SFB 1044

THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

The P2 Experiment: High precision determination of the weak mixing angle at MESA

Sebastian Baunack for the P2 collaboration

Johannes Gutenberg-Universität Mainz

Spin 2016, Sepember 26-30, 2016

Urbana-Champaign, Illinois, USA

PRISMA

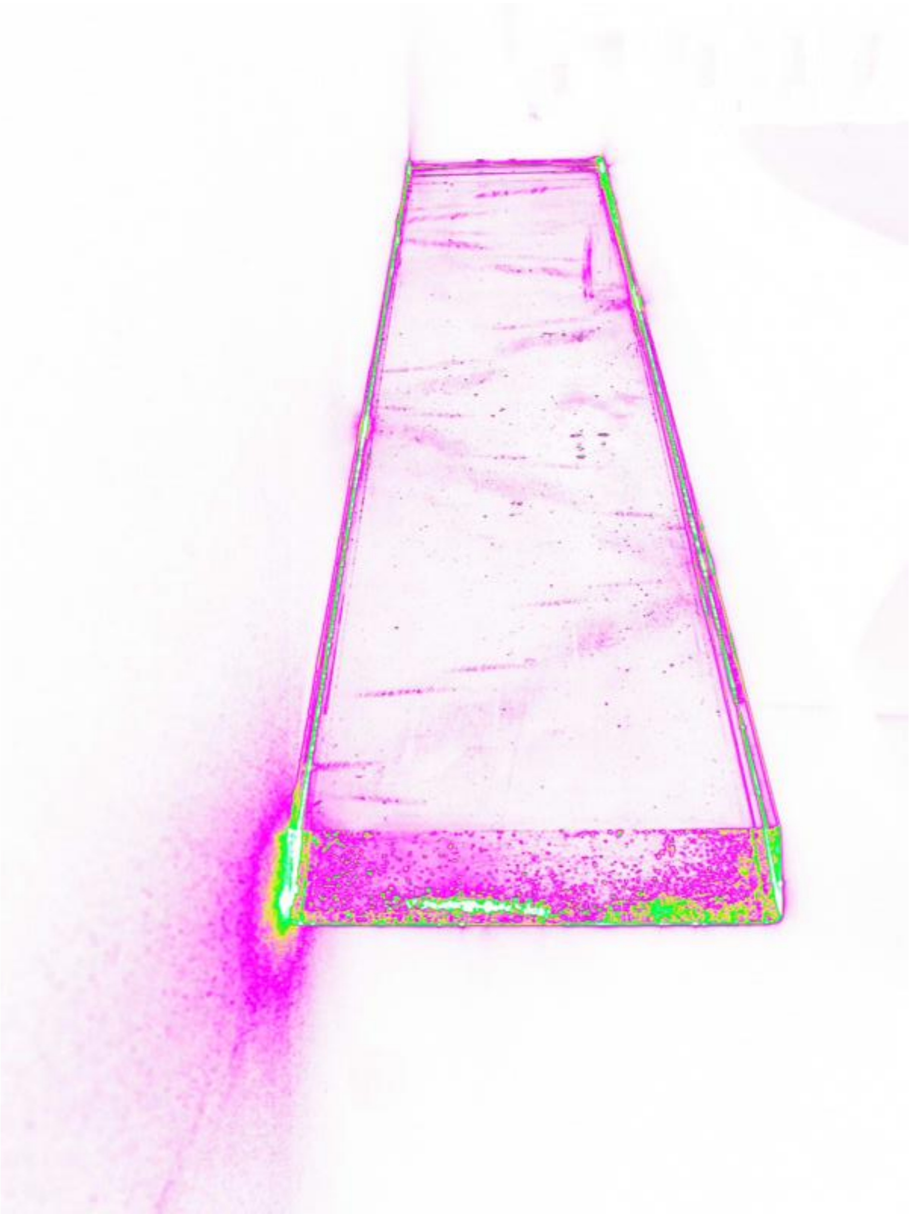
MAINZER MIKROTRON

The P2 Experiment

- Weak mixing angle $\sin^2\Theta_W$ and search for New Physics

- Experimental Design:
  Parity violating electron scattering
  Precision studies

- Status of the project
  Beam stabilization
  Theory
  Solenoid design
  Determination of Q^2
  Polarimetry
  Integrating detectors



The weak mixing angle $\sin^2\Theta_W$

Central parameter of the Standard Model

Tree level relations:

- Electric charge $e = \sqrt{4\pi\alpha} = g_1 \cos\theta_W = g_2 \sin\theta_W$
- Masses of W and Z Boson $\cos\theta_W = M_W / M_Z$
- Myon decay constant $G_\mu = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W M_W^2}$

The weak mixing angle $\sin^2\Theta_W$

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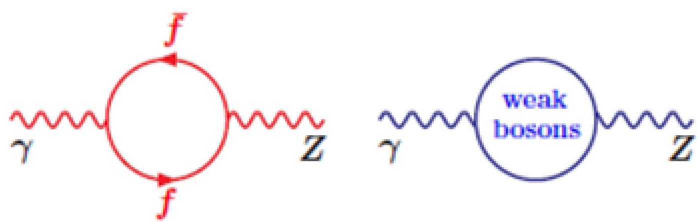
Including radiative corrections:



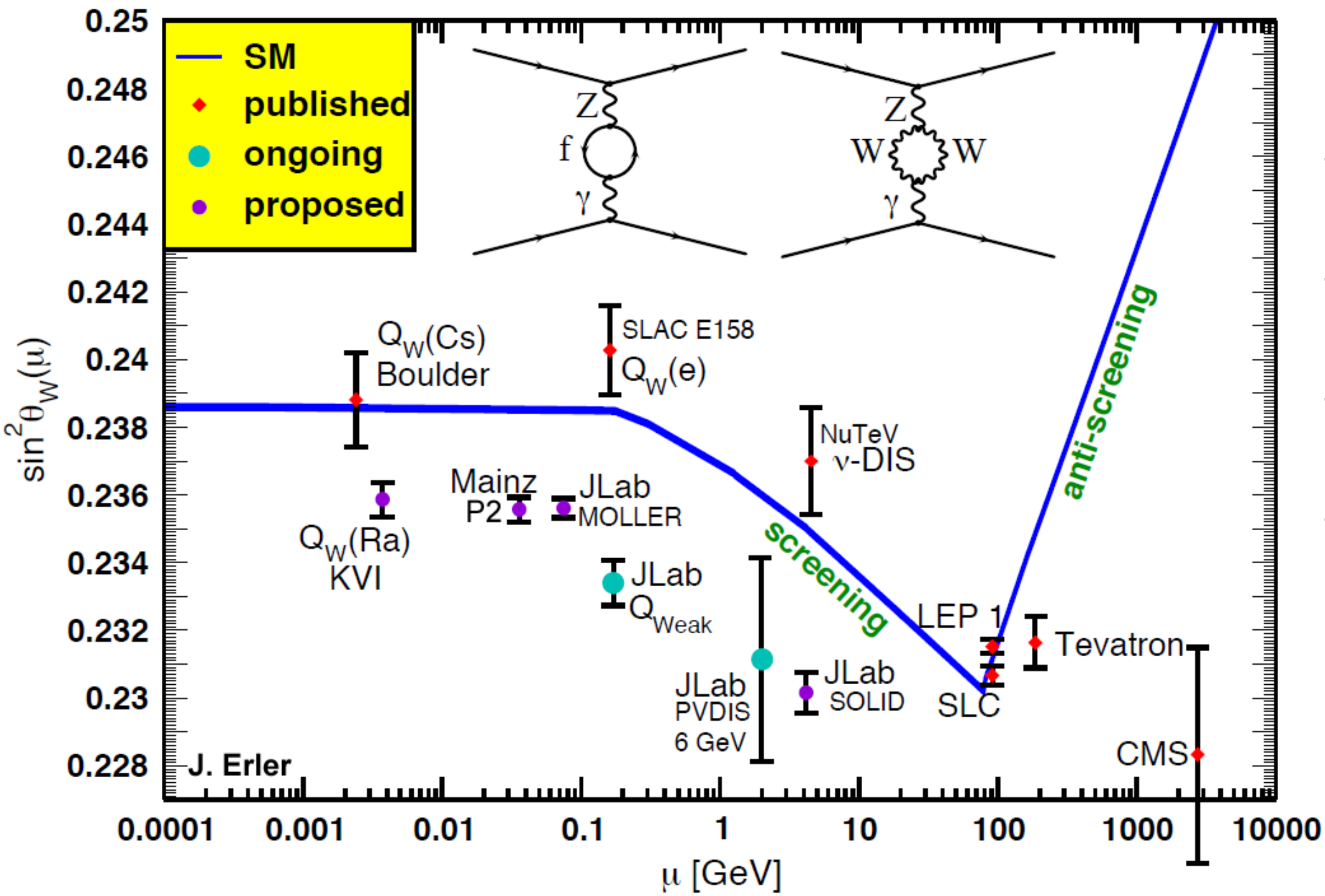
$$G_\mu = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W M_W^2}(1+\Delta r)$$

