epsilon = [1 + 2(1+\tau)\tan^2\theta/2]^{-1}$$
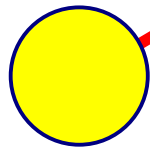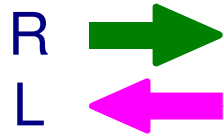
Measurements

$Q^2 (\mathrm{GeV}/c)^2$	e+p forward	e+p backward	e+^{4}He forward	e+d backward
SAMPLE MIT/BATES		0.1		0.04, 0.1
HAPPEx JLAB	0.1, 0.48 0.6		0.1	
G0 JLAB	0.12...1.0	0.23, 0.62		
A4 MAMI	0.1, 0.22 0.6	0.22		0.22

Experimental principle

longitudinally polarised
electron beam

detector

R

L

$N_{\mathrm{R}}, N_{\mathrm{L}}$

$$\Rightarrow A_{\mathrm{RL}} = \frac{N_{\mathrm{R}} - N_{\mathrm{L}}}{N_{\mathrm{R}} + N_{\mathrm{L}}}$$

proton target

- <u>Statistical uncertainty</u>

  for a counting experiment:

  $$\begin{aligned} A &= 10^{-6} \\ \delta A &= \frac{1}{\sqrt{N}} \simeq 10^{-7} \\ &\Rightarrow N \simeq 10^{14} \end{aligned}$$

  1000 hours $\Rightarrow$ ~10 MHz

  - high luminosity
  - large acceptance
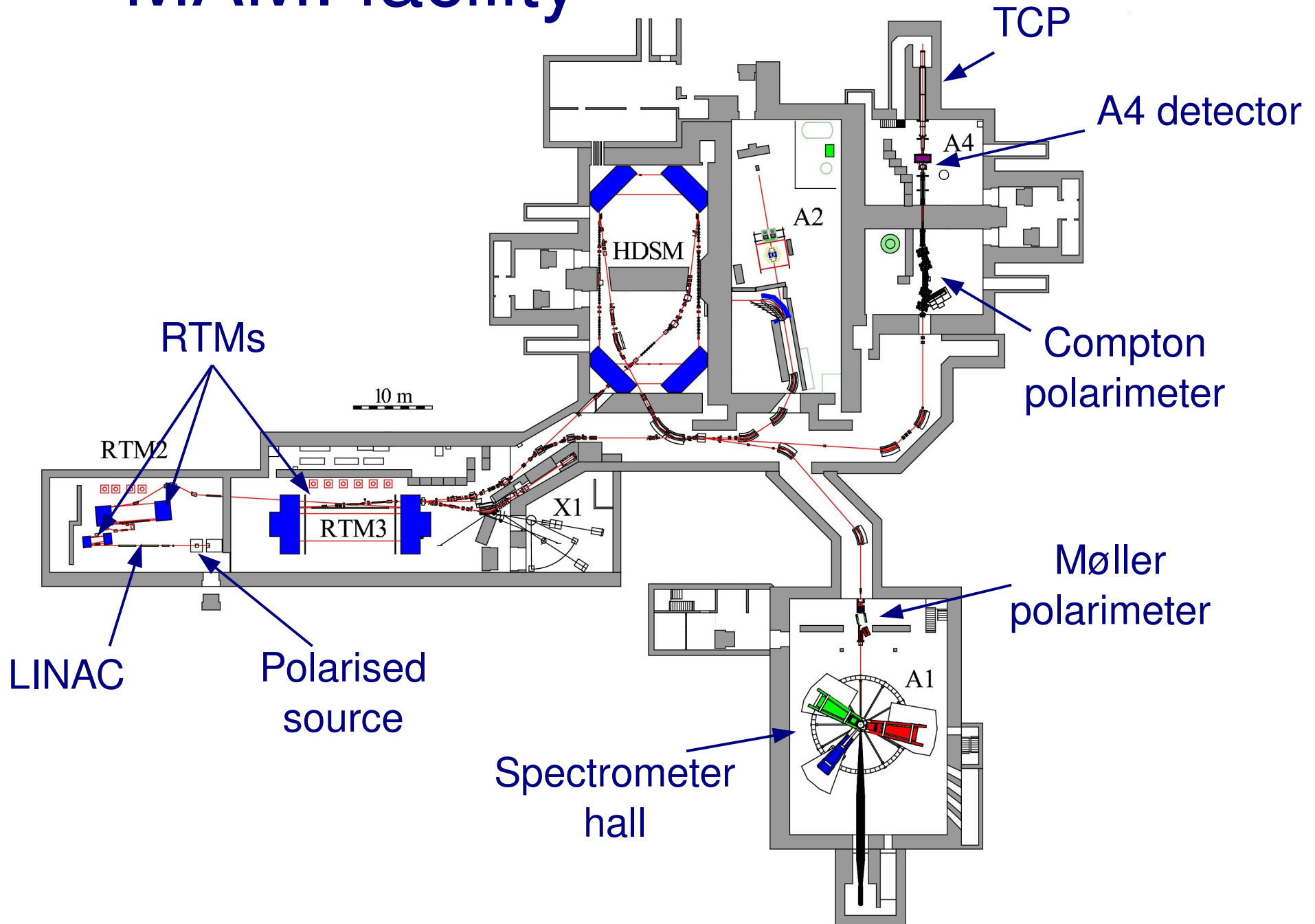 - fast detector

