The P2 Experiment at MESA

Sebastian Baunack

Johannes Gutenberg-Universität Mainz

Intense Electron Beams Workshop

June 17 - 19, 2015

Cornell University

External target experiments: Challenges and opportunities

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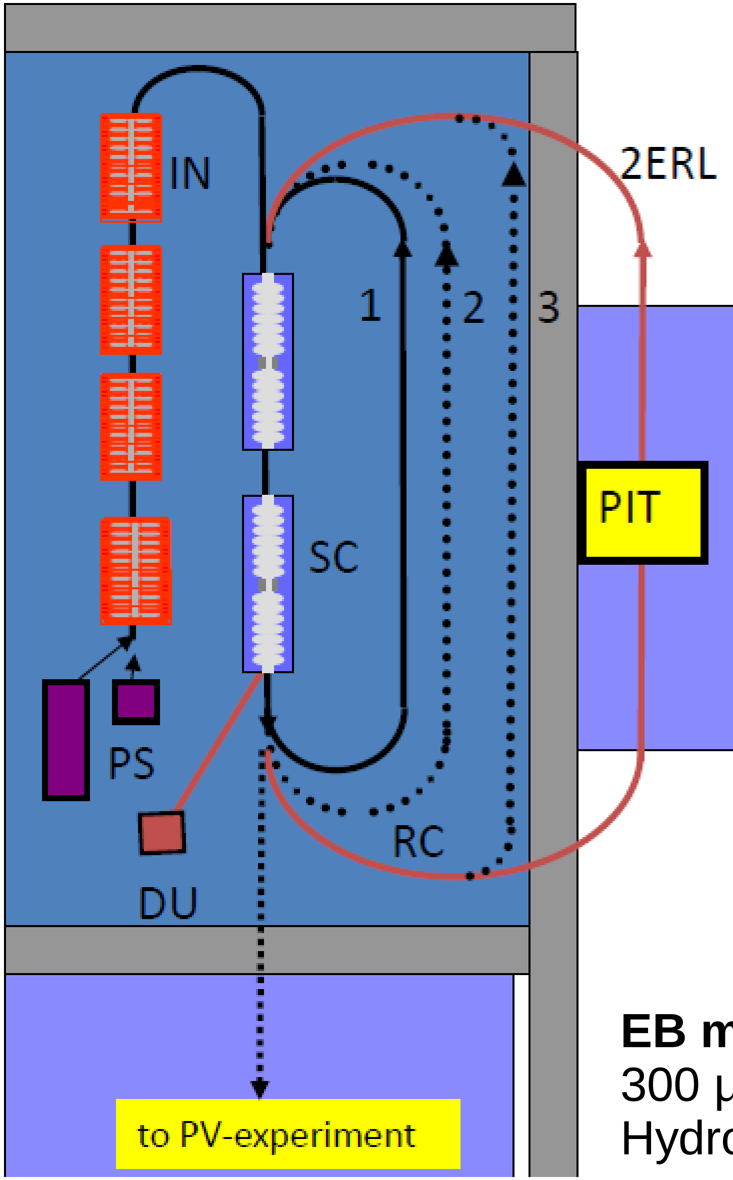
External target experiments

- Opportunities: Measurement of very small asymmetries with parity violating electron scattering
- Challenges: Technique, form factor input, targets
- Studies for the upcoming P2 experiment at MESA

Concept of an ERL



Mainz **e**nergy recovering **s**uperconducting **a**ccelerator

1.3 GHz c.w. beam
Normal conducting injector LINAC
Superconducting cavities in recirculation beamline

ERL mode (Energy recovering mode):
10 mA, 100 MeV unpolarized beam (pseudo internal gas hydrogen target L~10^{35} $cm^{-2}s^{-1}$)

EB mode (External beam):
300 µA, 150 MeV polarized beam (liquid Hydrogen target L~10^{39} $cm^{-2}s^{-1}$)

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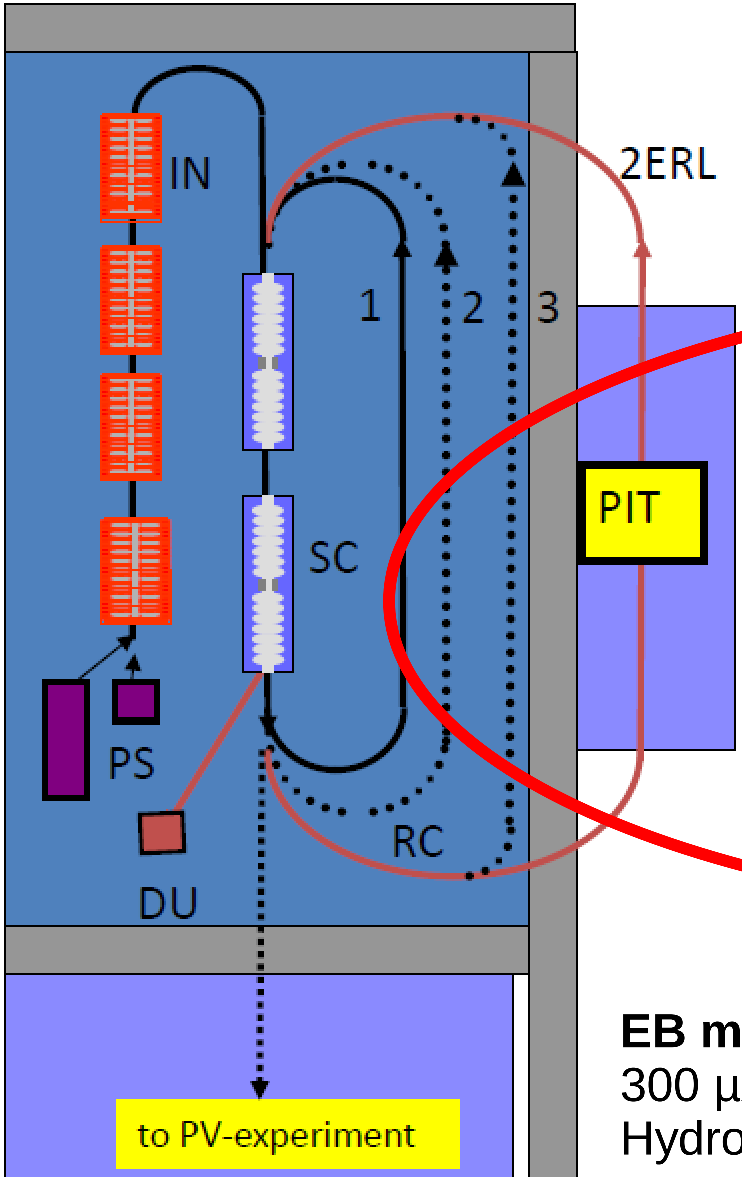

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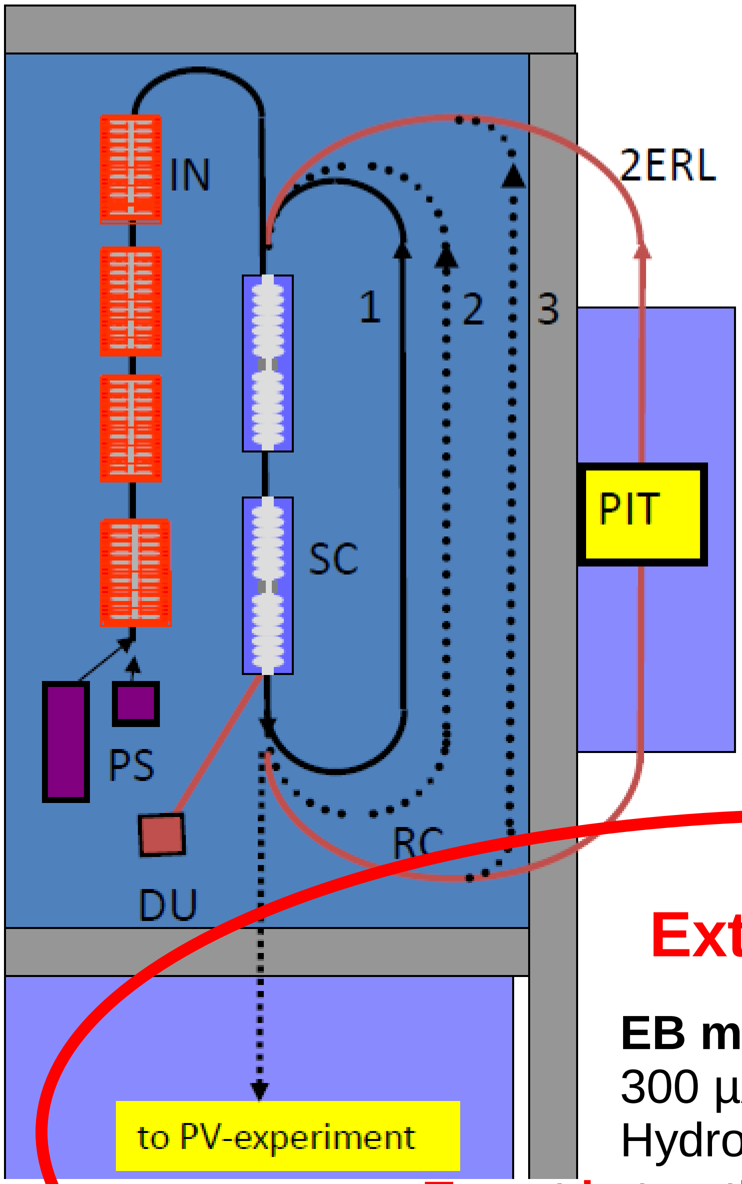
Internal target

ERL mode (Energy recovering mode):
10 mA, 100 MeV unpolarized beam (pseudo internal gas hydrogen target $L \sim 10^{35}\ cm^{-2}s^{-1}$)

Electrons that pass the internal target are decelerated and their energy recovered: Very intense electron beams possible!

EB mode (External beam):
300 µA, 150 MeV polarized beam (liquid Hydrogen target $L \sim 10^{39}\ cm^{-2}s^{-1}$)

Concept of an ERL



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External target

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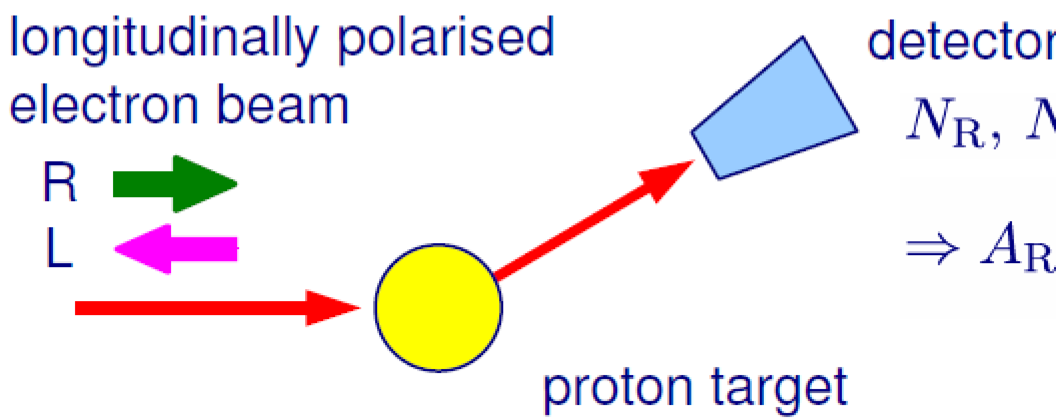
Target is too thick: Electrons can't be decelerated and go directly into a beam dump
Very high luminosity possible!

Parity violating electron scattering



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

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

- <u>Statistical uncertainty</u>

  for a counting experiment:

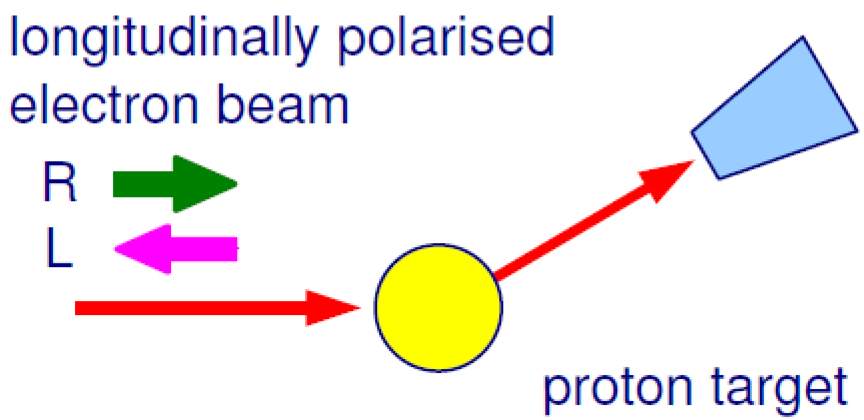
$$\begin{aligned} A &= 10^{-6} \\ \delta A &= \frac{1}{\sqrt{N}} \simeq 10^{-7} \\ &\Rightarrow N \simeq 10^{14} \end{aligned}$$

1000 hours $\Rightarrow$ $\sim$10 MHz

- high luminosity
- large acceptance
- fast detector

- <u>Systematic uncertainty</u>
  - helicity correlated fluctuations
  - polarisation measurement

Parity violating electron scattering



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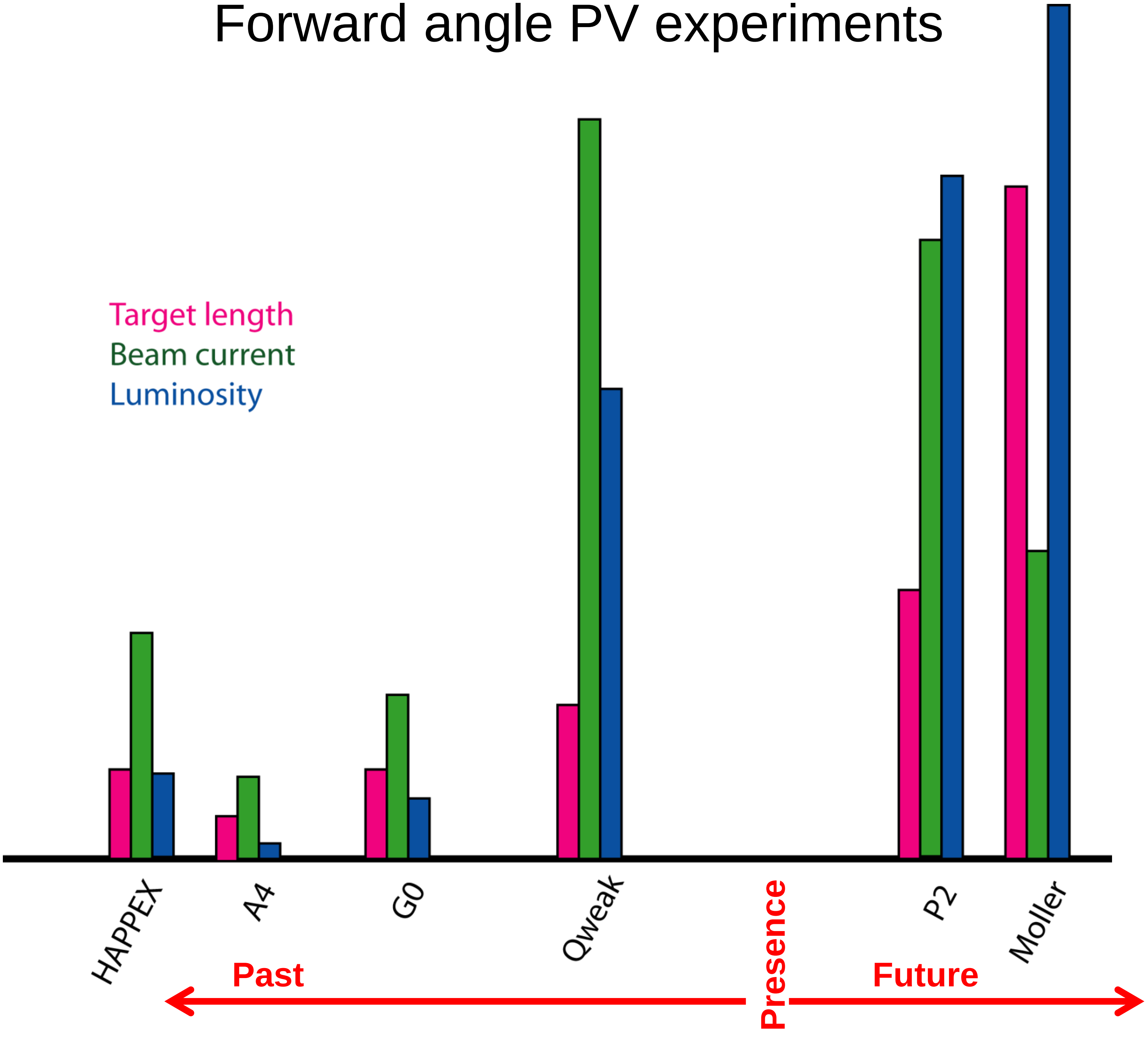
Forward angle PV experiments