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

Absorb universal quantum corrections in an ***effective, running*** weak mixing angle:

$\sin^2\theta_W \rightarrow \sin^2\theta_{\mathrm{eff}}$ or $\sin^2\theta_W(\mu)$ mit μ as energy scale

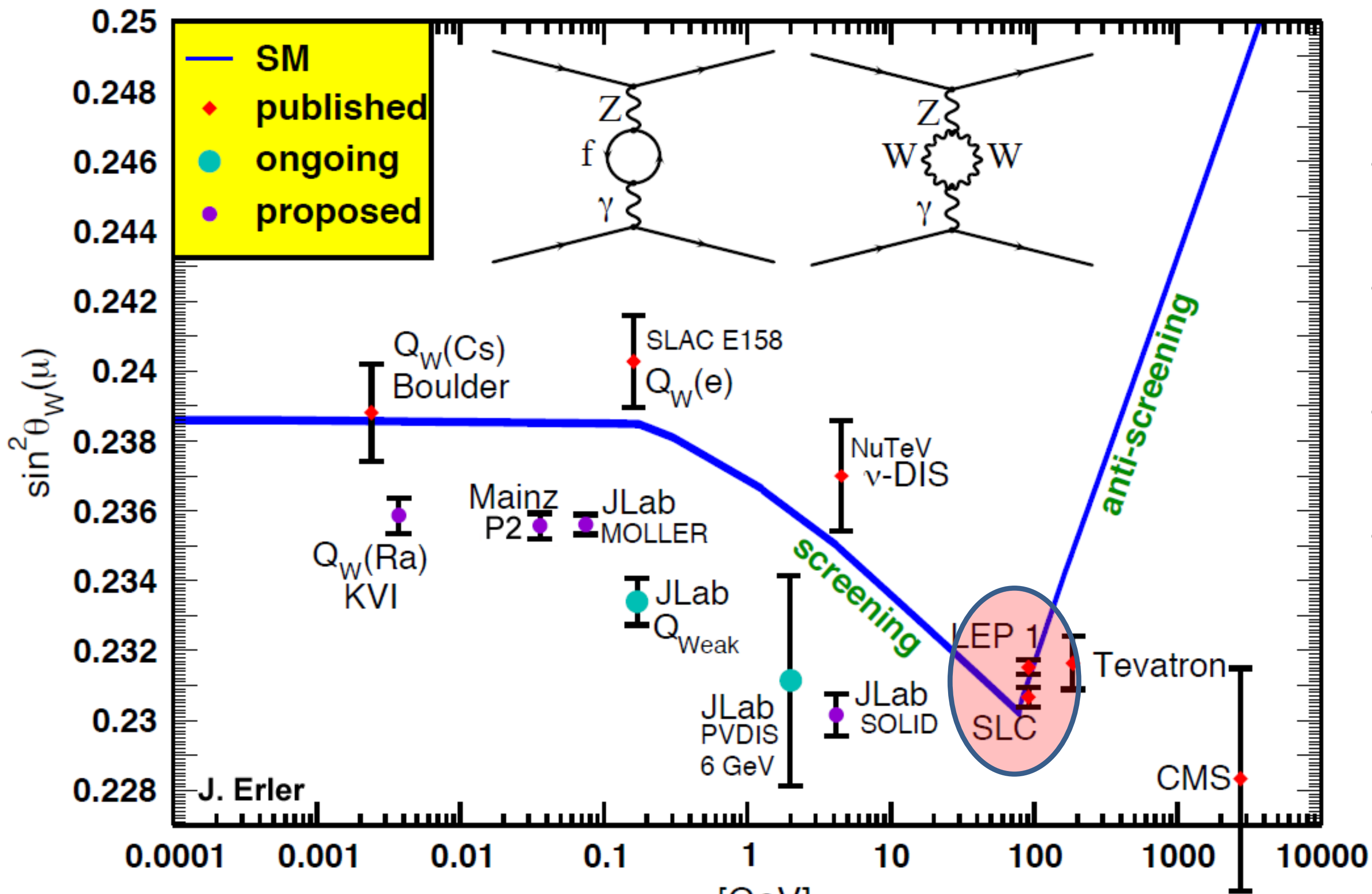
The weak mixing angle $\sin^2\Theta_W$



PDG 2014:

- $Q_W(Cs)$: Atomic parity violation
- SLAC E158: Møller scattering
- NuTeV: Neutrino scattering
- Z-Pole Measurements
  LEP
  SLAC
  Tevatron
  LHC