- <u>Systematic uncertainty</u>

  – helicity correlated fluctuations

  – polarisation measurement

Experimental setup
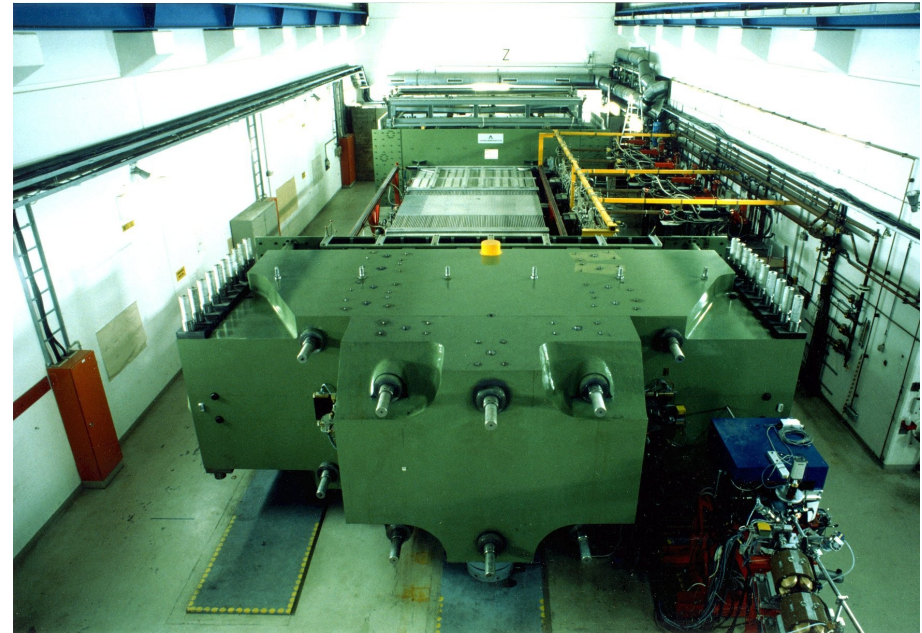
MAMI facility

Electron beam
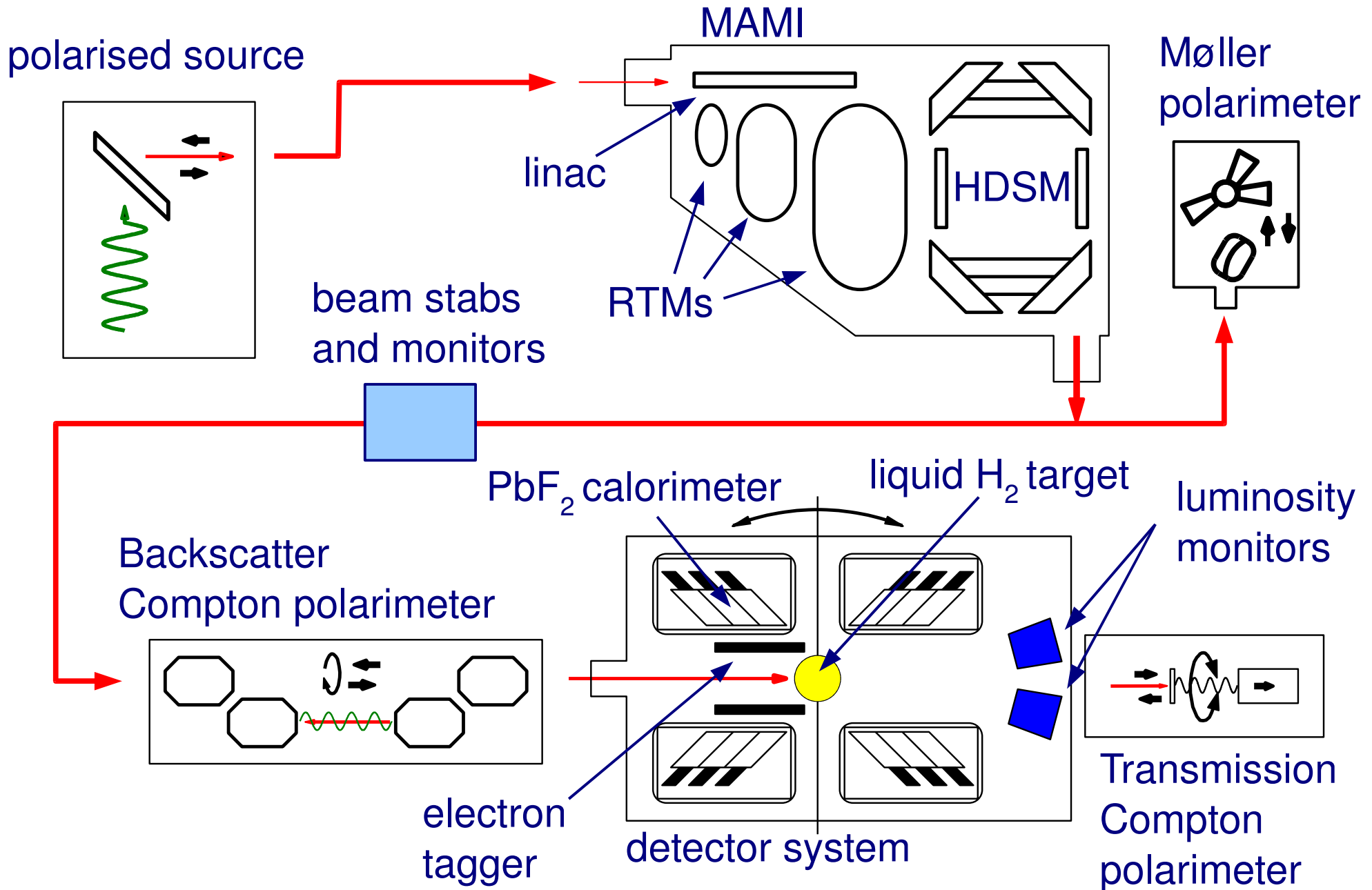