Forward angle PV experiments

Experiment	Luminosity (10^{38} s^{-1} cm^{-2})	Target cooling power (kW)
HAPPEX	2.9	0.5
A4	0.5	0.2
G0	2.1	0.4
Qweak	16	2.8
P2	24	4.0
Moller	30	5.0

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Measure tiny asymmetries in ppb range

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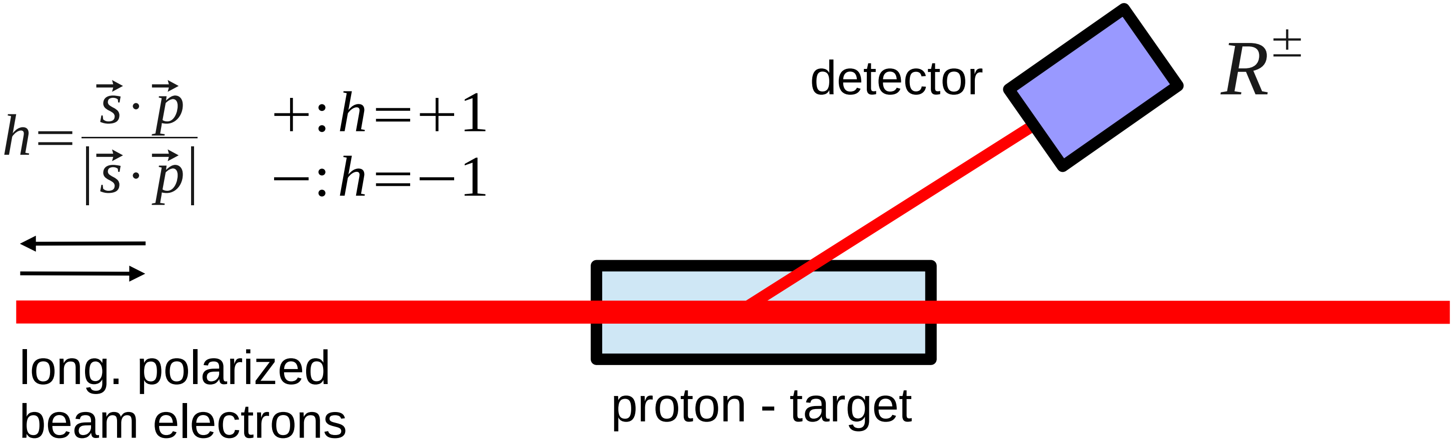
Opportunity!
Measure tiny asymmetries in ppb range

Challenge!
Huge energy deposition in the hydrogen target

PVES and the weak mixing angle $\sin^2\Theta_W(\mu)$

$$h = \frac{\vec{s}\cdot\vec{p}}{|\vec{s}\cdot\vec{p}|} \qquad \begin{array}{l} +: h=+1 \\ -: h=-1 \end{array}$$



At low momentum transfer:

$\underline{Q^2 \longrightarrow 0:}$ $$A_{PV} = \frac{-G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W(p) - F(Q^2)\right)$$

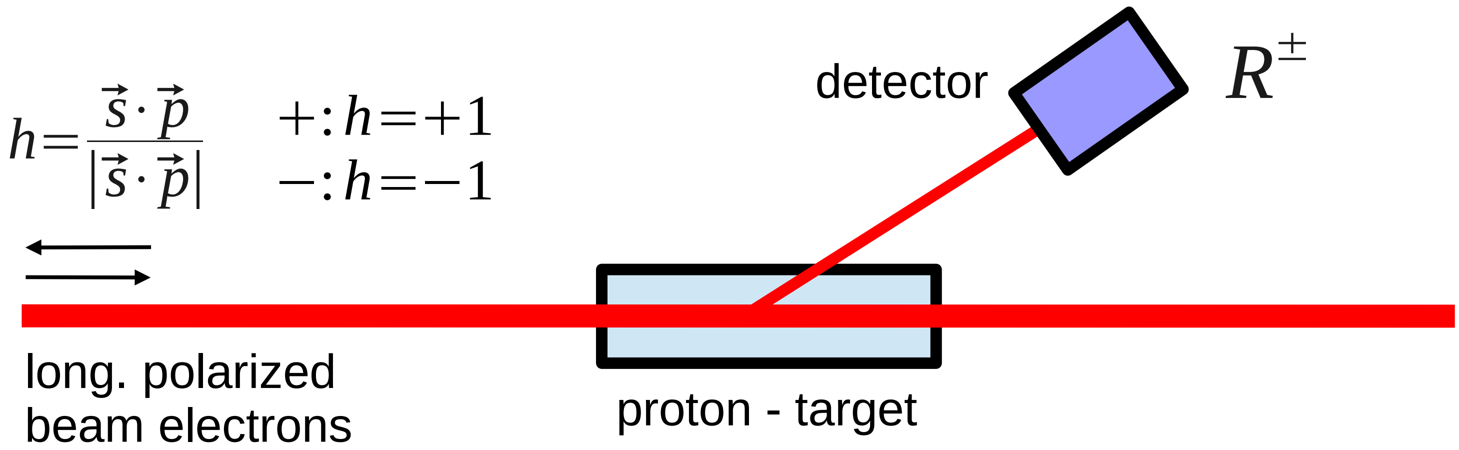
Weak charge of the proton:

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

Proton structure:

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

PVES and the weak mixing angle $\sin^2\Theta_W(\mu)$



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Weak mixing angle

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The weak mixing angle / standard model relations

Relations at tree-level (classical level), e.g.,

- electric charge $e = \sqrt{4\pi\alpha} = g_1 \cos\theta_W = g_2 \sin\theta_W$
- $\cos\theta_W = M_W / M_Z$
- Muon decay constant: $G_\mu = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W M_W^2}$
- … and many more

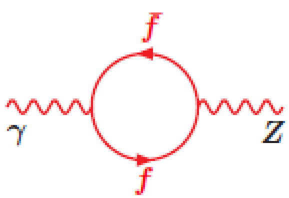
Including quantum corrections (perturbation theory):

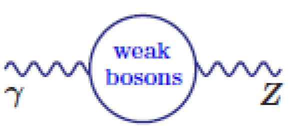
- $G_\mu = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W M_W^2}(1+\Delta r)$

  with

  $\Delta r = \Delta r(\alpha, M_W, \sin\theta_W, m_{top}, M_{Higgs}, \dots)$

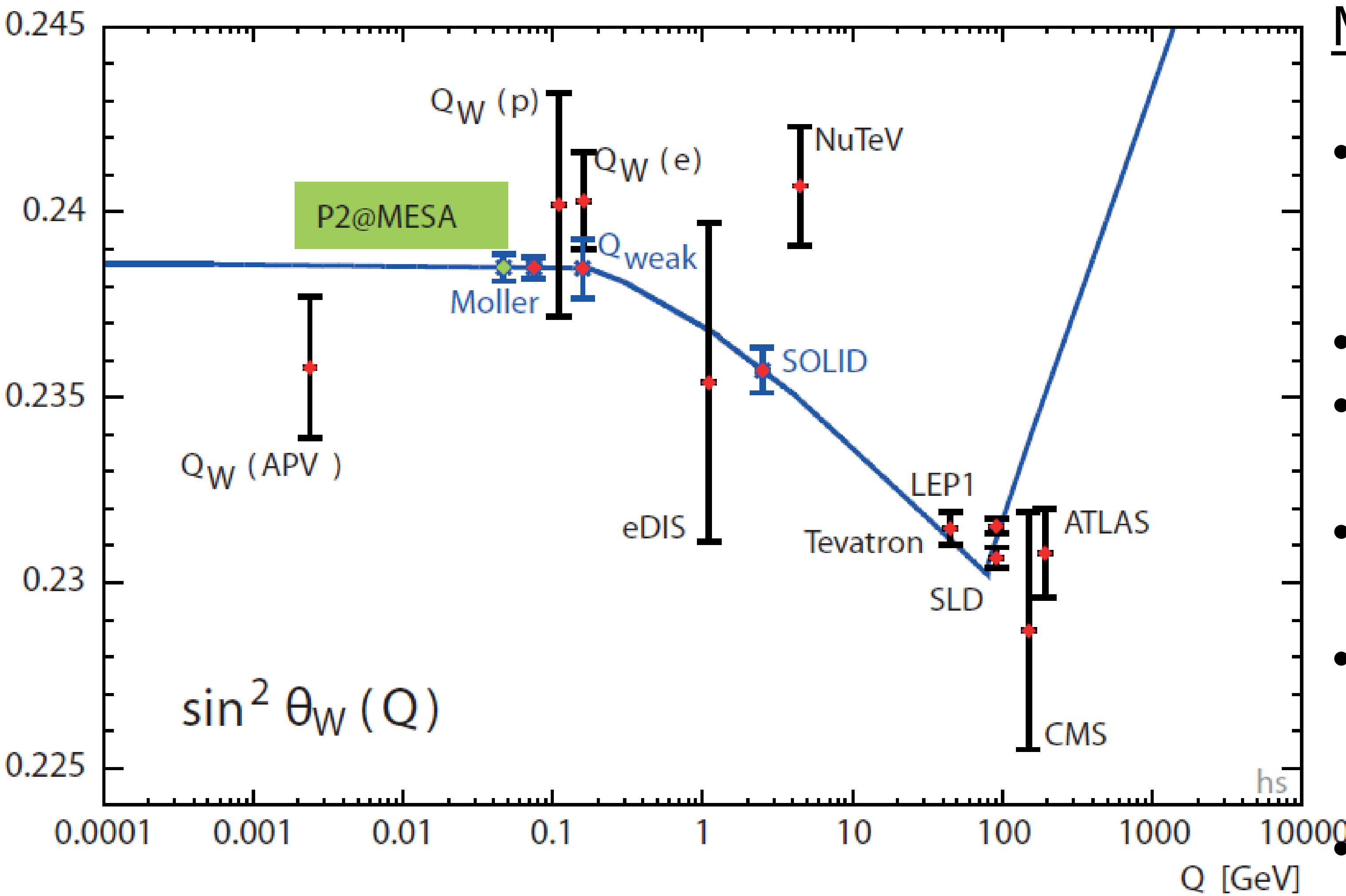
- Absorb universal quantum corrections





  into effective, running, scale-dependent parameters, denoted $\sin^2\theta_{\text{eff}}$ or $\sin^2\theta_W(\mu)$ where μ is a characteristic energy scale

The weak mixing angle $\sin^2\Theta_W(\mu)$



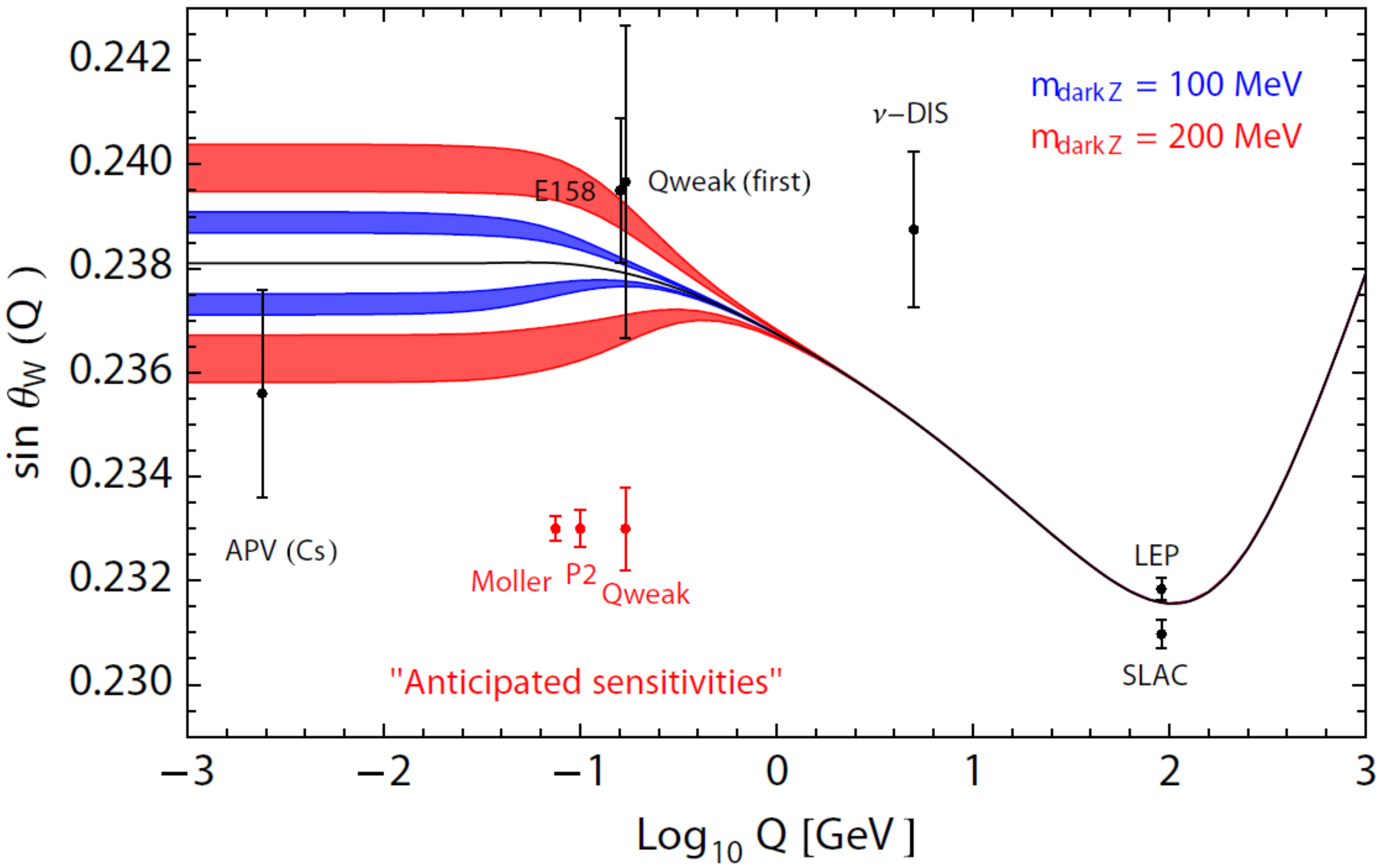
<u>Measurements</u>:

- Atomic parity violation
- Neutrino scattering
- LEP and SLAC
- Tevatron
- Q_{weak} (finished data taking)
- Moller (planned)
- **P2 (planned)**