The weak mixing angle $\sin^2\Theta_W$



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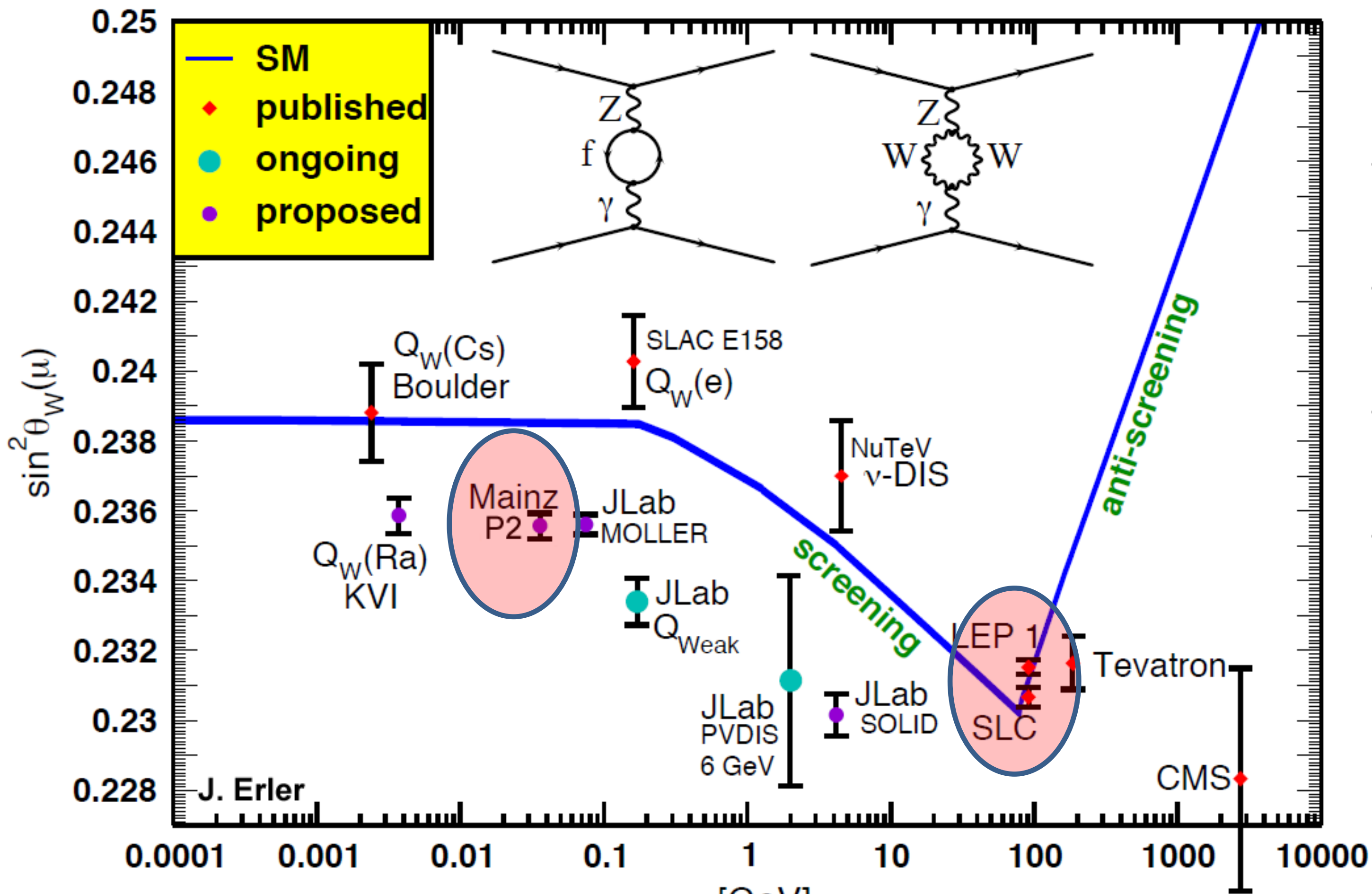
Most precise measure-ments at Z-Pole

The weak mixing angle $\sin^2\Theta_W$



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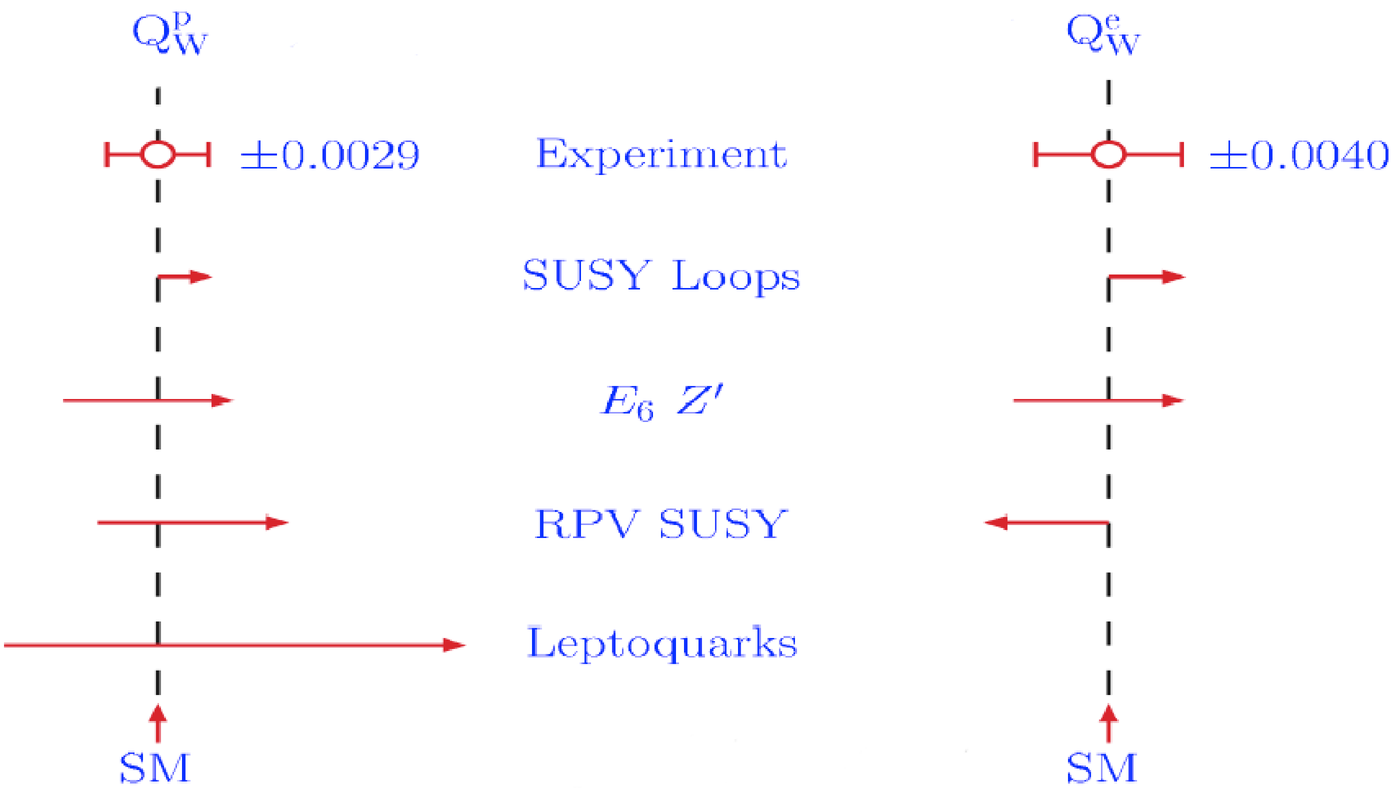
Most precise measure-ments at Z-Pole

P2: New measurement with high precision at low energy

Physics beyond the Standard Model

Weak charges of proton and electron (tree level):