Polarised Source

- Polarisation: up to 80%

- Current: 20 µA

- Pockels cell: 50 Hz pol. switch

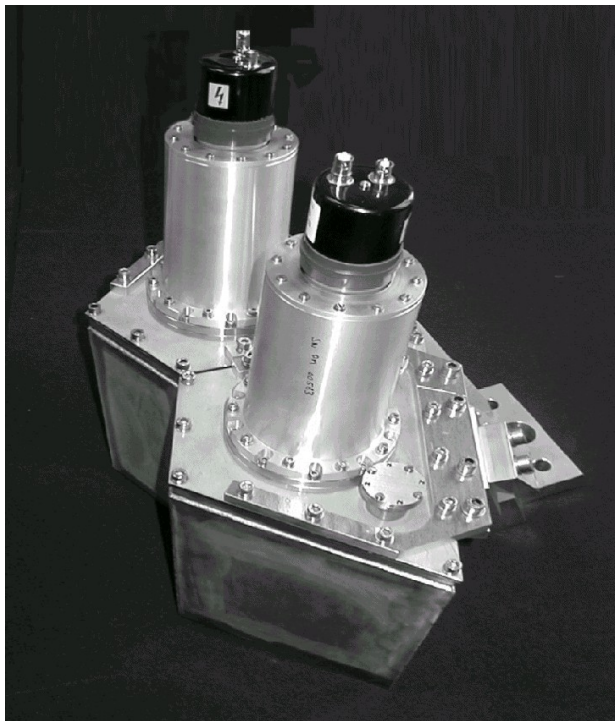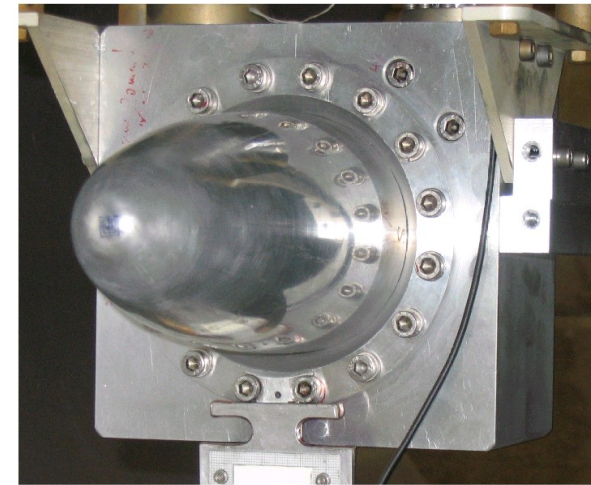- $\lambda/2$-plate: global pol. inversion