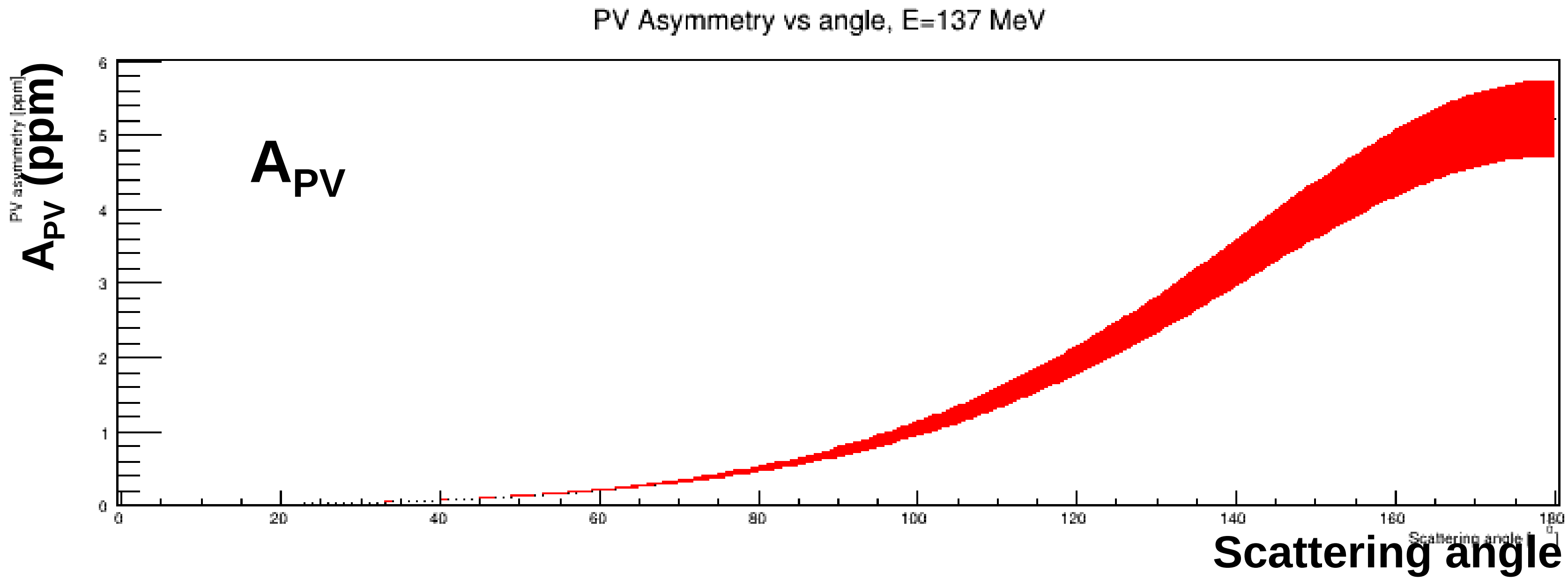
Sensitivity to a new Physics

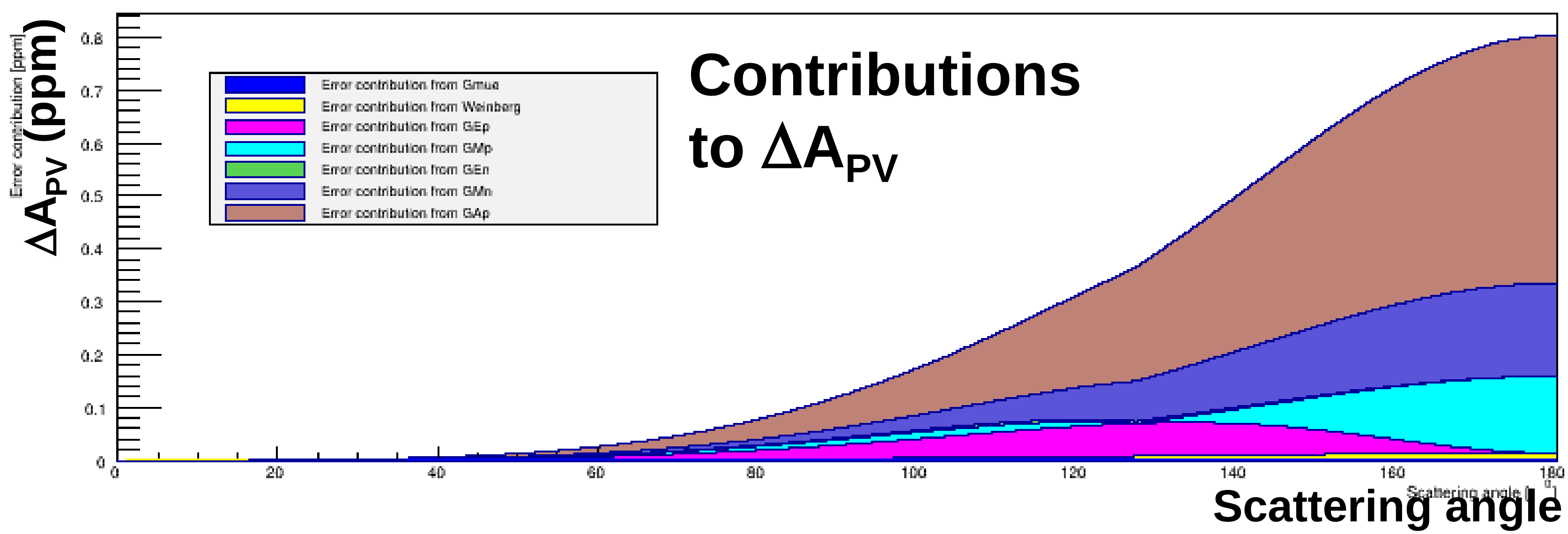
Example: Dark Z boson

H. Davoudiasl, H. S. Lee and W. J. Marciano, Phys. Rev. D **89** (2014) 9, 095006



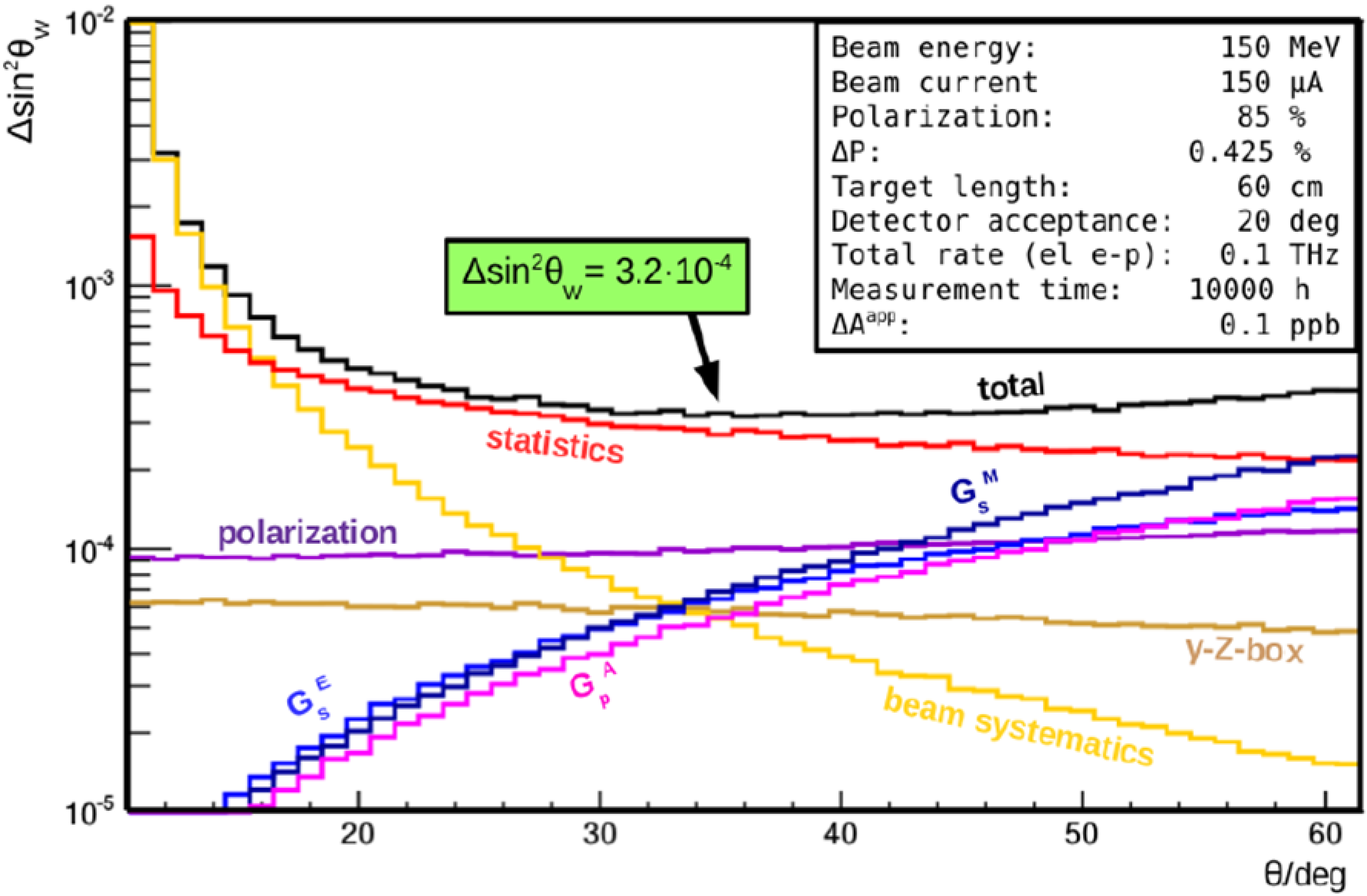
Finding a scattering angle for an experiment





=> Forward scattering angles preferred!

Choice of kinematics for the P2 experiment



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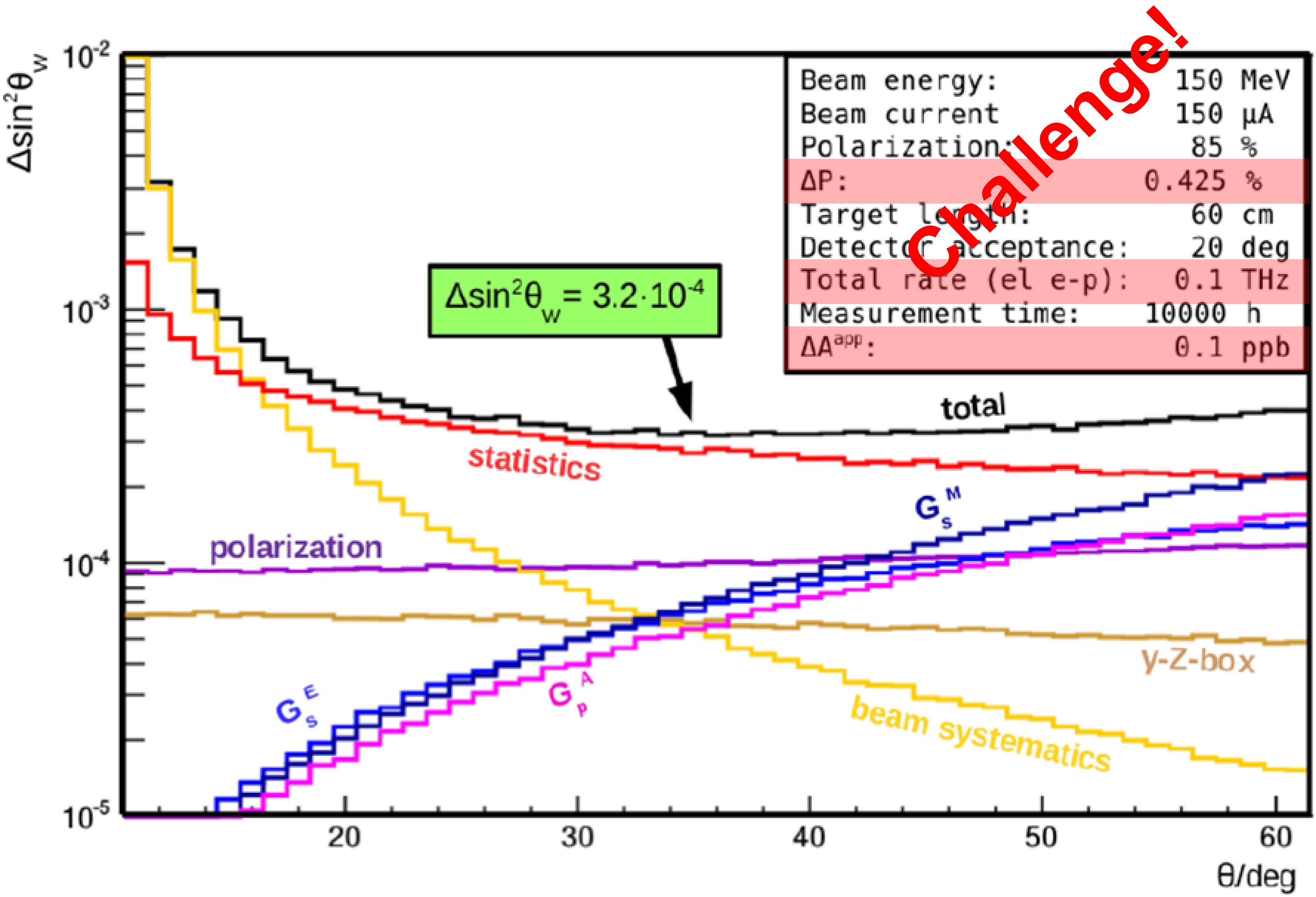

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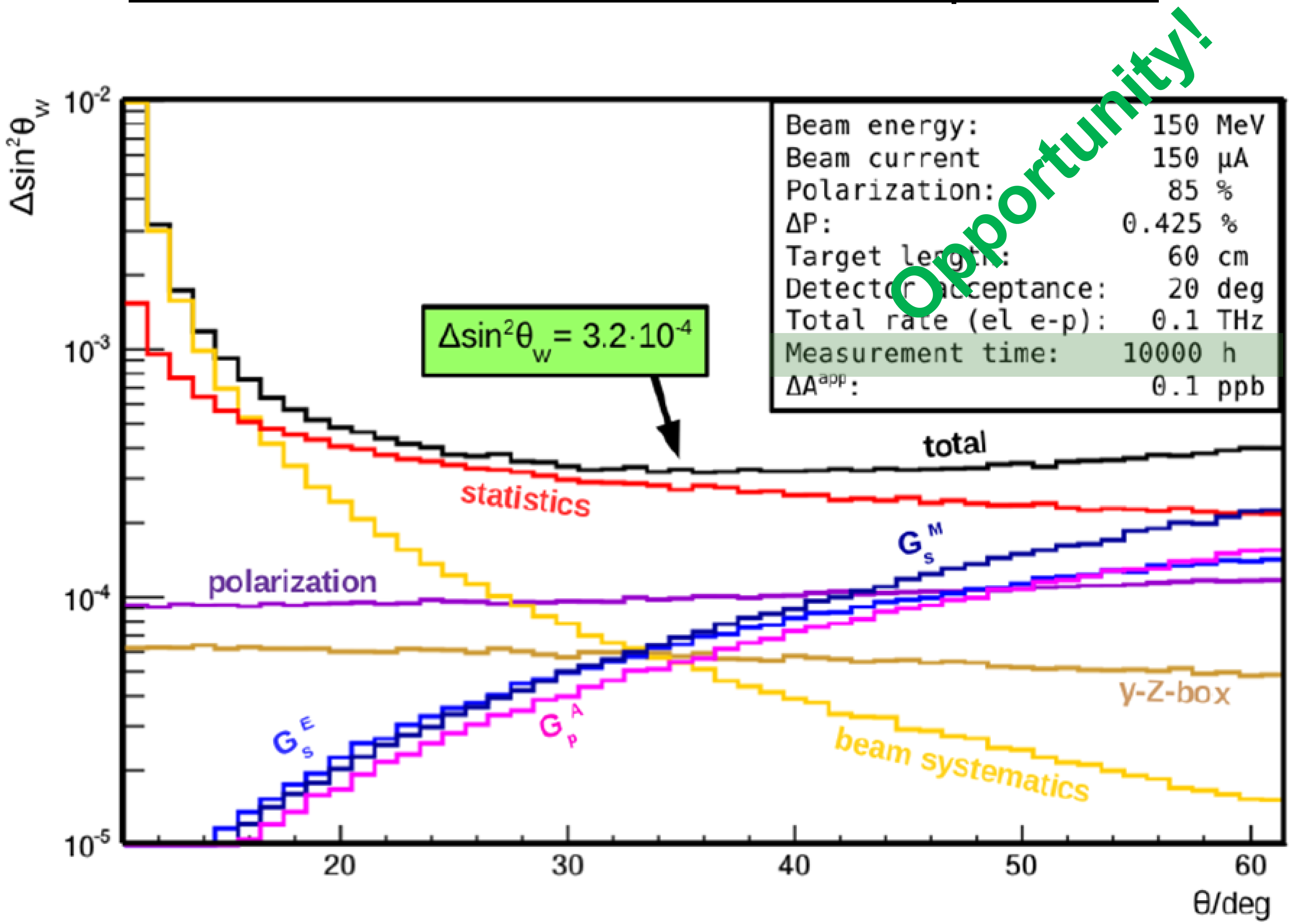
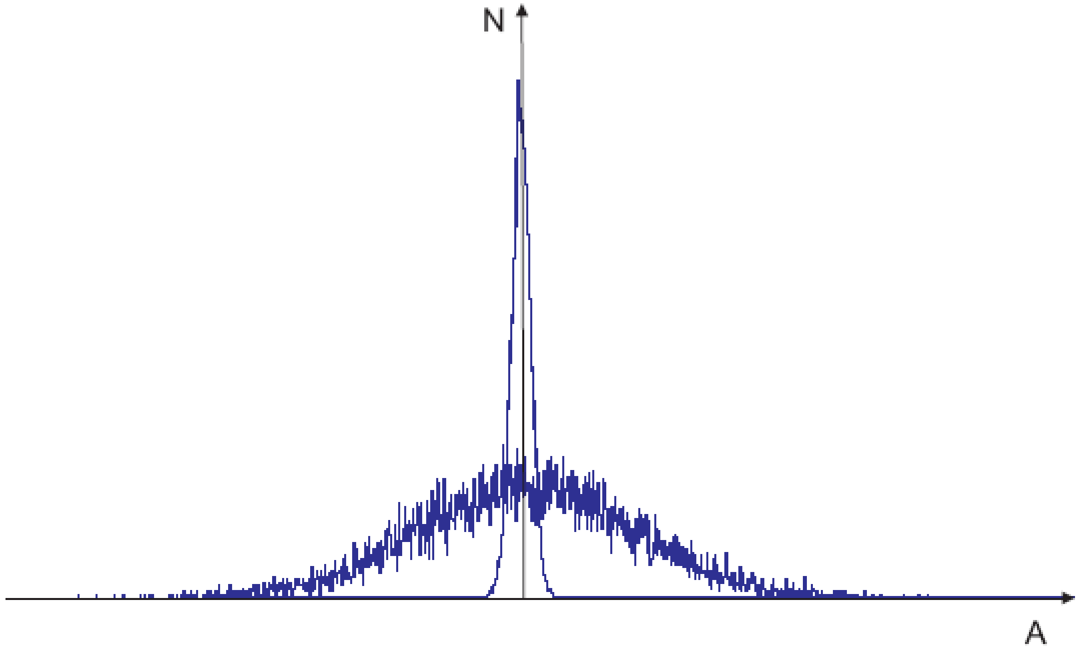