Proton	$Q_W(p)$ =	$1-4\sin^2\Theta_W$
Electron	$Q_W(e)$ =	$-1+4\sin^2\Theta_W$

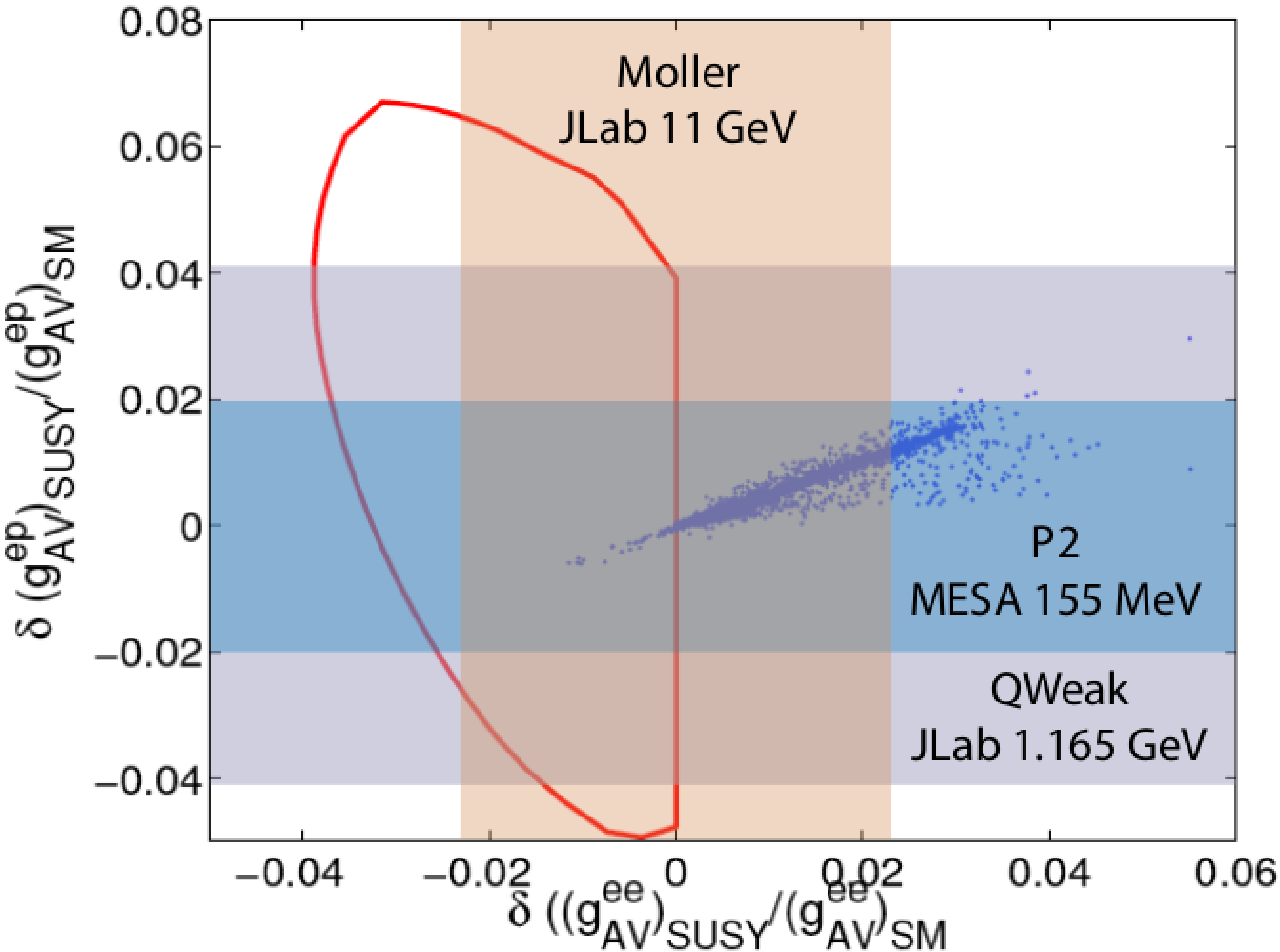


Standard Model extensions:

- Characteristic shifts in $Q_W(p)$ und $Q_W(p)$
- Measurements of $Q_W(p)$ and $Q_W(p)$ are complentary

Super Symmetric Models

Example: Super symmetric Standard Model extension (SuSy) with and without R-Parity violation



Shifts in the weak charges of p und e-

- Blue dots: Minimal super-symmetric models
- Red "Ellipse": Allowed range for R-parity violating super-symmetric models

Parity violating electron scattering

Asymmetry in the cross section of elastic electron-proton scattering for left- and right-handed polarized electrons

$$A_{LR} = \frac{\sigma(e_\downarrow) - \sigma(e_\uparrow)}{\sigma(e_\downarrow) + \sigma(e_\uparrow)} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W(\mathcal{N}) - F(Q^2)\right)$$

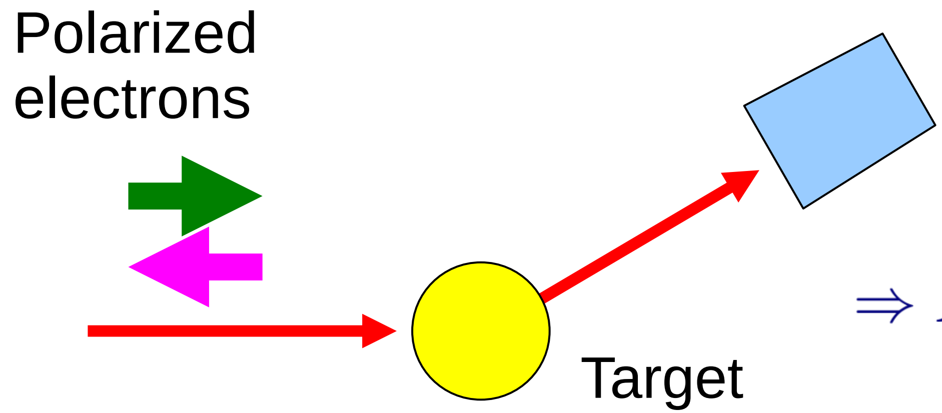
The weak charge of the proton (tree level):

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

$$\frac{\Delta \sin^2\theta_W}{\sin^2\theta_W} = \frac{1 - 4\sin^2\theta_W}{4\sin^2\theta_W}\frac{\Delta Q_W(p)}{Q_W(p)}$$

1.5% precision in $Q_W(p)$ results in a precision of 0.13% in $\sin^2\Theta_W$

Parity violating electron scattering



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

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

Statistics:

One needs about 10^{18} events

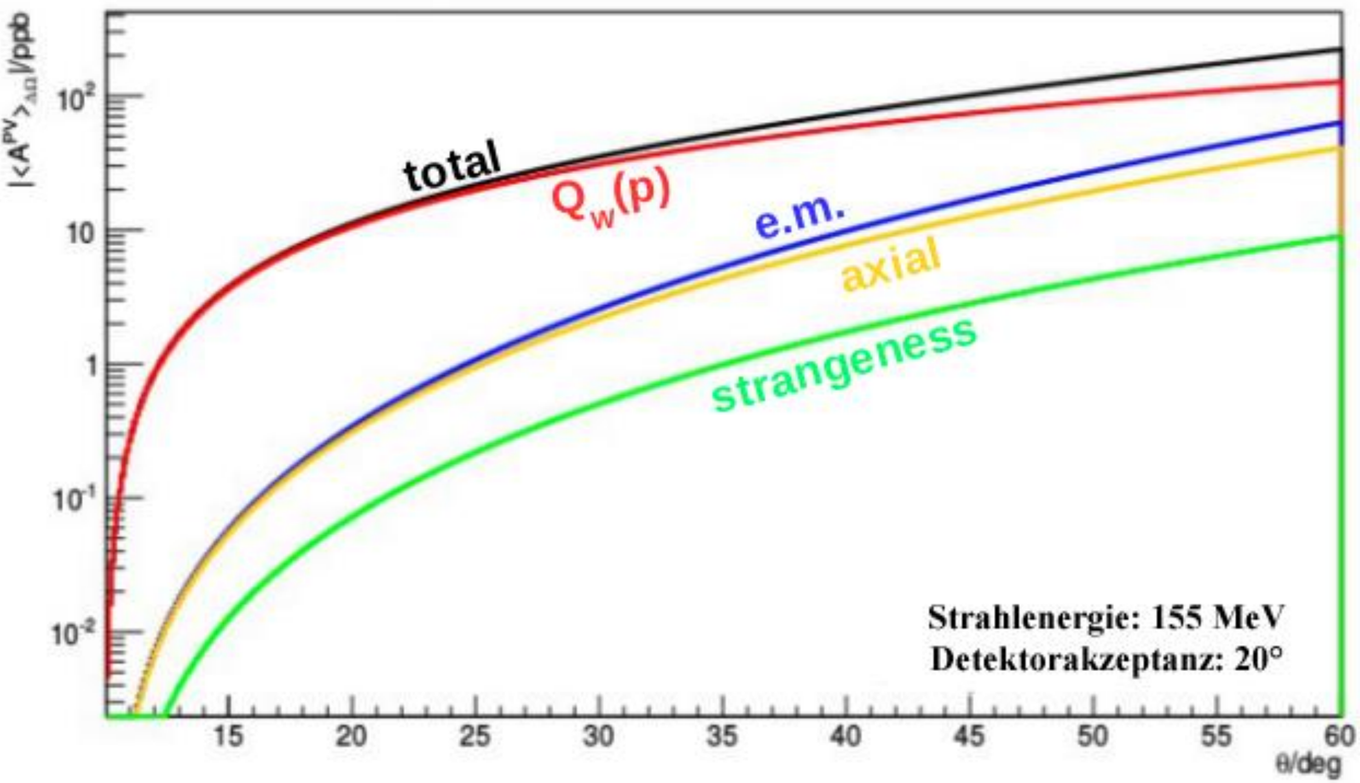
- High Luminosity
- High degree of polarization
- Large acceptance
- Fast detectors

Systematics:

- Separation ot the elastic scattered electrons
- Beam polarization measurement
- Helicity correlated beam fluctuations
  - *Beam intensity*
  - *Beam position*
  - *Beam energy*

Parity violating asymmetry

$$A_{LR} = \frac{\sigma(e_\downarrow) - \sigma(e_\uparrow)}{\sigma(e_\downarrow) + \sigma(e_\uparrow)} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W(\mathcal{N}) - F(Q^2)\right)$$