MAMI Accelerator

- Continuous wave

- Energy up to 1.5 GeV

- Beam stabilisation systems

- Beam monitors: parameter measurement every 20 ms
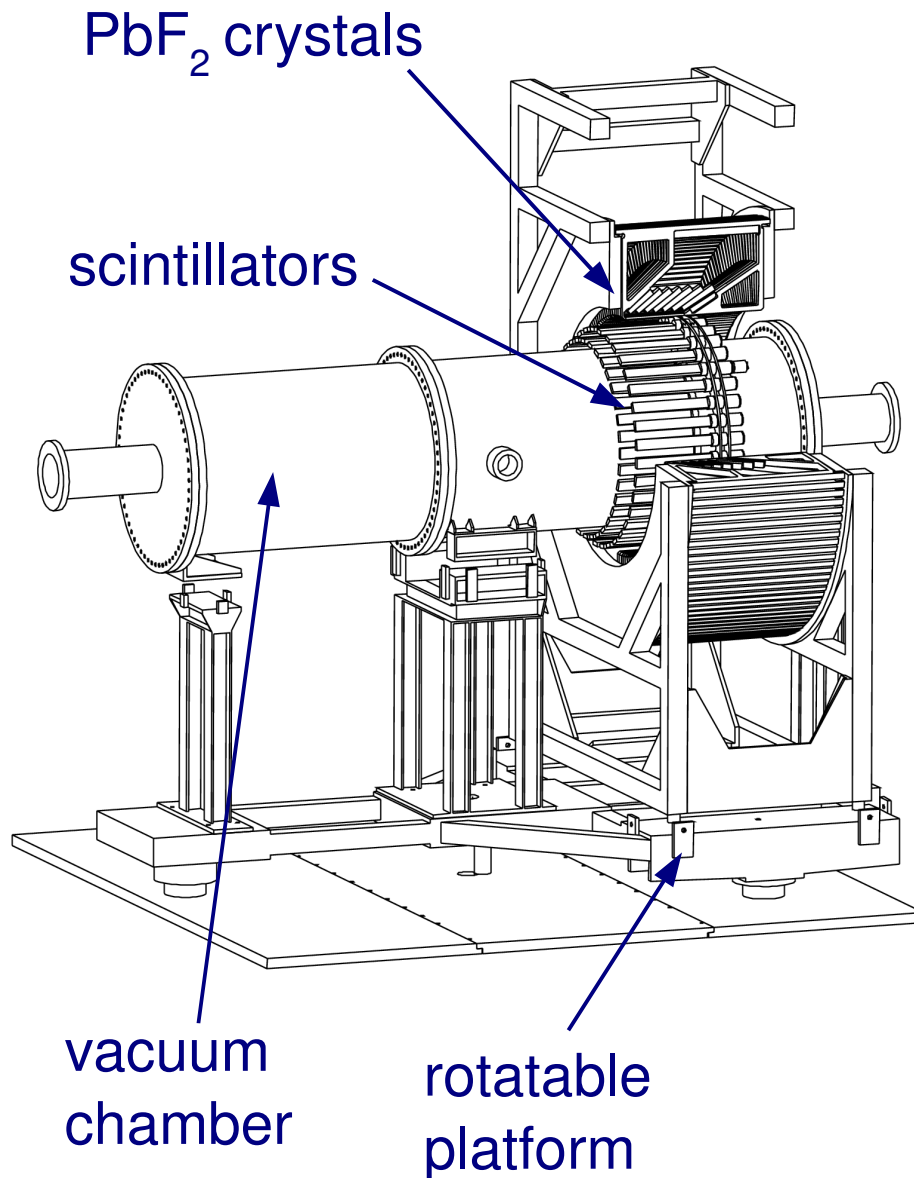
Target