Beam fluctuations

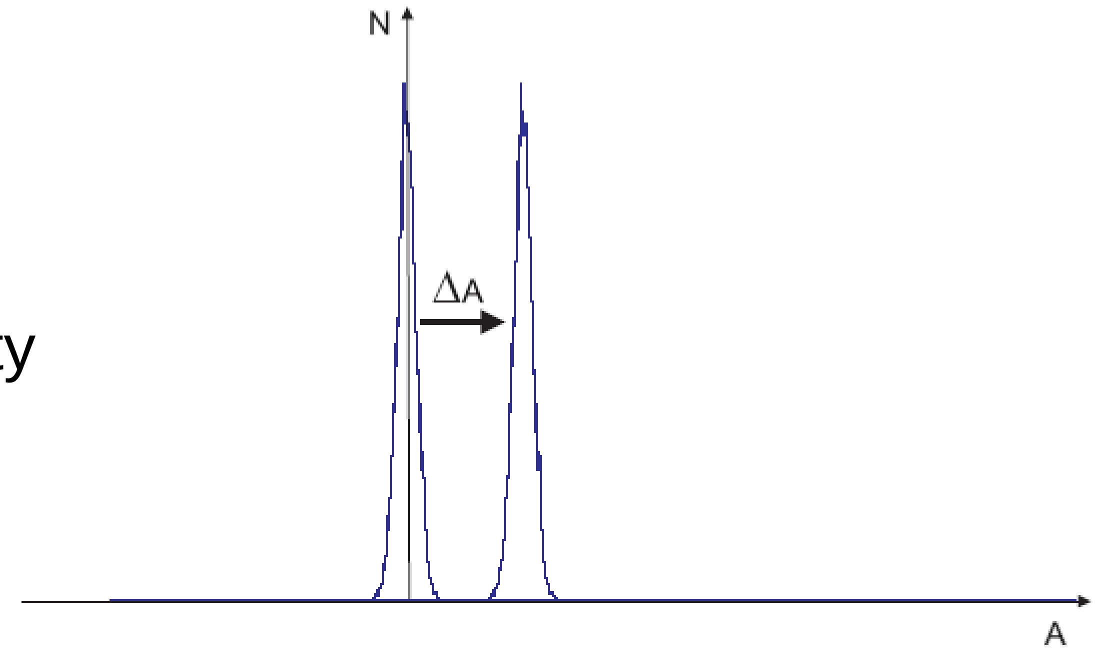
Uncorrelated
beam fluctuations:

Larger uncertainty



Helicity correlated
beam fluctuations:

Systematic uncertainty



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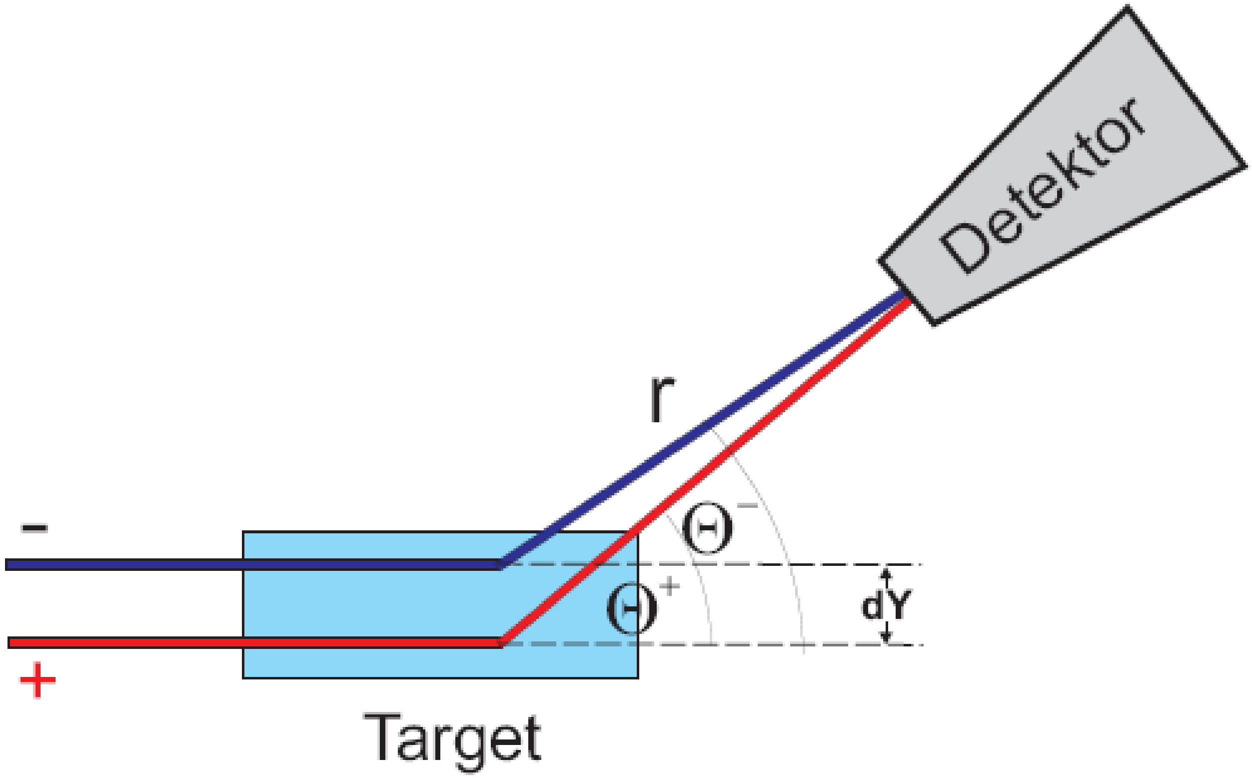


Example:

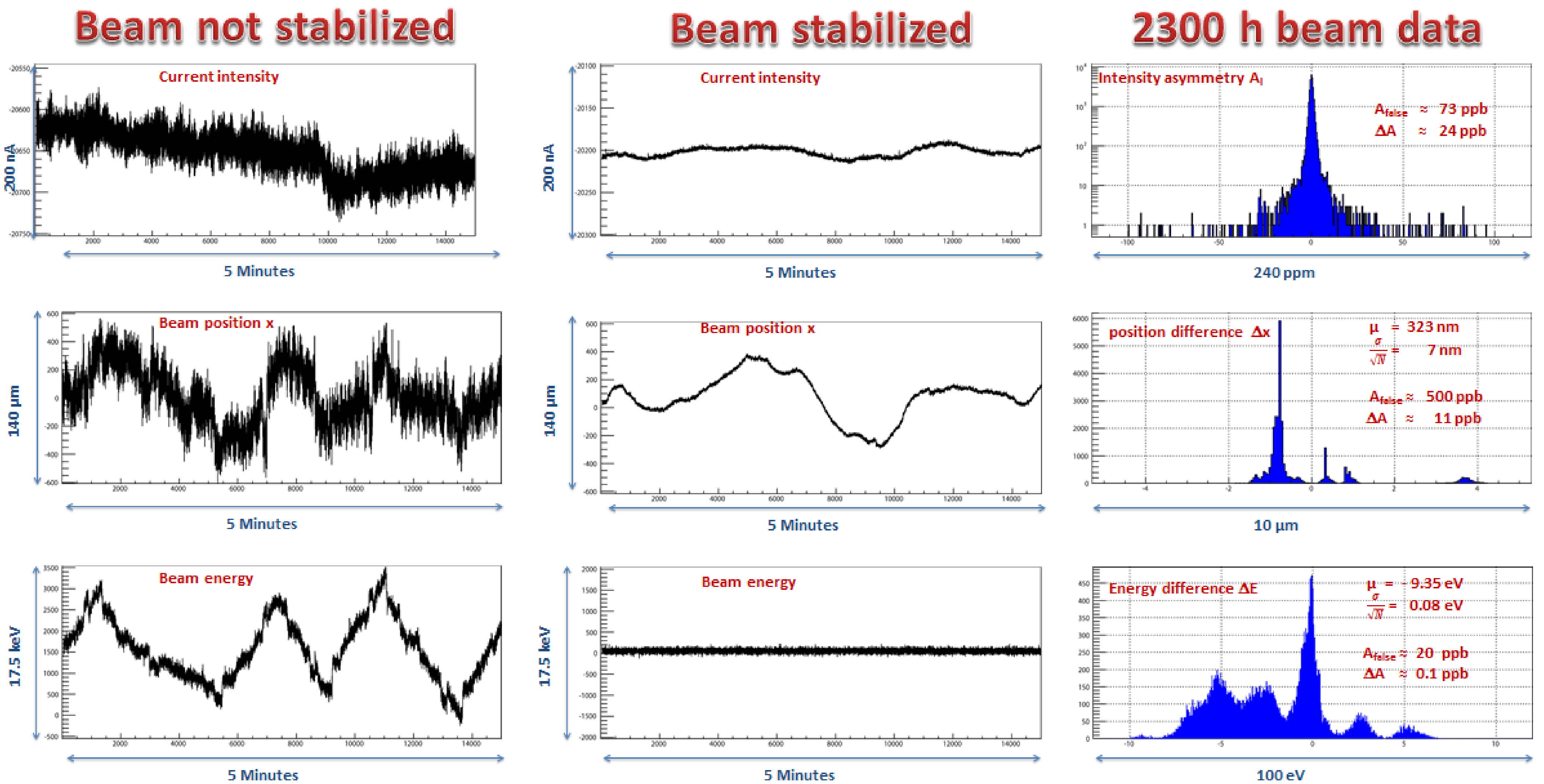
Different positions of the beam for the helicities "+" and "-"

- Different scattering angles
- Different cross sections
- Different solid angles
- Different scattering rates

=> False asymmetries

Beam stabilization at MAMI/A4

- Analog feedback loops
- Helicity flip 50 Hz
- Beam energy 315 MeV



Helicity correlated beam fluctuations

Which uncertainty contribution to A_{PV} would be realistic with the existing MAMI technique after 10.000 hours of data taking?

Requirement from the experiment: ΔA<0.1 ppb

Helicity correlated beam parameter	Expected average after 10.000 hours	Uncertainty contribution after 10.000 hours
Beam intensity asymmetry	23 ppb	11 ppb
Beam position difference	7 nm	5 ppb
Beam energy difference	0.04 eV	< 0.1 ppb

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Improvements for the new accelerator MESA:

- Digital feedback loops (FPGA based)
- Stabilizations directly on the beam differences / asymmetries
- Increased bandwidth / sensitivity for the beam monitors

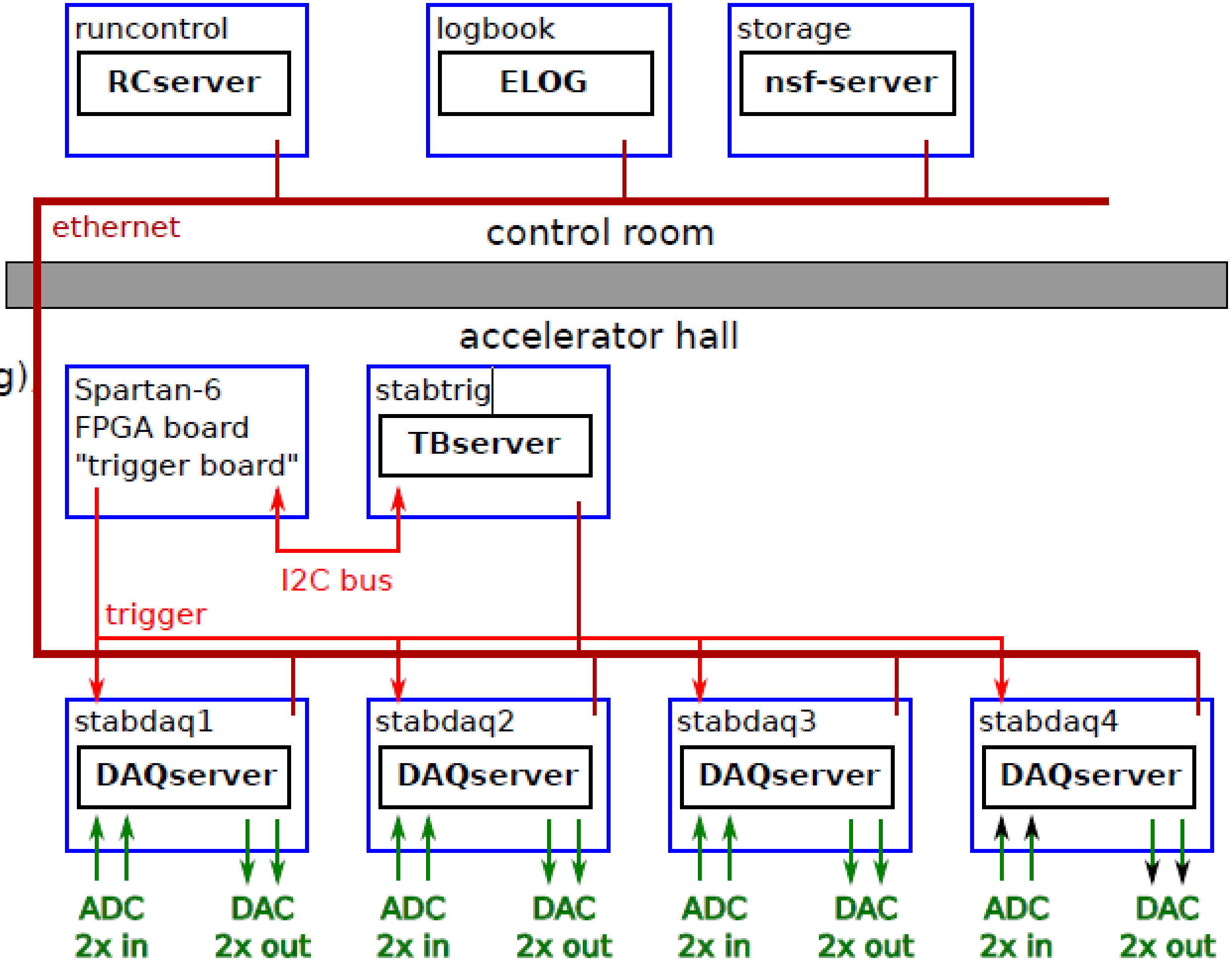
Helicity correlated beam fluctuations

Test of new feedback techniques already started with 180 MeV beam at MAMI

PCs for runcontrol, electronic logbook (ELOG), and data storage

embedded PC (stabtrig) Spartan-6 FPGA board with IP cores for i2c and trigger

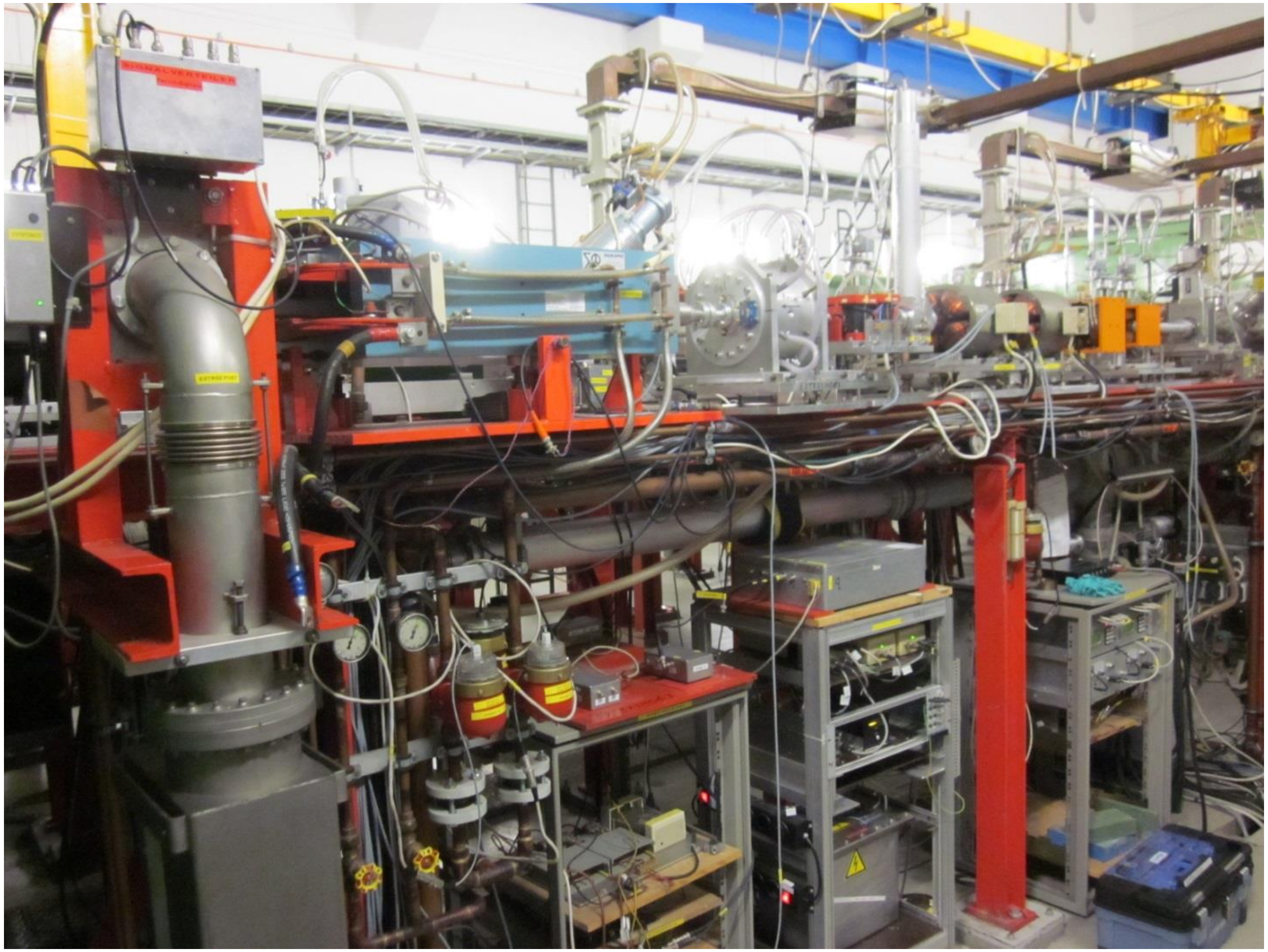
Zynq7000-based DAQ boards
2 ADCs, 2 DACs each, all 125 MSa/s