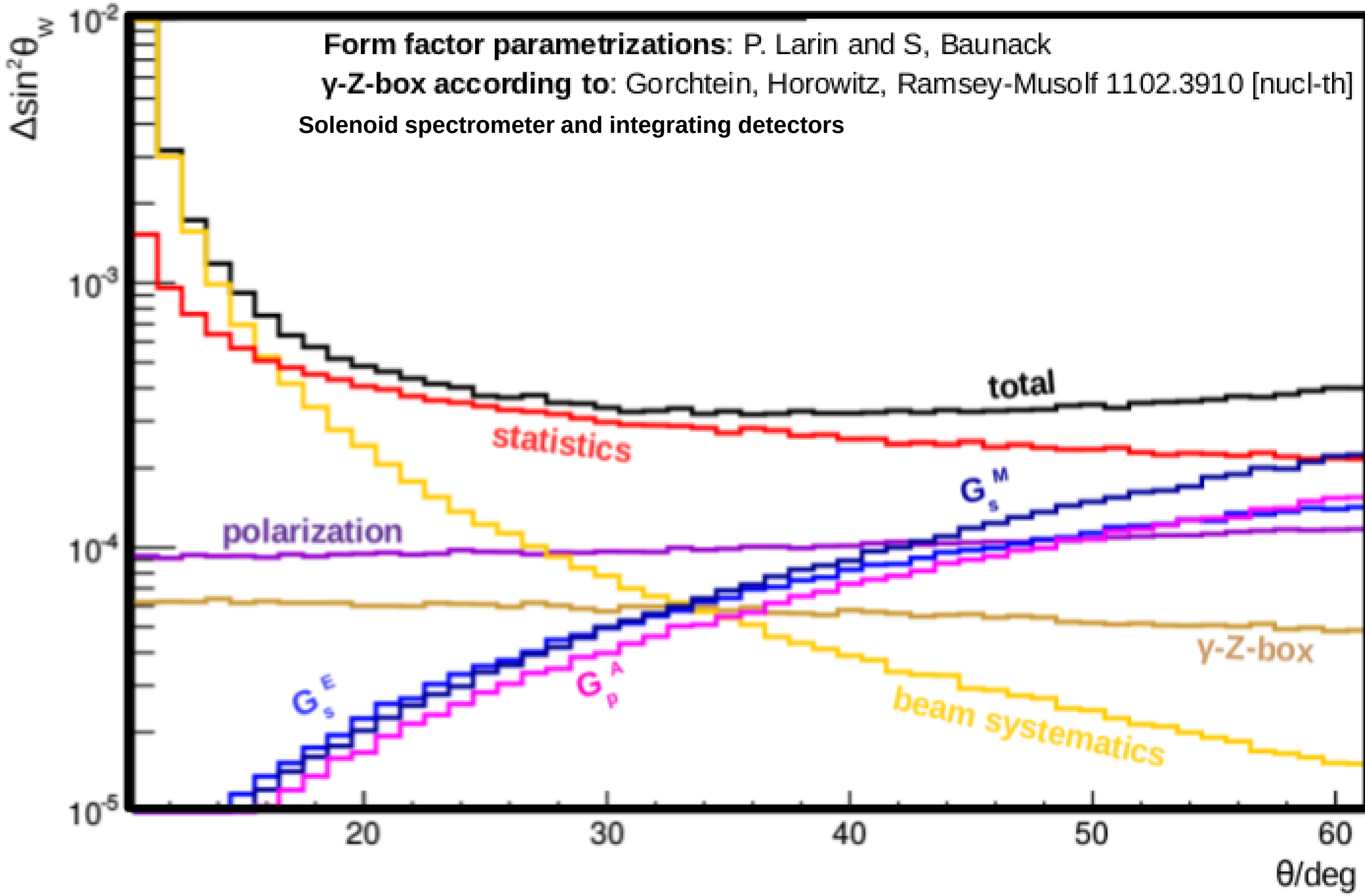


$Q_W(p) = 1 - 4\sin^2\Theta_W$

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

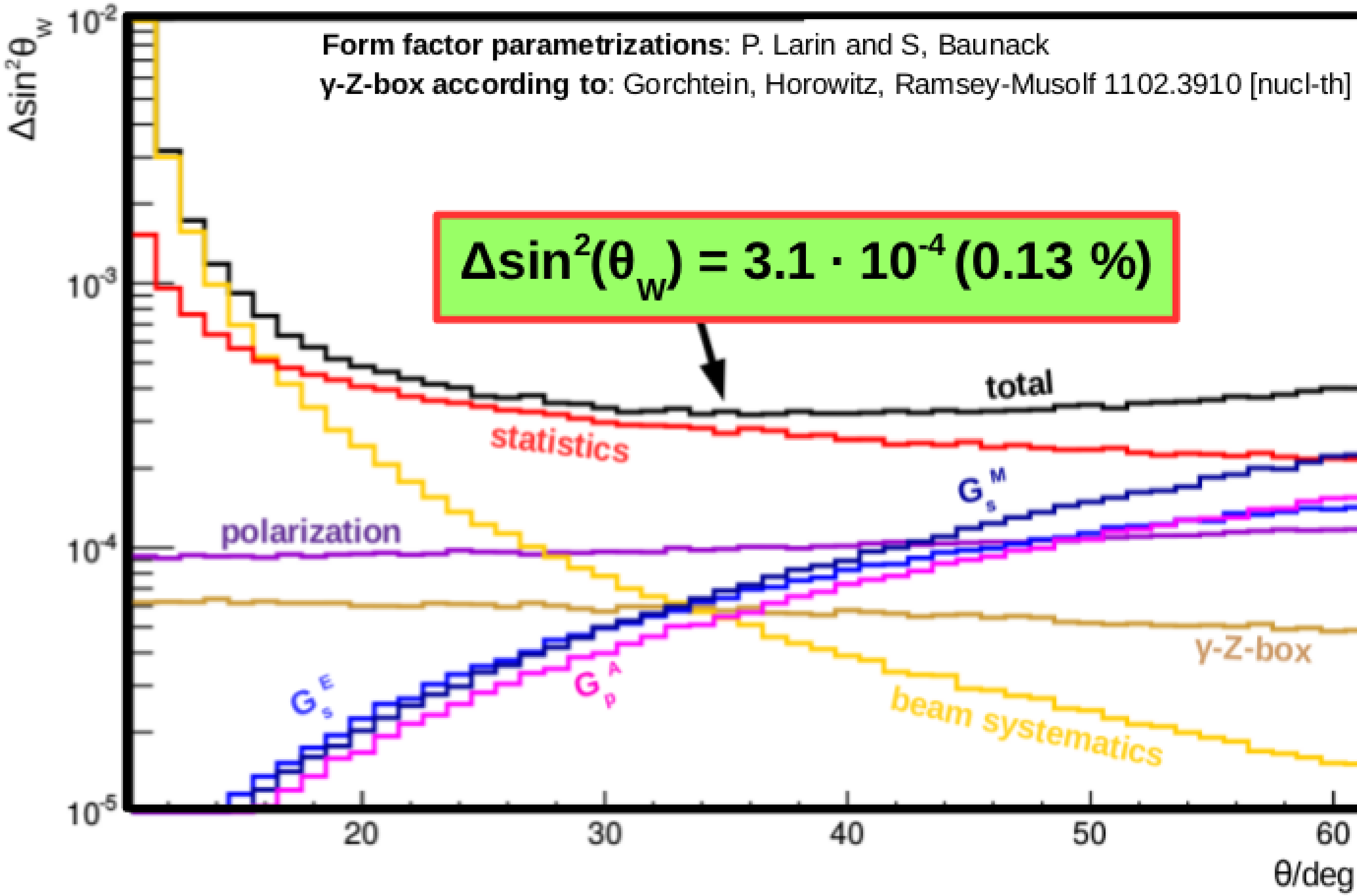
Precision studies

Determination of the reachable precision by Monte-Carlo studies
Variation of all input parameters (Form factors, apparative asymmetries etc.)



Beam energy:	155 MeV
Beam current:	150 μA
Polarization:	(85±0.5)%
Target:	60 cm lH2
Acceptance:	2π·(35°±10°)
Rate:	0.5 THz
Runtime:	10000 h
ΔA^{app}:	0.1 ppb

Precision studies



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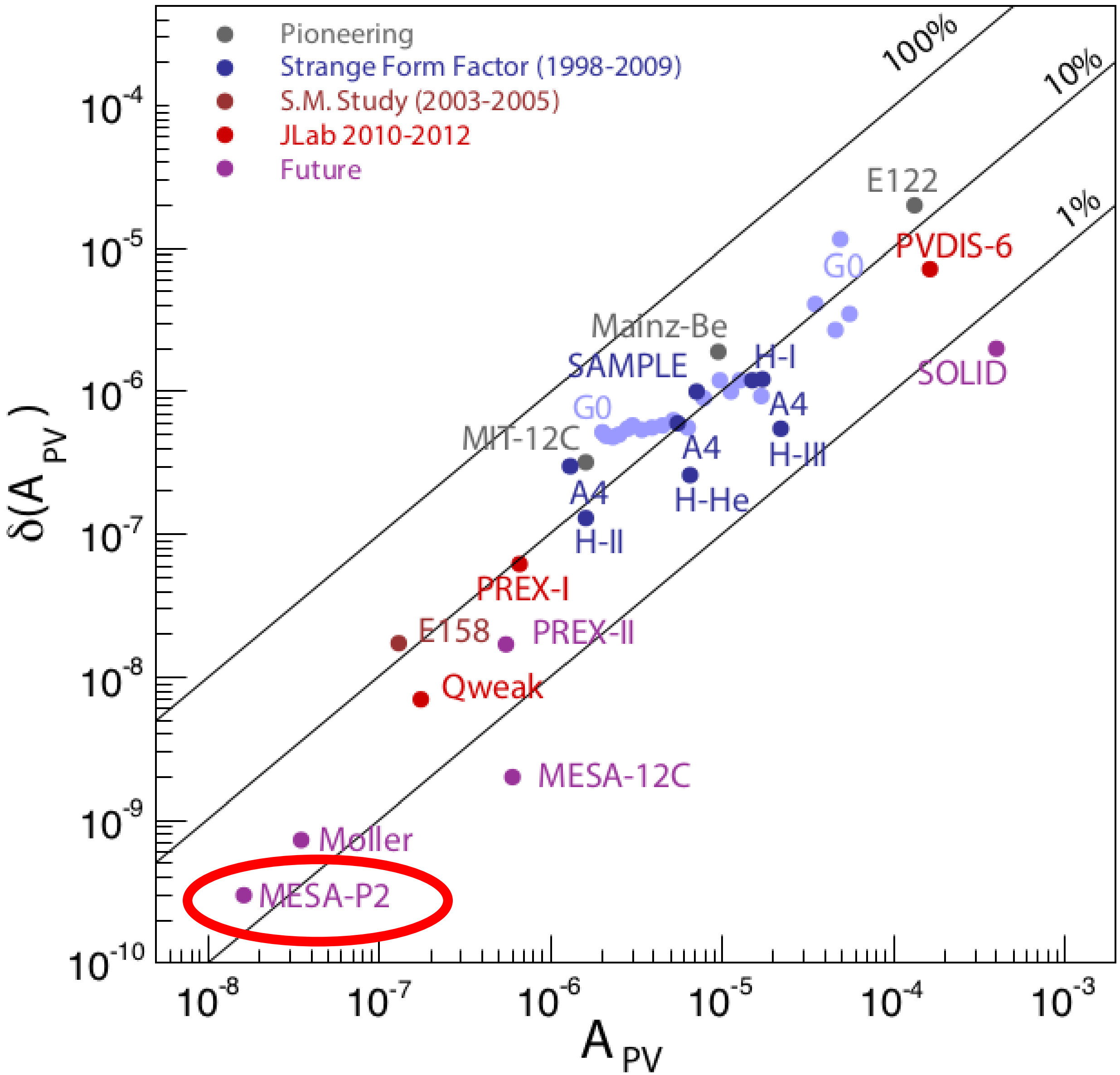
	Total	Statistics	Polarization	Apparative	FF	Re($\square_{\gamma ZA}$)
$\Delta\sin^2(\theta_W)$	3.1e-4 (0.13 %)	2.6e-4 (0.11 %)	9.7e-5 (0.04 %)	7.0e-5 (0.03 %)	1.4e-4 (0.04 %)	6e-5 (0.03 %)
ΔA^{exp}/ppb	0.44 (1.5 %)	0.38 (1.34 %)	0.14 (0.49 %)	0.10 (0.35 %)	0.11 (0.38 %)	0.09 (0.32 %)