- liquid hydrogen (deuterium)

- forward: 10 cm, backward: 23.4 cm

- T=14 K, fluctuation $< 10^{-3}$

- absorbed power: 100 W @ 20 μA

Luminosity monitors
- water Cherenkov
- flux integrating
- acceptance: 4° to 10°
- monitor target density fluctuations

A4 detector

PbF$_2$ crystals

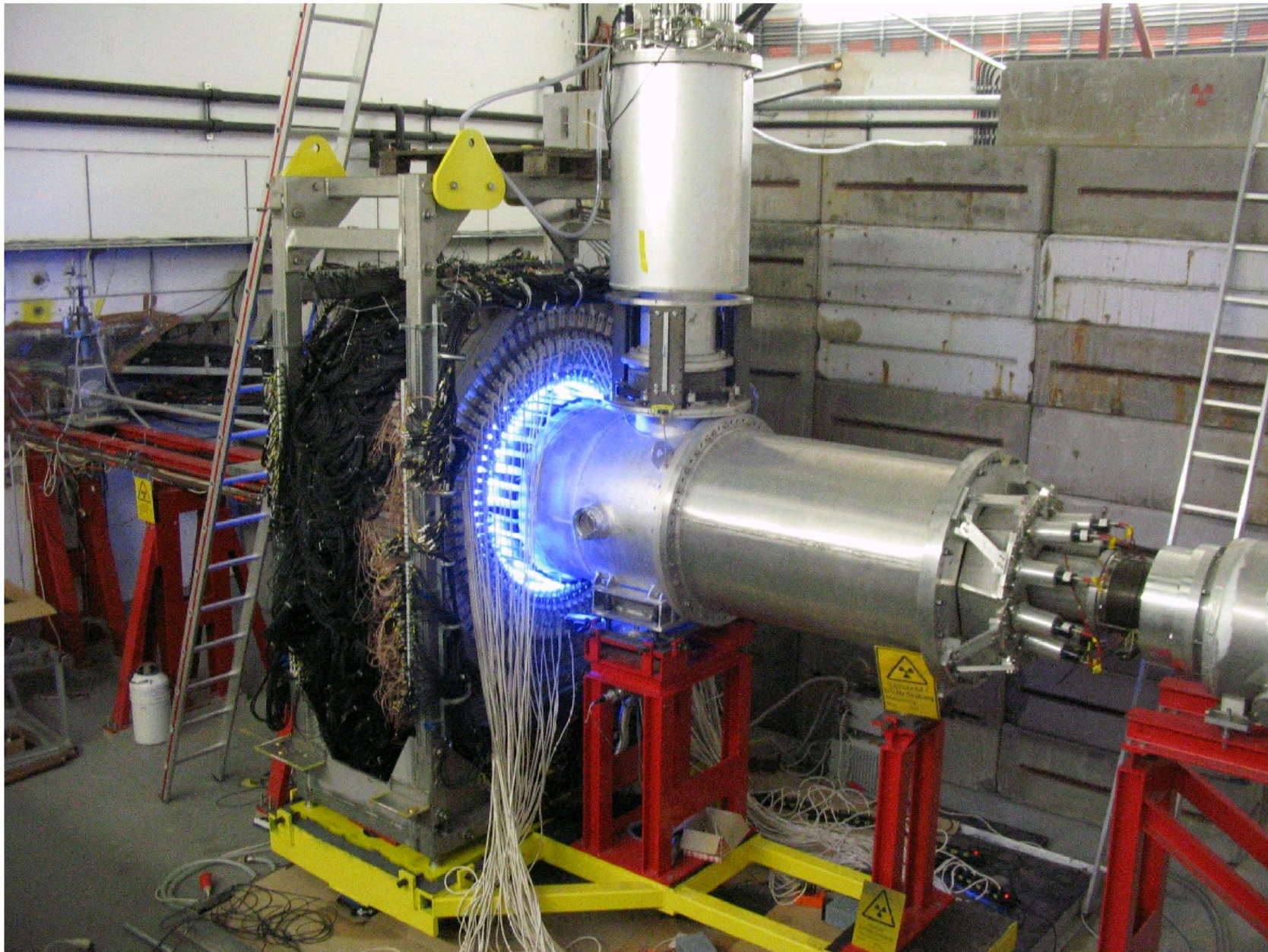scintillators