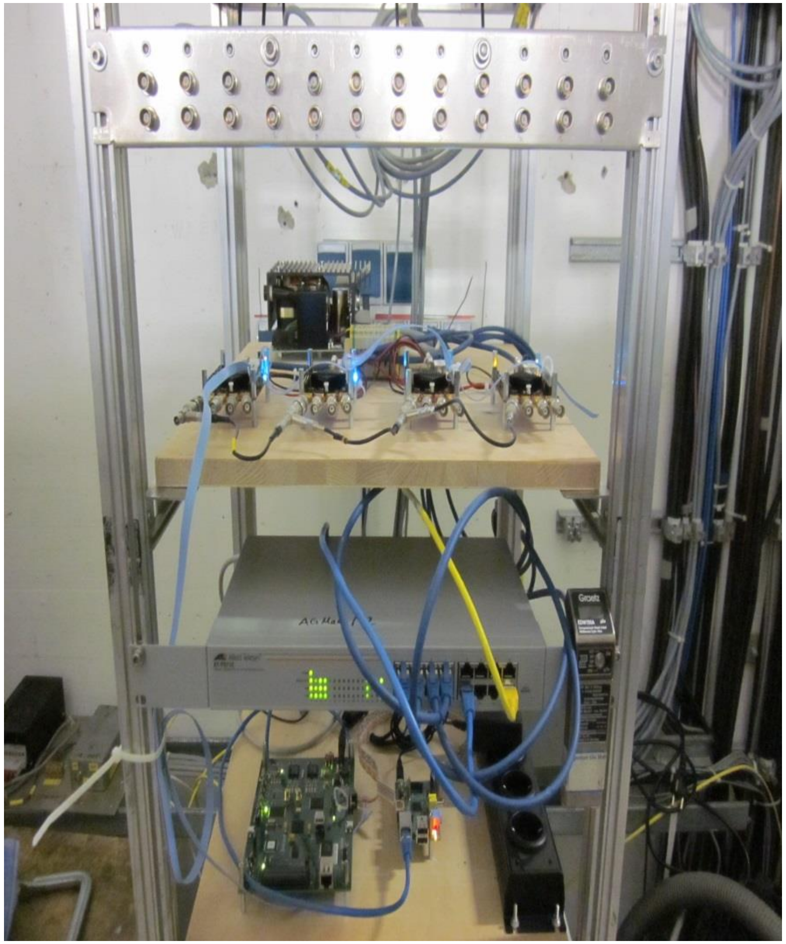


ADCs and DACs for readout and control of beamline elements: XYMOs (beam position monitors), fast steerers

Installations at MAMI

Test of new feedback techniques already started with 180 MeV beam at MAMI





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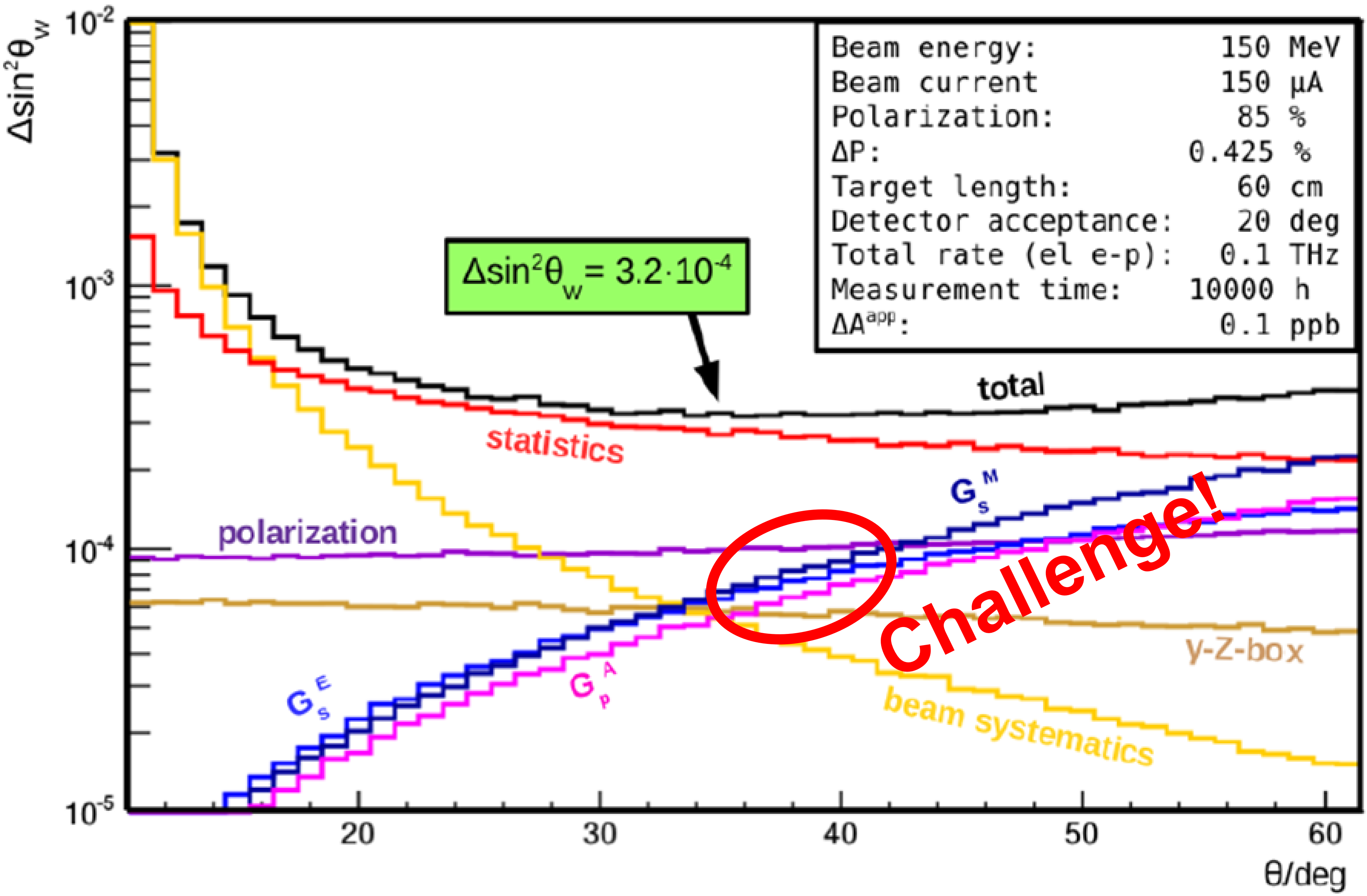

Form factor input

Parity violating asymmetry

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

Vector coupling without strangenes

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

Axial coupling

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

Vector coupling, strangeness contribution

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

$$\tau = \frac{Q^2}{4M_p^2} \qquad \varepsilon = \frac{1}{1+2(1+\tau)\tan^2\frac{\theta}{2}}$$

Form factor input

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Largest contributions to the uncertainty

Vector coupling, strangeness contribution

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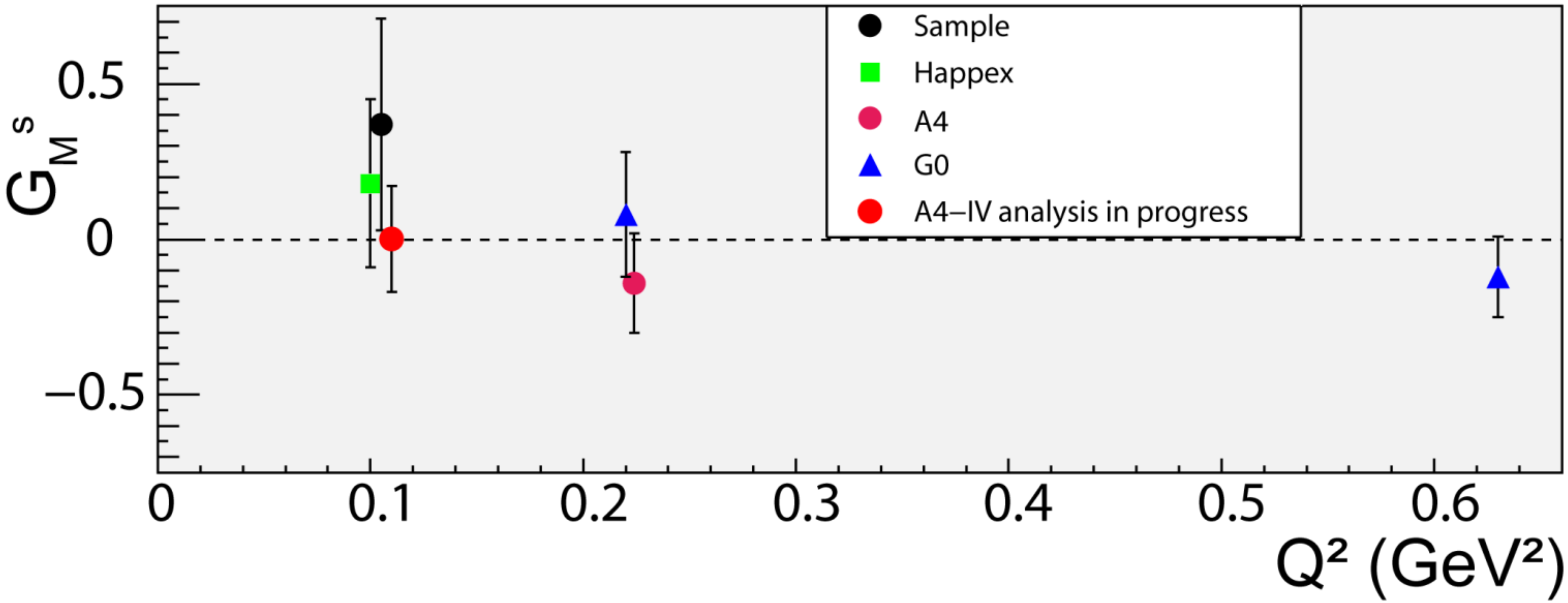
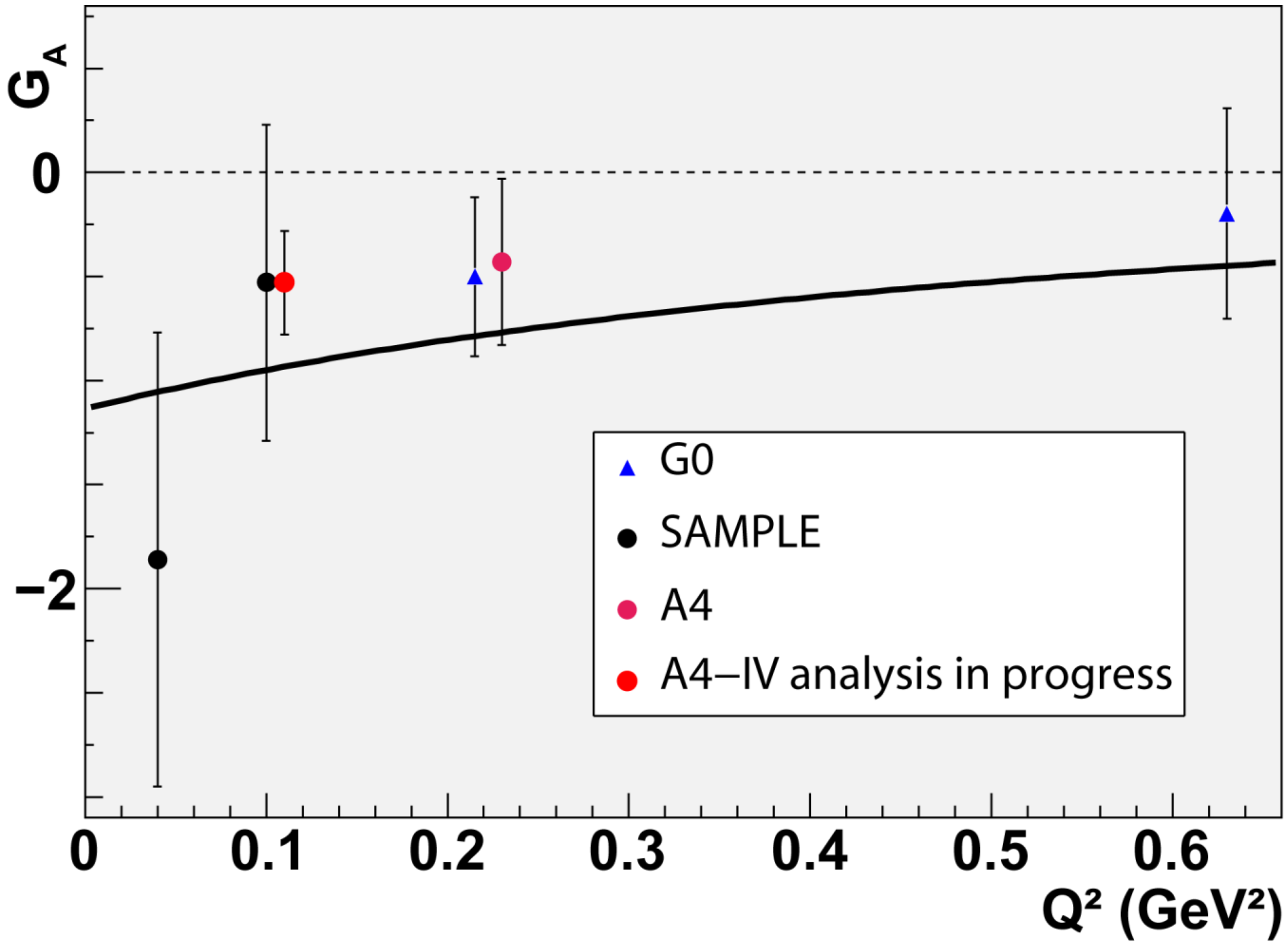
Experimental data for G_M^s