Precisions reached by PVES



P2 experiment

A = -28.35 ppb

ΔA = 0.44 ppb

The P2 collaboration

- Collaboration was enlarged during the past years
- Integreating detectors, magnetic spectrometer, theory, electronics, target, polarimetry

Hubert Spiesberger
Razvan Bucoveanu
Stephan Wezorke
Frank Maas
Sebastian Baunack
Dominik Becker
Kathrin Schier
Thomas Jennewein
Kurt Aulenbacher
Dr. Valery Tioukine
Matthias Molitor

Niklaus Berger
Iurii Sorokin
Alexey Tyukin
Marco Zimmermann
Silviu Covrig
Sandesh Gopinath
Krishna Kumar
Paul Souder
Michael Gericke
Rakhita Beminiwattha

Institut für Kernphysik, Universität Mainz
Institut für Physik, Universität Mainz
Department of Physics and Astronomy, Stony Brook, NY
Jefferson Lab, Newport News, VA
University of Manitoba, Winnipeg
Syracuse University, Syracuse, NY
Lousisiana Tech, Ruston, LA

PRISMA

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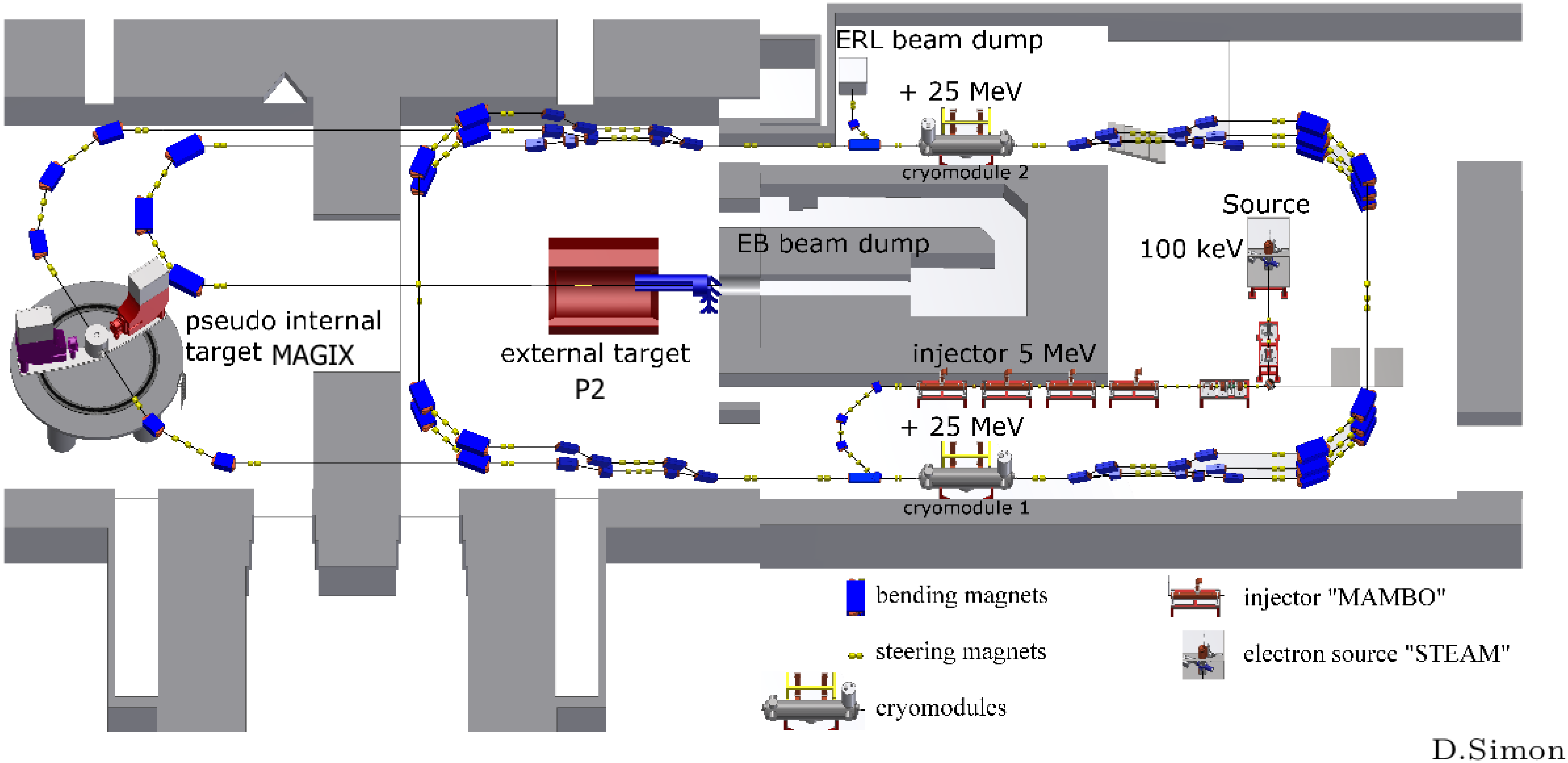
MESA