vacuum chamber

rotatable platform

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
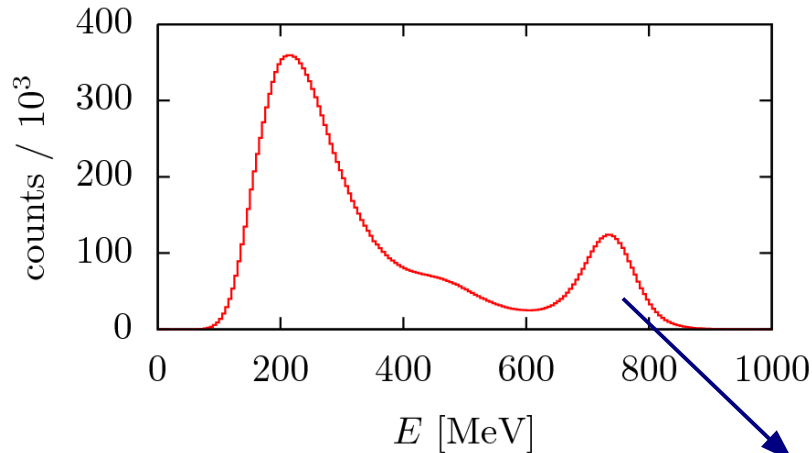
- fully absorbing

Electron tagger (backward):

- 72 plastic scintillators

A4 hall

Data analysis

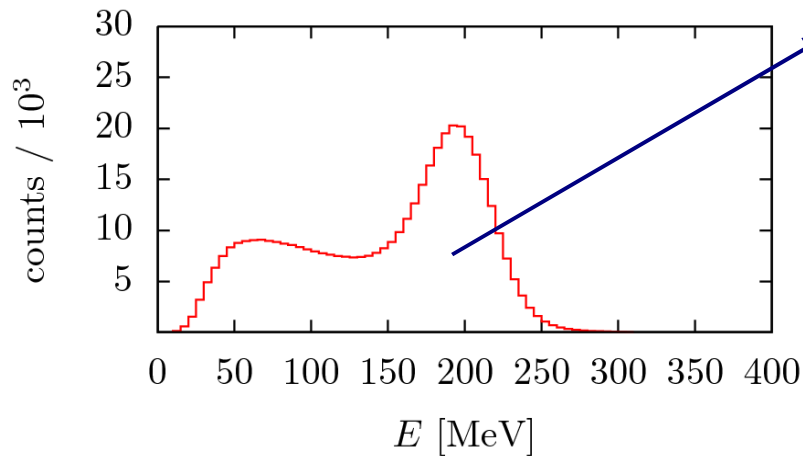## 855 MeV forward

315 MeV backward

N_R, N_L

- 2044 spectra every 5 min.