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

Experimental data for G_A



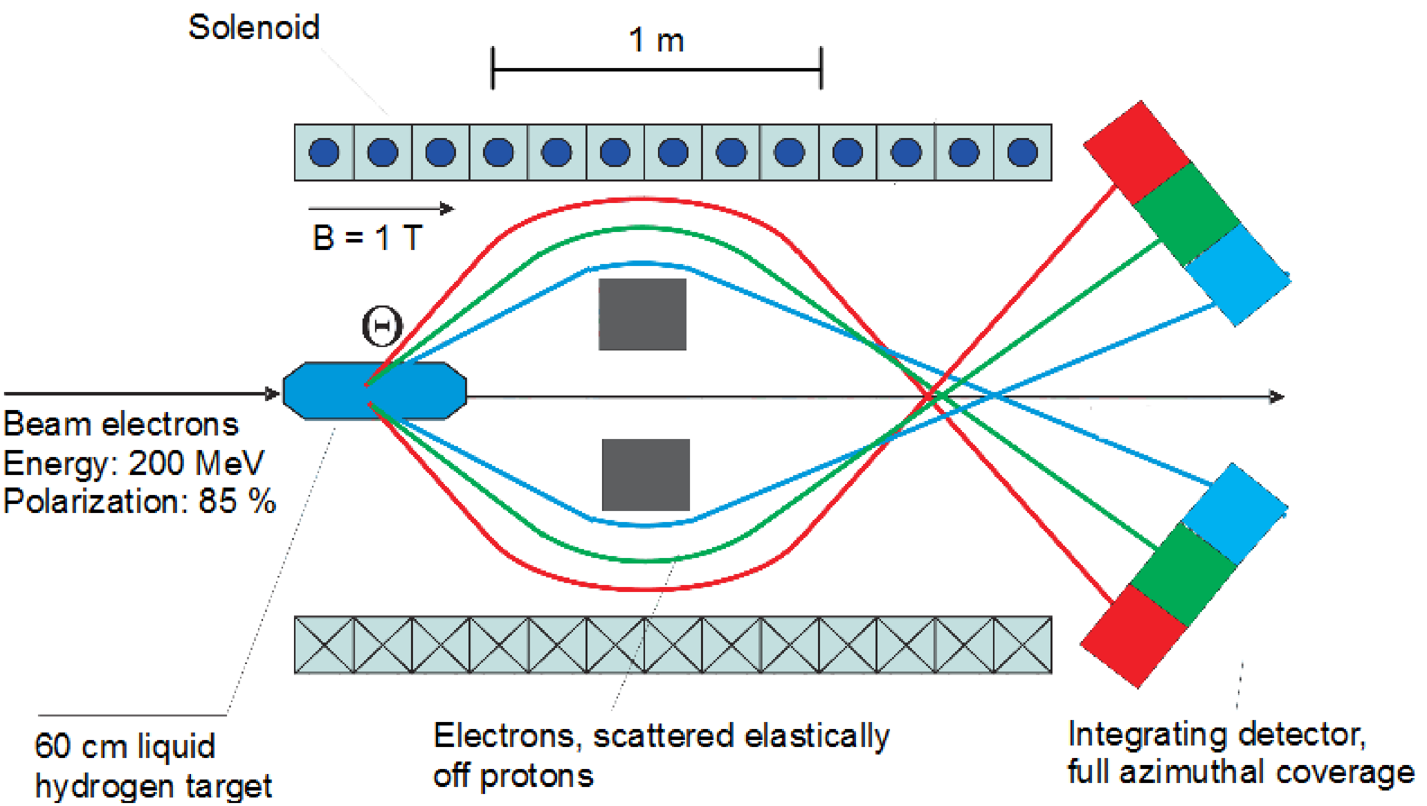
SAMPLE: T. M. Ito *et al*., Phys.Rev.Lett. 92 (2004) 102003
G0: D. S. Armstrong *et al.*, Phys.Rev.Lett. 95 (2005) 092001
D. Androic *et al.*, Phys.Rev.Lett. 95 (2005) 092001
A4: Paper in progress

A4-IV: about 700 hours deuterium data on tape

Can we measure G_M^s and G_A with better precision?

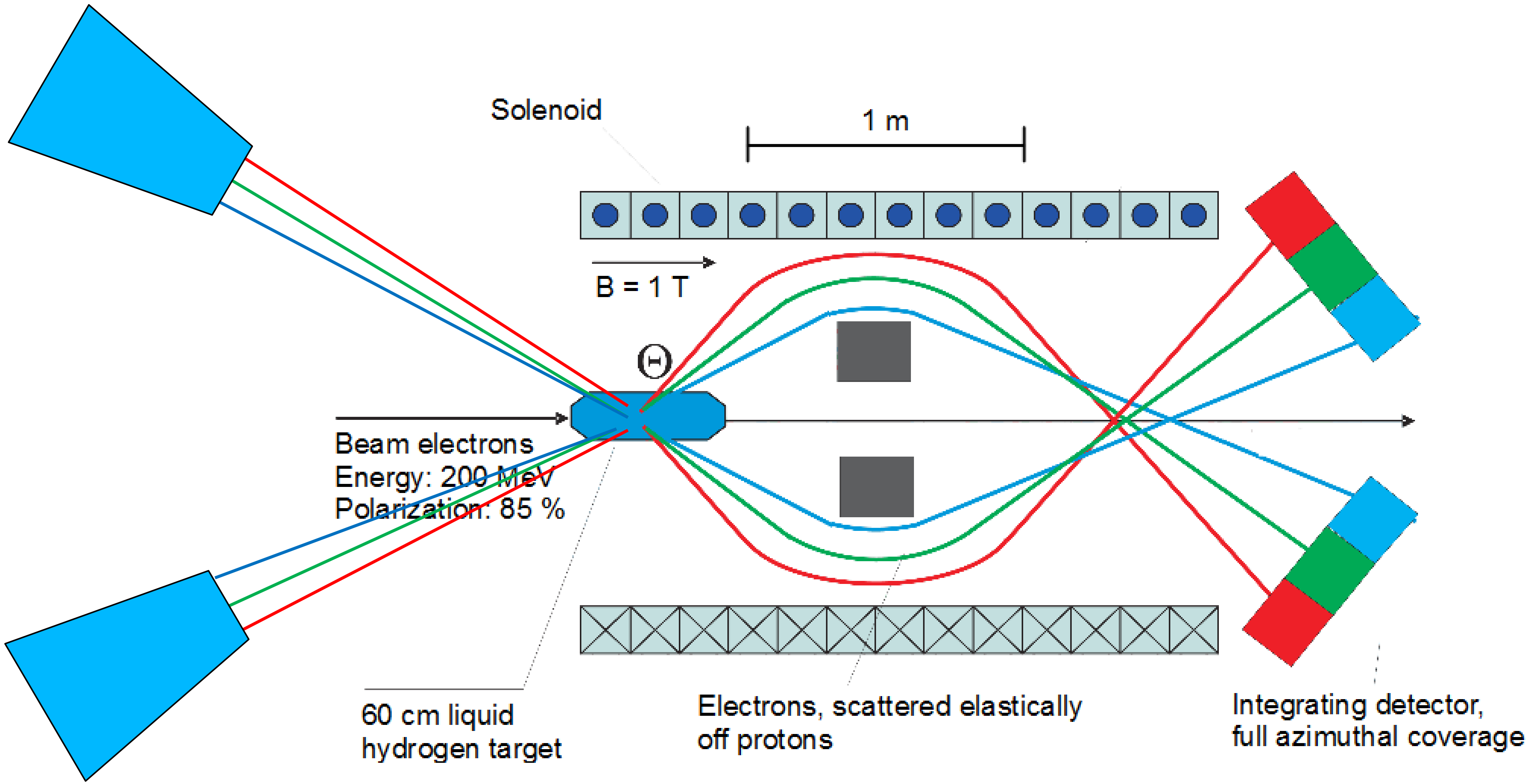
Sketch of P2 main experiment:

- Liquid hydrogen target
- Elastic ep-scattering $\Delta\Theta = 20°$
- Measurement time: T=10.000 h
- Luminosity $L=2.5 \cdot 10^{39} \frac{1}{s \cdot cm^2}$



P2 back angle measurement!

Back angle measurements: Determination of G_M^s and G_A



P2 back angle measurement

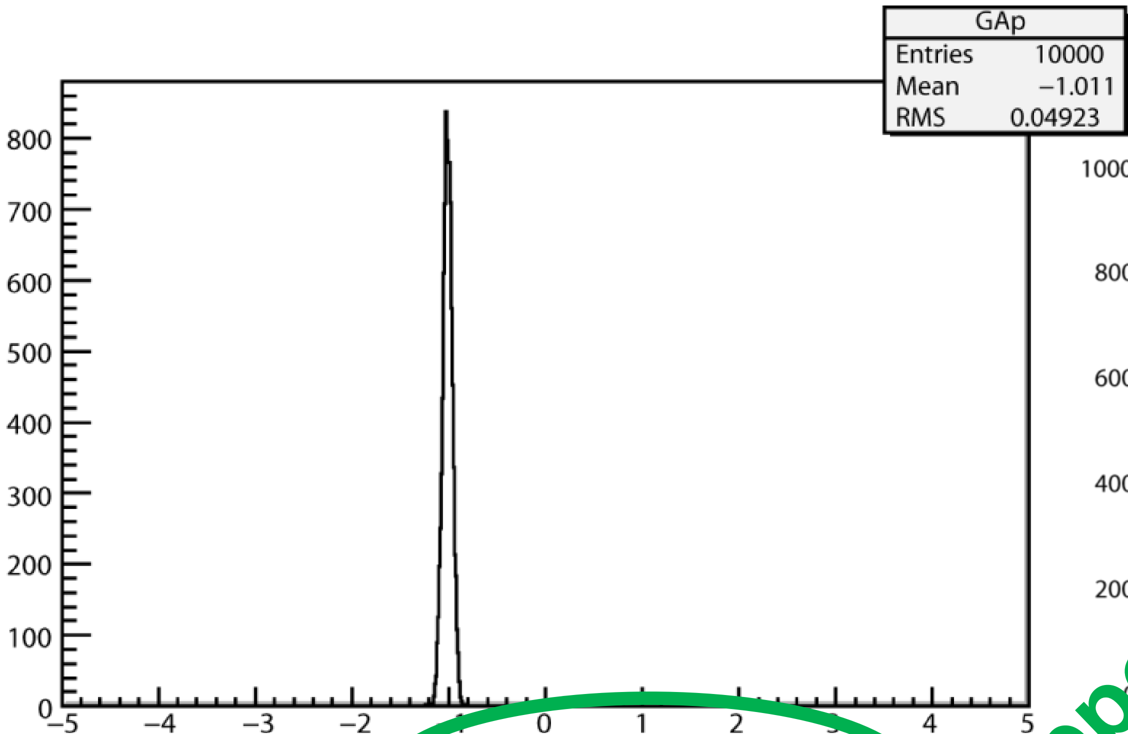
Imagine to place an A4-like detector ($\Delta\Omega$=0.63 sr, 140° ≤ Θ ≤ 150°) into the P2 setup:
$A_{PV} \approx 7.5$ ppm

Parameter		P2 back angle experiment
Integrated luminosity		$8.7 \cdot 10^7$ fb^{-1} ΔA_{stat}= 0.03 ppm
HC correlated false asymmetries		ΔA_{HC} = 0.0001 ppm
Polarimetry		ΔP = 0.5% ΔA_{Pol} = 0.04 ppm
Uncertainty in the measured asymmetry		**ΔA_{tot} = 0.05 ppm (0.7 %)**

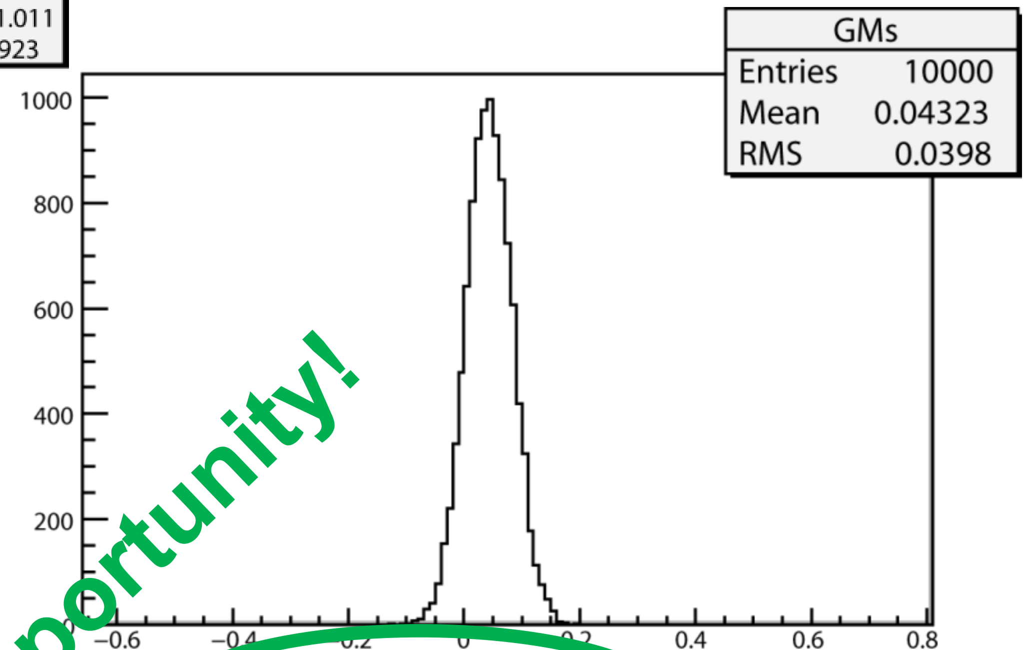
Ideal solution: Separate measurements with hydrogen and deuterium target

Possible uncertainties of G_A and G_M^s with P2 back angle measurement

- 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 factors input taken into account



$$\Delta G_A = 0.05$$

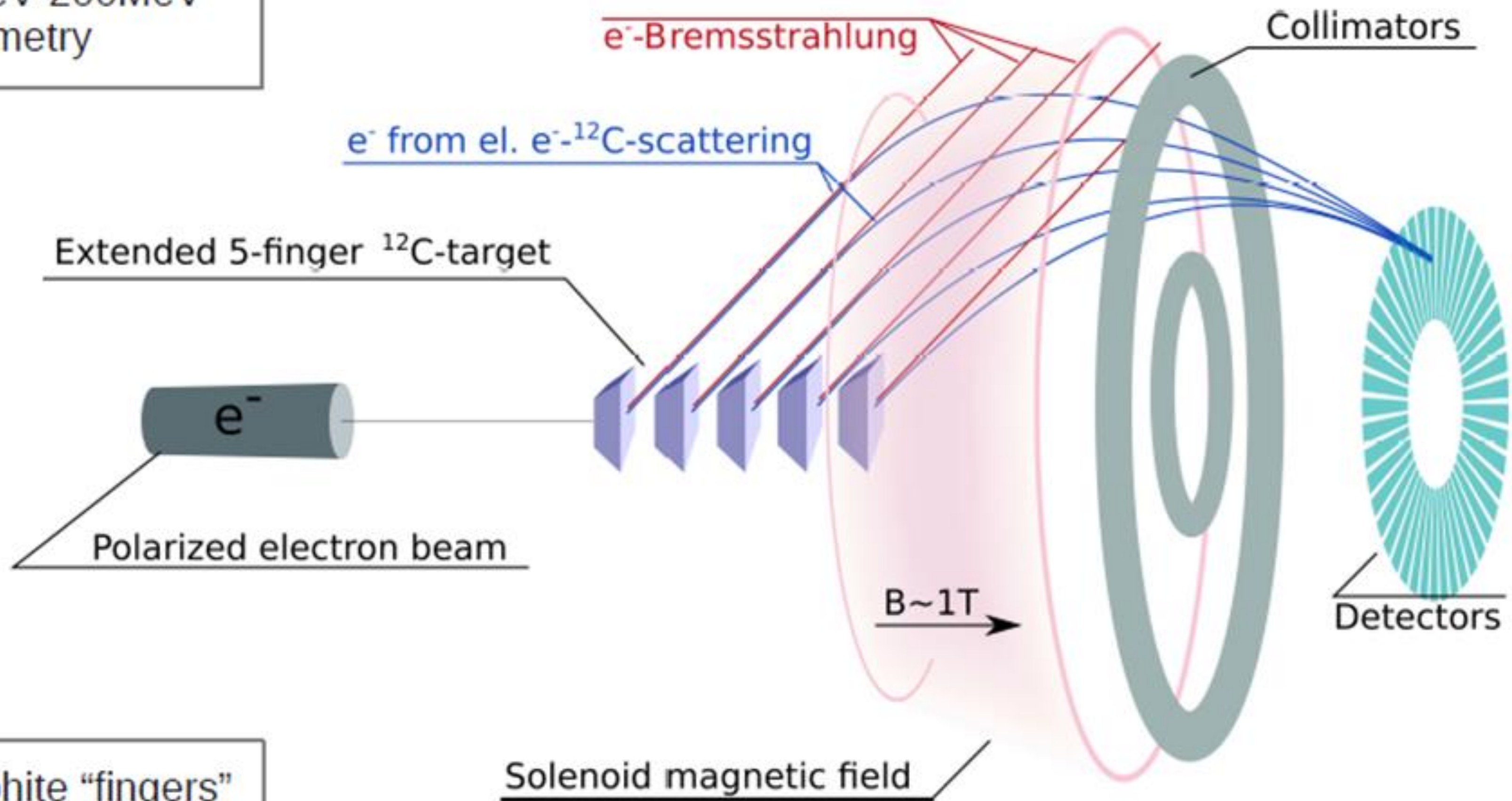


Opportunity!

$$\Delta G_M^s = 0.04$$

Measurements with other targets at P2

MESA:
- 150µA
- 150MeV-200MeV
- Polarimetry



Target:
- 5 graphite "fingers"
- 5 g/cm² total
- 36mm spacing

Sensitivity of the weak charges to New Physics

Parametrization of “new” quantum loop corrections:

$$Q_W^C = -5.5080(5)[1 - 0.003T + 0.016S - 0.034X(Q^2) + \chi]$$

$$Q_W^p = +0.0708(9)[1 + 0.150T - 0.200S + 0.4X(Q^2) + 4\chi]$$

$$Q_W^e = -0.0458(6)[1 + 0.240T - 0.34S + 0.7X(Q^2) + 7\chi]$$

$$Q_W^{Cs} = -73.24(4)[1 + 0.010S - 0.023X(Q^2) - 0.9\chi]$$

$$\chi = m_Z^2 / m_{Z_\chi}^2$$

SM

“NEW PHYSICS”

→ Measurements of different Weak Charges are complementary!