- Extraction of elastic events

- Target density normalisation:

$$A_{\mathrm{meas}} = \frac{N_R/\rho_R - N_L/\rho_L}{N_R/\rho_R + N_L/\rho_L}$$

- Correction for false asymmetries and polarisation:

$$A_{\mathrm{meas}} = P A_{\mathrm{RL}} + \sum a_i X_i$$

Backward measurement

Parameter	X		a X (ppm)
Current asymmetry	-0.30	ppm	-0.25
Horiz. position diff.	-86.97	nm	0.61
Vert. position diff.	-23.84	nm	-0.86
Horiz. angle diff.	-8.53	nrad	-0.09
Vert. angle diff.	-2.40	nrad	0.10
Energy diff.	-0.41	eV	0.16

	Factor	Error
Polarisation	0.68	0.04
	Corr. (ppm)	Error (ppm)
Hel. corr. asym.	0.14	0.39
Random coinc.	-0.19	0.02
Al windows	0.29	0.04
Background subtr.	-1.49	0.28
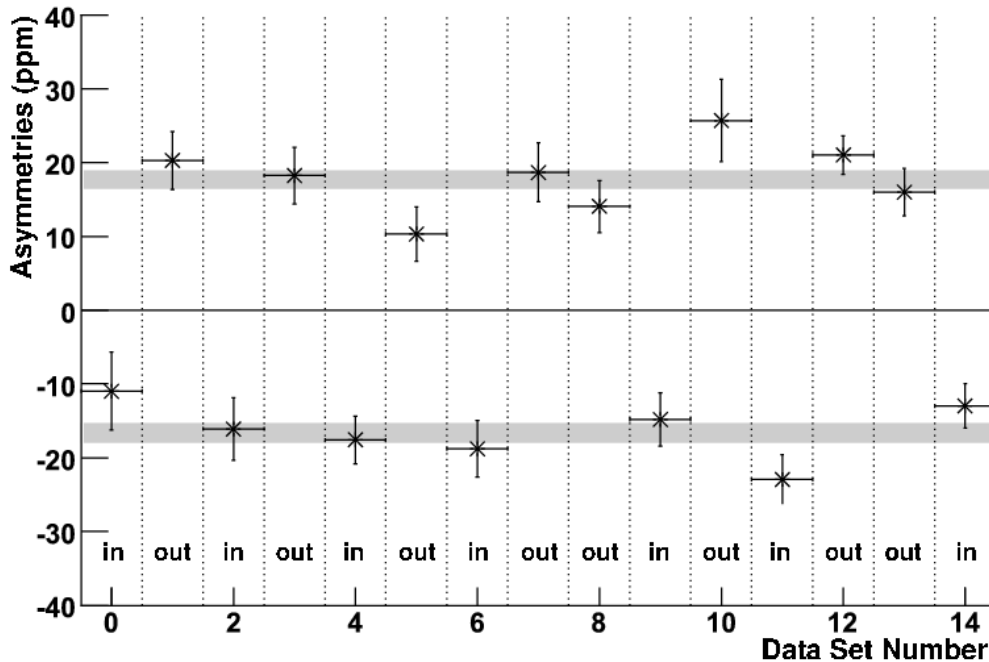
$$A_{\mathrm{RL}}=(-17.23 \pm 0.82_{\mathrm{stat}} \pm 0.89_{\mathrm{syst}})\mathrm{ppm}$$