^{12}C measurement at P2

@ Beam energy E = 150MeV
Scattering angle Θ = 40° +- 9°
Target density d = 5g/cm²

Measuring time t = 2500h
Beam current I = 150µA

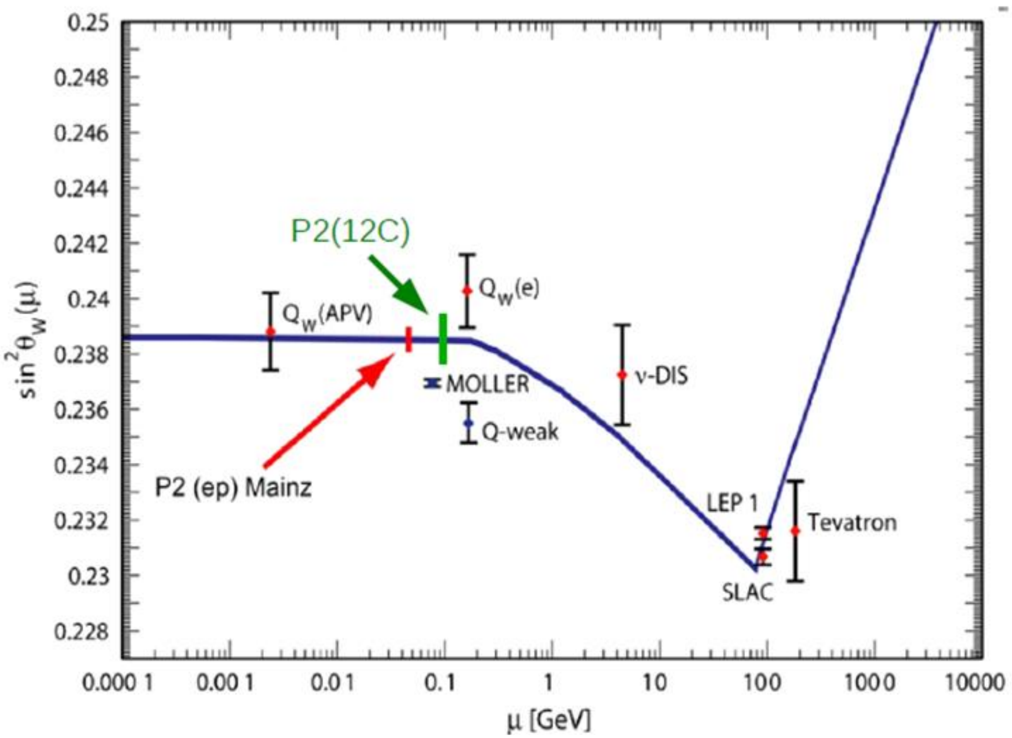
We can achieve $\frac{\delta \sin^2\Theta_W}{\sin^2\Theta_W} = 0.3\%$

$$A_{PV} = \frac{G_F \cdot Q^2}{\sqrt{2}\pi\alpha}\sin^2\Theta_W \longrightarrow$$

$$Q_W^C = -24\sin^2\Theta_W \longrightarrow$$

$$\frac{\delta A_{PV}}{A_{PV}} = \frac{\delta Q_W^C}{Q_W^C} = \frac{\delta \sin^2\Theta_W}{\sin^2\Theta_W} = 0.3\%$$

^{12}C measurement at P2



Opportunity:
Enhanced sensitivity to dark photon mass

$$Q_W^C = -5.5080(5)[1 - 0.003T + 0.016S - 0.034X(Q^2) + \chi]$$

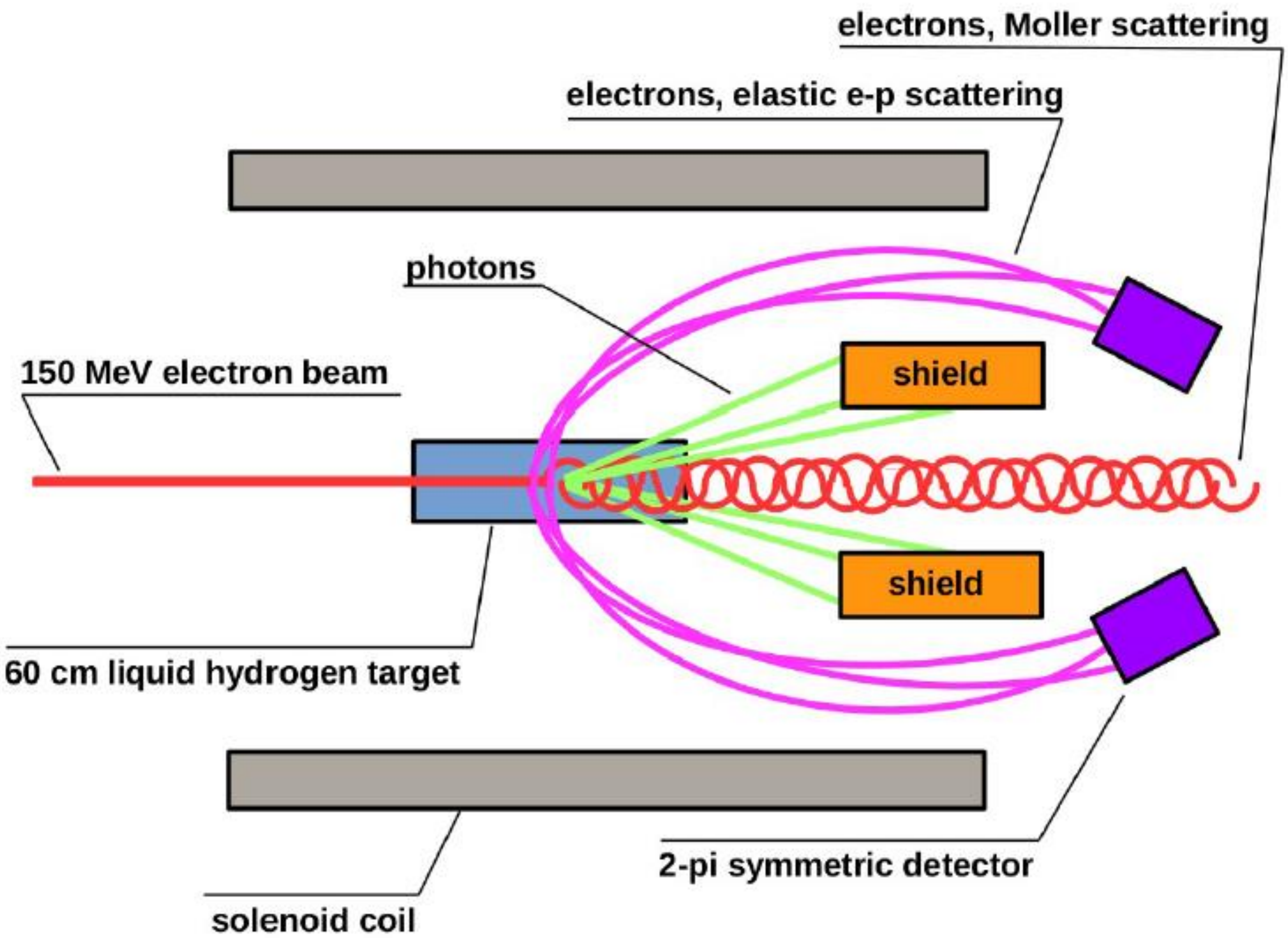
$$Q_W^p = +0.0708(9)[1 + 0.150T - 0.200S + 0.4X(Q^2) + 4\chi]$$

$$\chi = m_Z^2 / m_{Z_\chi}^2$$

$$\frac{\delta Q_W^C}{Q_W^C} = 0.003 \quad \frac{\delta Q_W^P}{Q_W^P} = 0.02$$

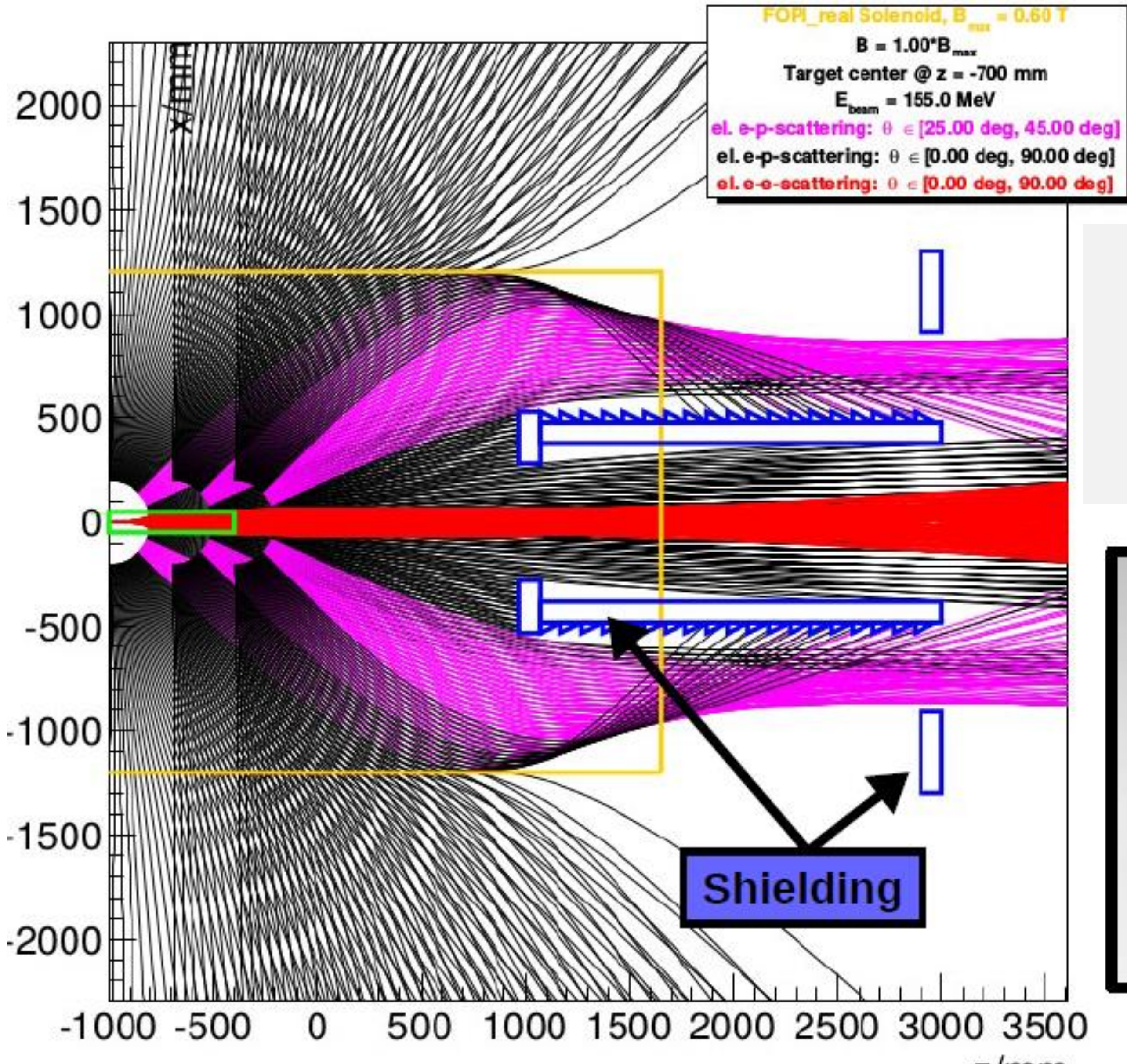
$$\delta\chi = 0.003 \quad \delta\chi = 0.005$$

P2 concept: Solenoid spectrometer



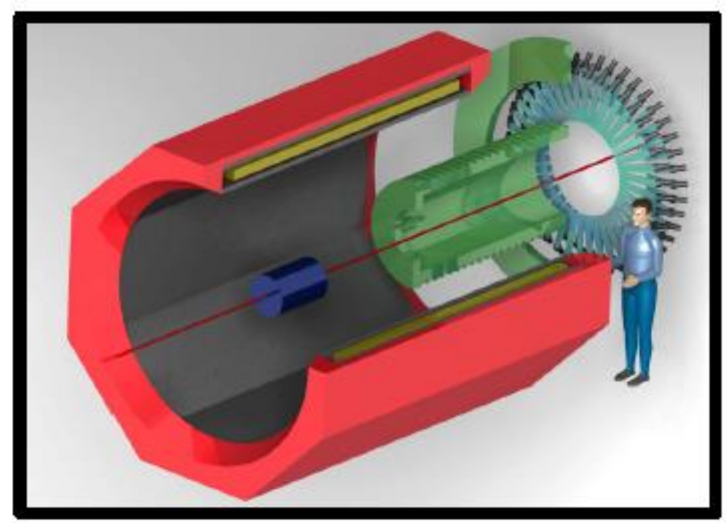
- Separation of charged background from electrons scattered elastically off protons with a solenoid spectrometer
- Superconducting coil: Radius ~ 1 m, Axial length ~ 3 m
- Magnetic field ~ 0.5 T
- Quartz-Cherenkov detectors in the stray field
- Full azimuth may be used to collect statistics
- Compact setup, suits our spatial requirements

P2 concept: Solenoid spectrometer



<u>Full GEANT4 simulation</u>:

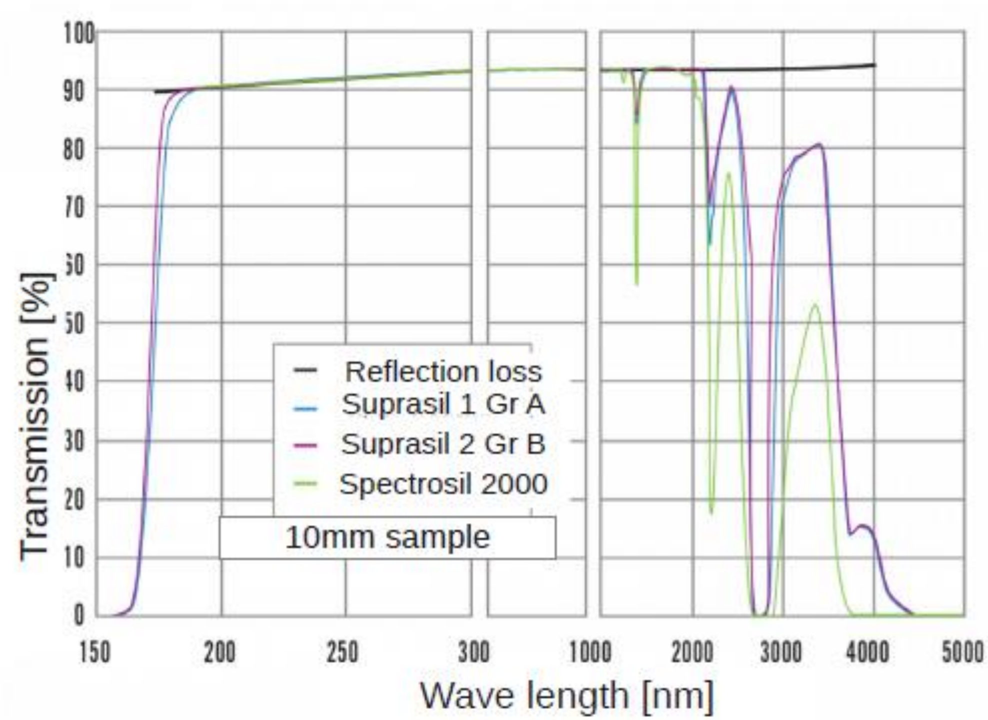
- Interface with CAD program (CATIA)
- Tests of various setups
- See talk of D. Becker for details

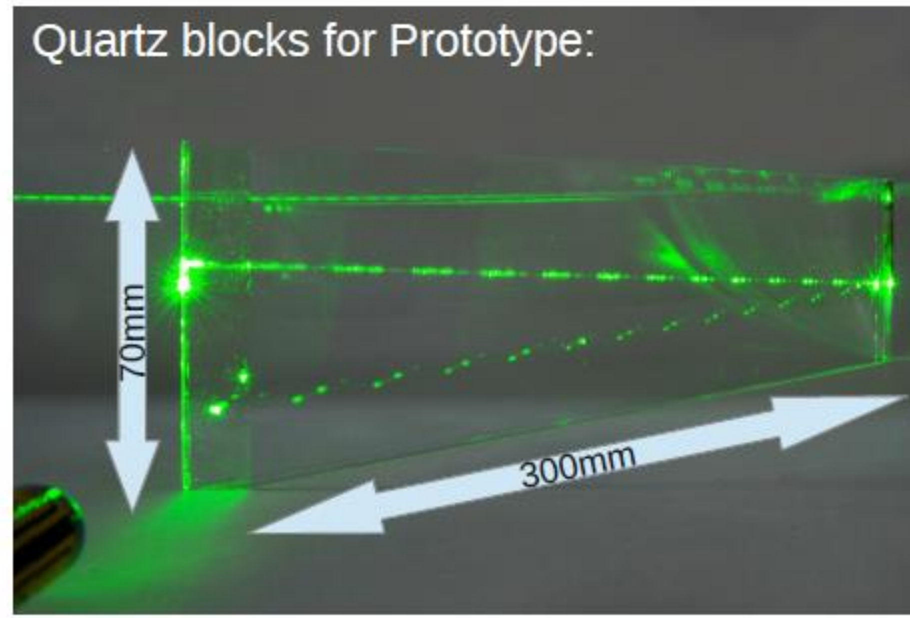


Detector development for P2

Cherenkov medium: Fused Silica (aka Quartz):

- Exceptional transmittance for UV ✓
- Very good radiation hardness ✓

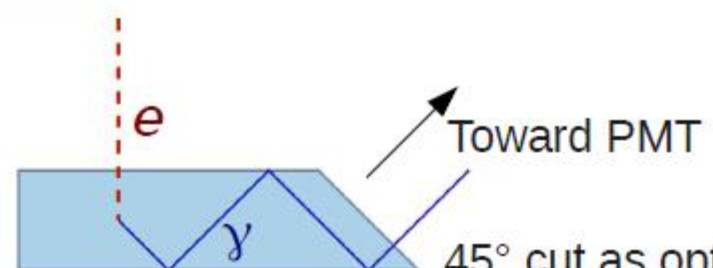




Yet another advantage:

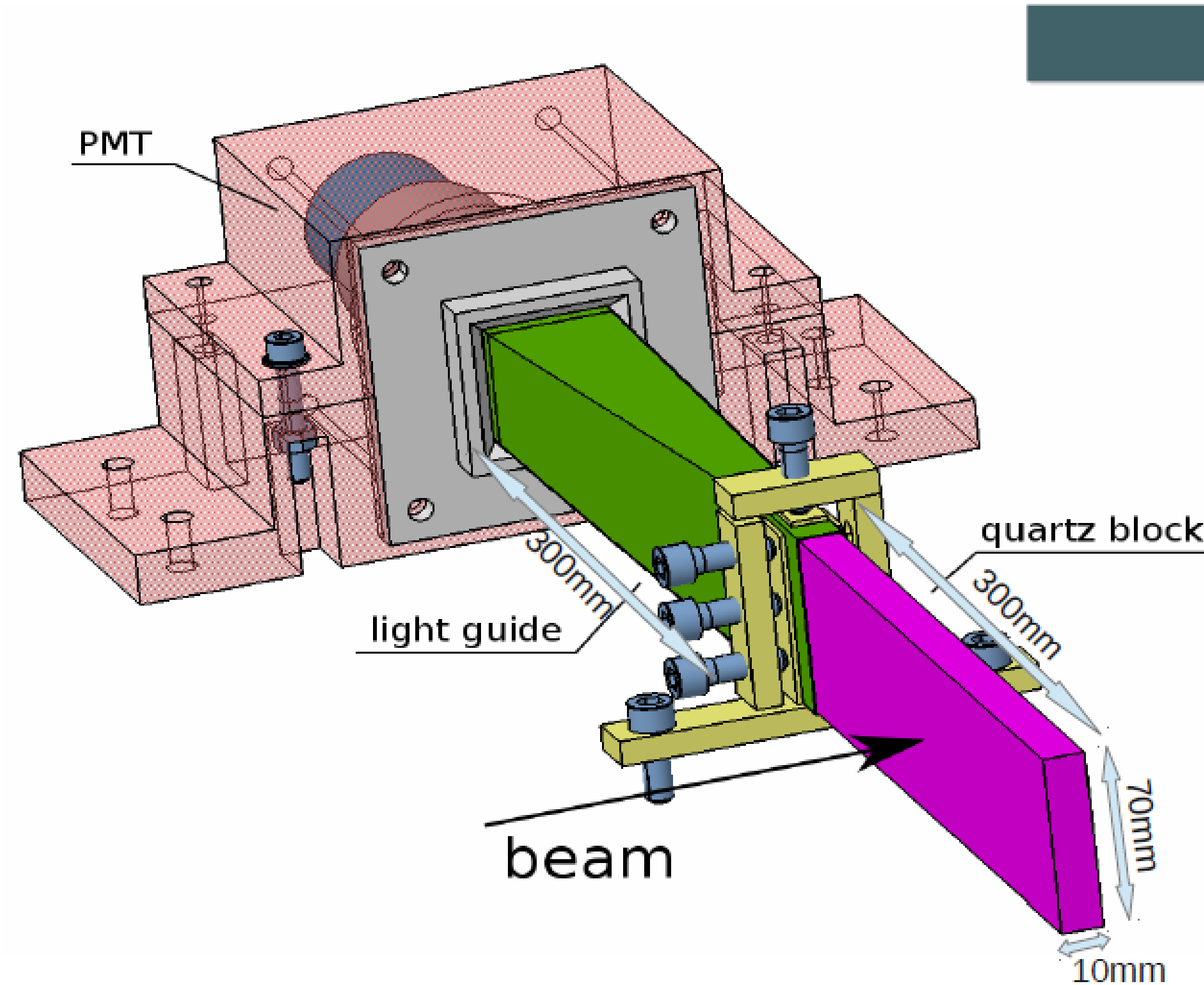
For fused silica: $n \approx \sqrt{(2)}$

$\longrightarrow \theta_C \approx \theta_{TR}$



Prototype detector tests at MAMI

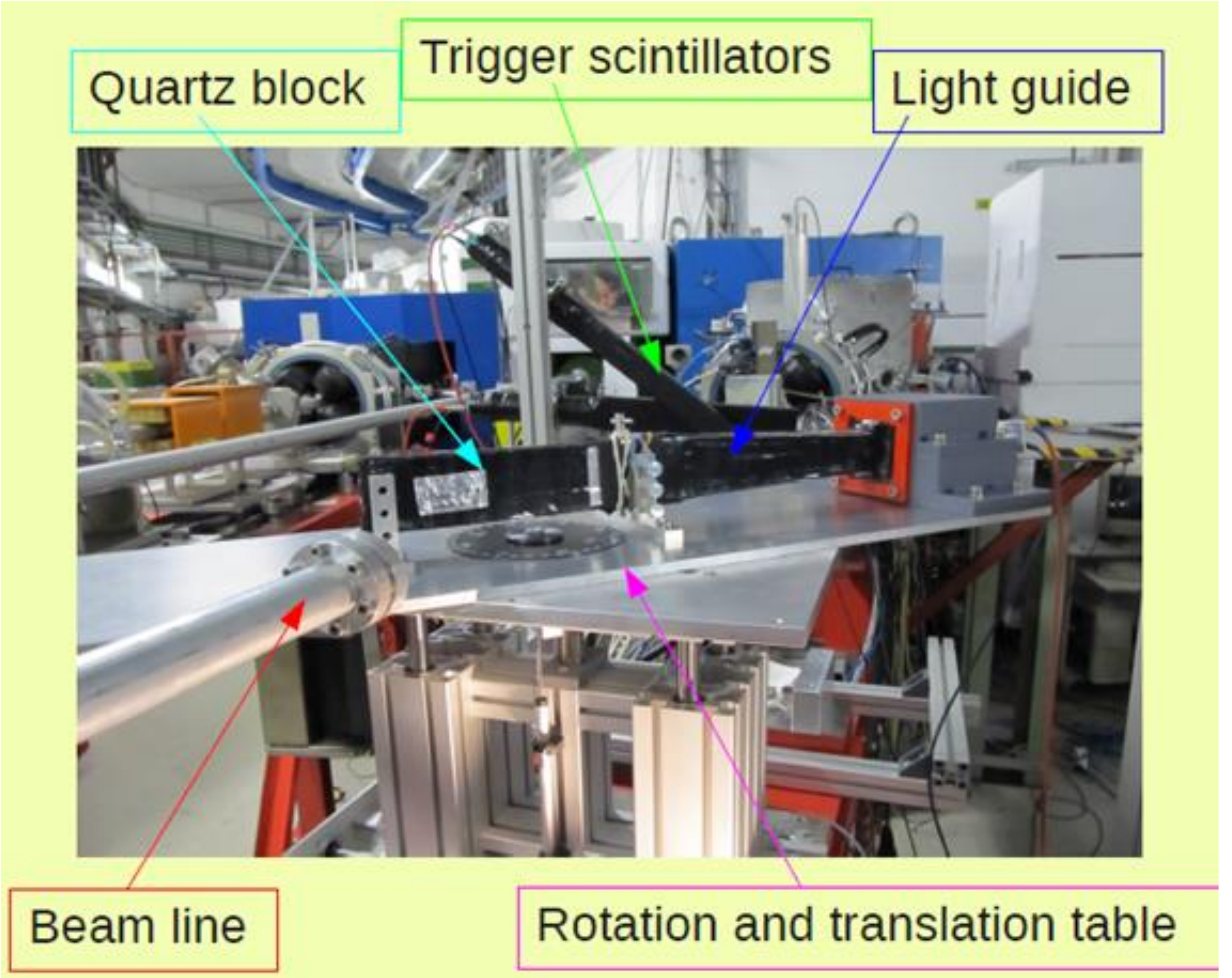
Detector module prototype tested at MAMI



What is needed

- Cherenkov medium (quartz)
- Wrapping material for quartz blocks
- Reflecting foil for light guides
- PMTs
- DAQ

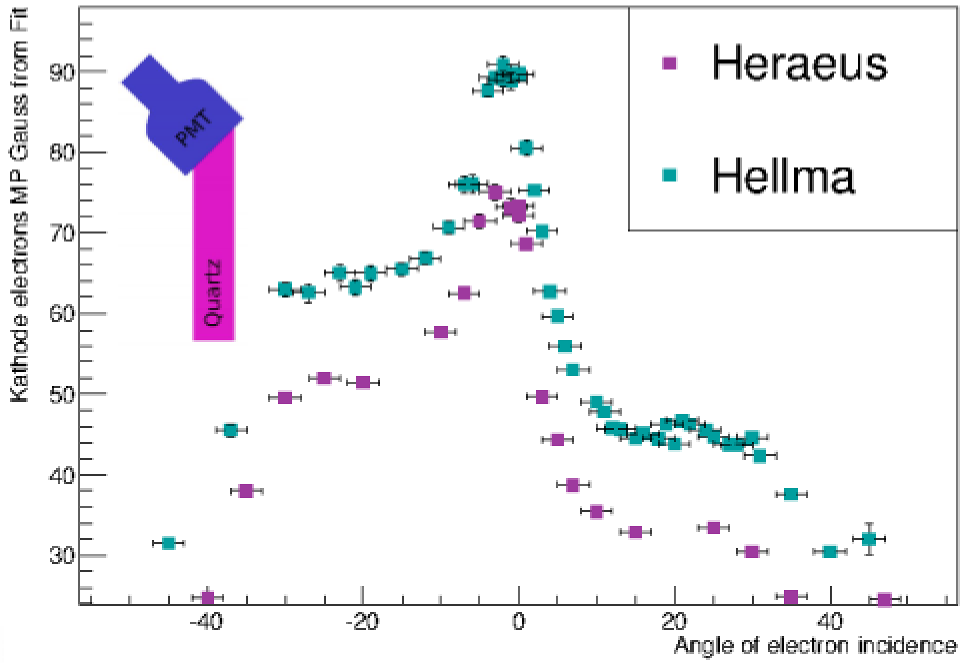
Prototype detector tests at MAMI

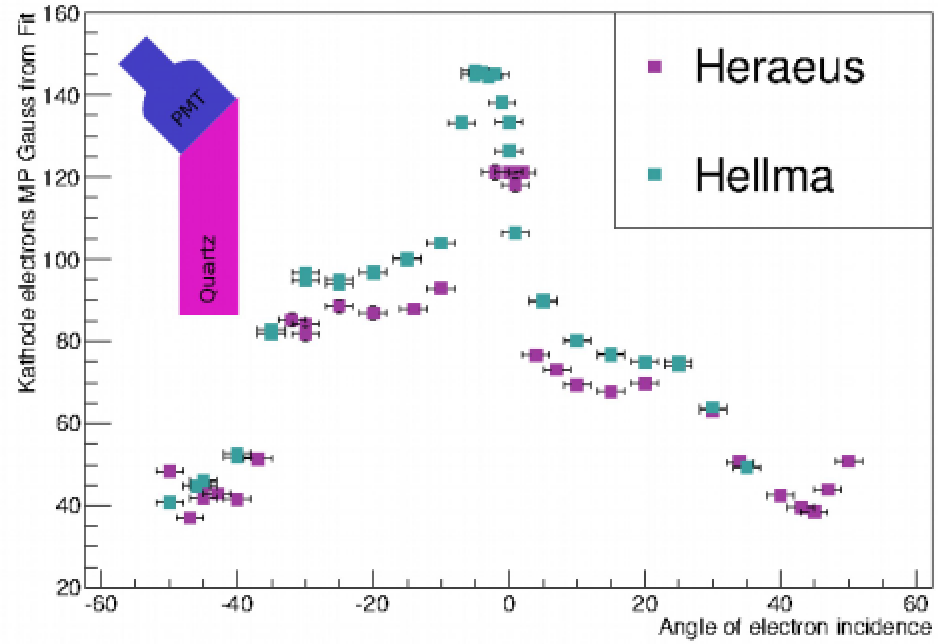


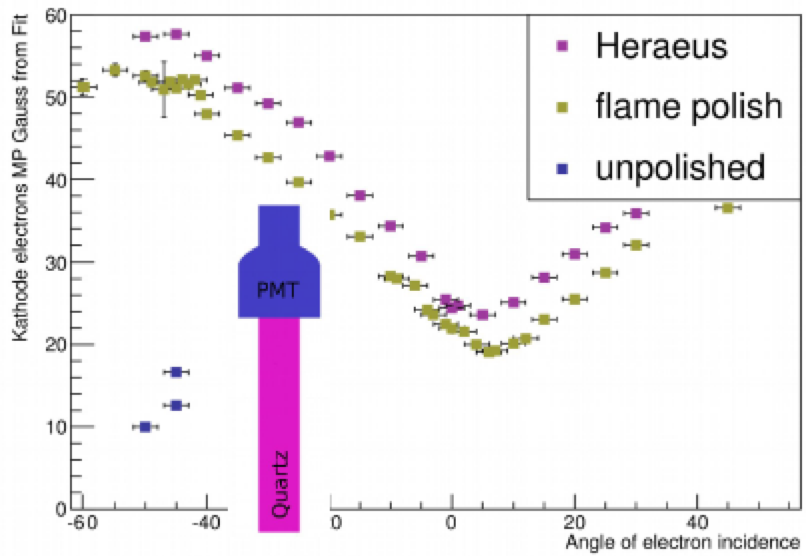
Summary

- Parity violating electron scattering: Ideal application for external target experiments
- Hydrogen target: Determination of the weak mixing angle at low Q^2 with high precision
- Technical challenges: Due to high rates and small asymmetries
- Additional benefits: Measurement of G_A and G_M^s , carbon target
- P2: Measurement of weak mixing angle at MESA, work in progress

Example: P.E. yield for different polishings and scattering angles







Hereaus	Polished up to transparancy
Hellma	Optical polish
Flame polish	Transparent but riffles visible