$$A_0=(-15.87 \pm 1.22)\mathrm{ppm}$$

$$G^{\mathrm{s}}_M + 0.26 G^{\mathrm{s}}_E = -0.12 \pm 0.11 \pm 0.11$$

$$G^{\mathrm{s}}_E + 0.224 G^{\mathrm{s}}_M = 0.020 \pm 0.029 \pm 0.016$$

$$G^{\mathrm{s}}_M = -0.14 \pm 0.11 \pm 0.11$$

$$G^{\mathrm{s}}_E = 0.050 \pm 0.038 \pm 0.019$$
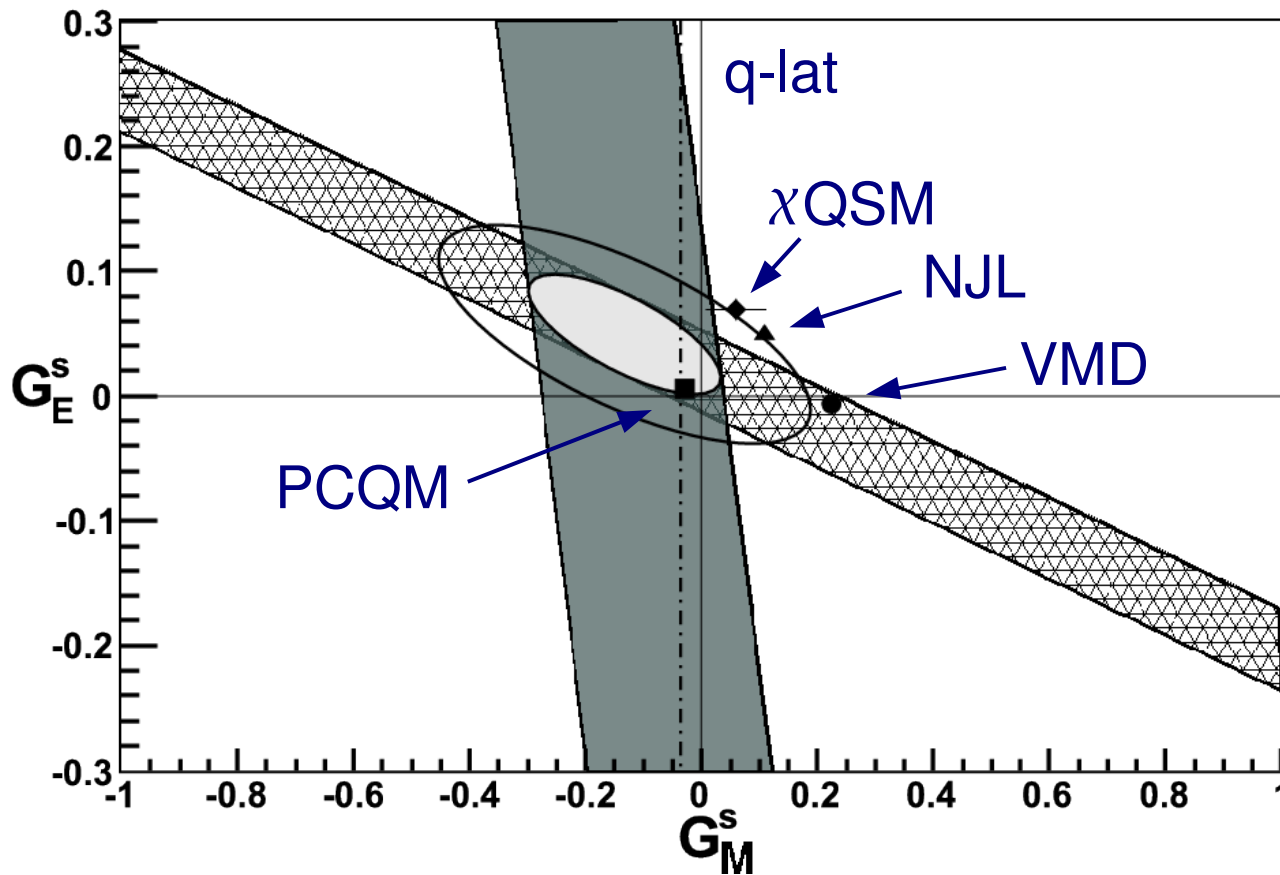
Baunack S. *et al.*, Phys. Rev. Lett. 102, 151803 (2009)

Summary

- Strangeness matrix elements as a link between QCD and EFTs

- Accessible via neutral current observables

- Landscape of PV electron scattering experiments

- A4 Measurement at 0.22 (GeV/c)^2 and G_E^{s}, G_M^{s} separation

- Strangeness contribution to nucleon vector coupling is small.

Outlook

- Measurement/analysis programme still ongoing

- Even more precise measurements are needed