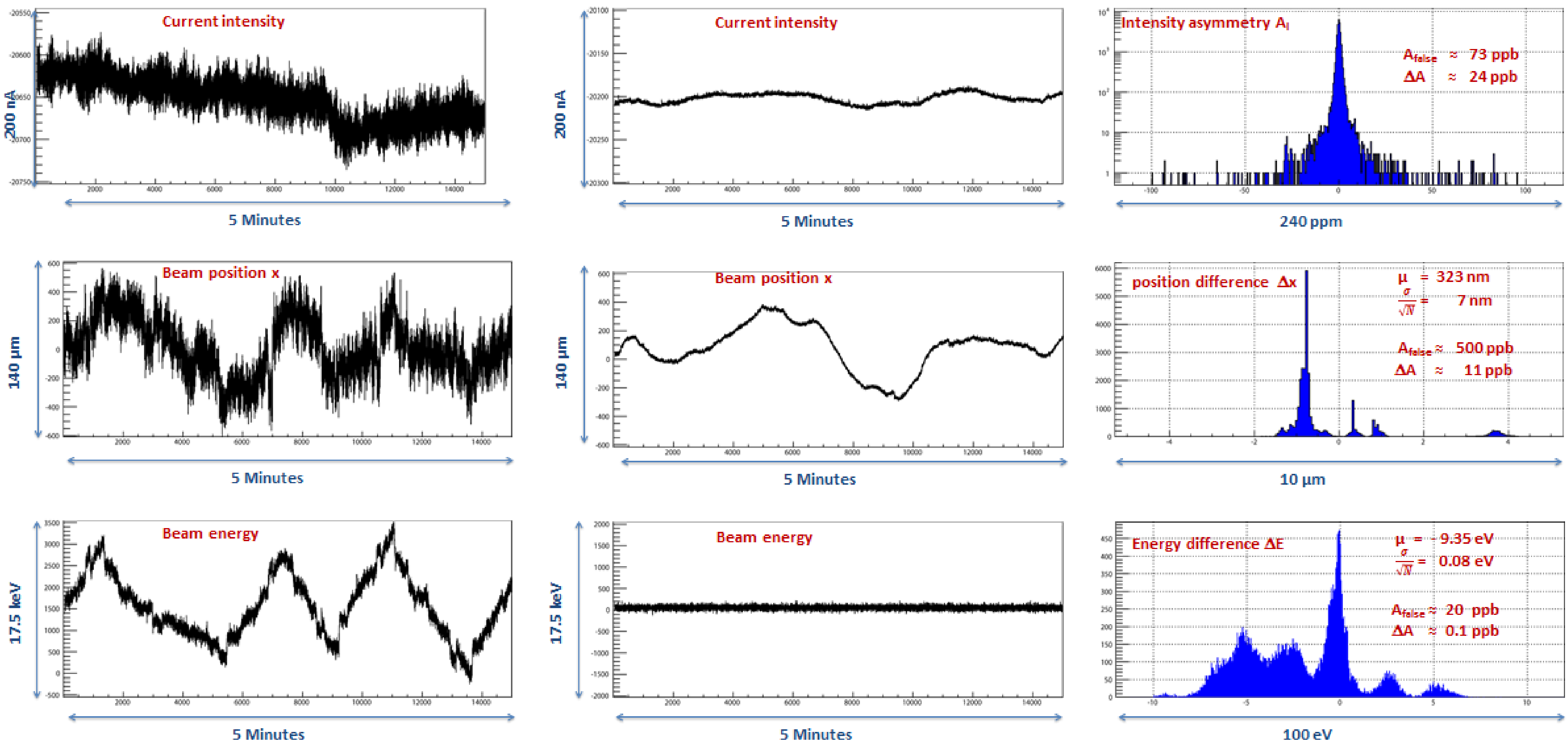
- **M**ainz **E**nergy Recovering **S**uperconducting **A**ccelerator
- New facility at the Institute for Nuclear Physics, University of Mainz
- External Beam Mode: Beam current I=150 µA, Polarisation P=0.85



Beam stabilization

- Experience with parity violating electron scattering at MAMI/A4 (and now A1)
- Shown here: Beam parameters for E=315 MeV.
- Stabilization with analogue feedback loops

Beam not stabilized | **Beam stabilized** | **2300 h beam data**



Beam stabilization

From former A4 data: Estimation of possible values with the exisiting MAMI technique:

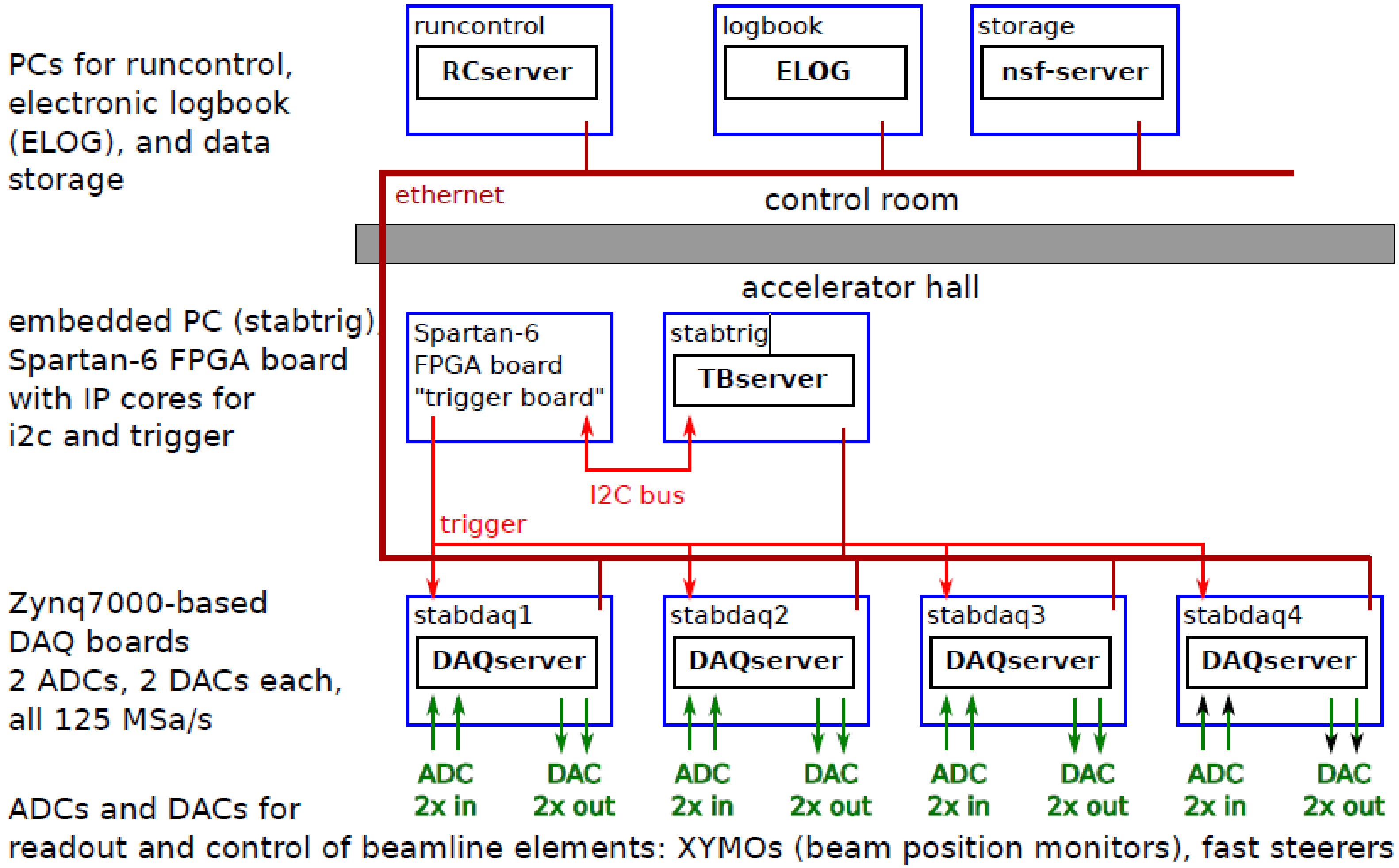
Helicity correlated beam parameter	Extrapolated values for 10.000 h of beam	Corresponding apparative asymmetry
Beam intensity asymmetry	11 ppb	11 ppb
Beam position differrence	7 nm	5 ppb
Beam energy difference	0.04 eV	< 0.1 ppb

Planned for MESA:

- Digital Feedback loops (based on FPGA)
- Stabilization works directly with the helicity correlated beam differences
- Increased bandwith / sensitivities the beam monitors

Beam stabilization

R&D for new beam stabilizations already ongoing with MAMI beam



(R. Herbertz, J. Diefenbach)

Beam stabilization

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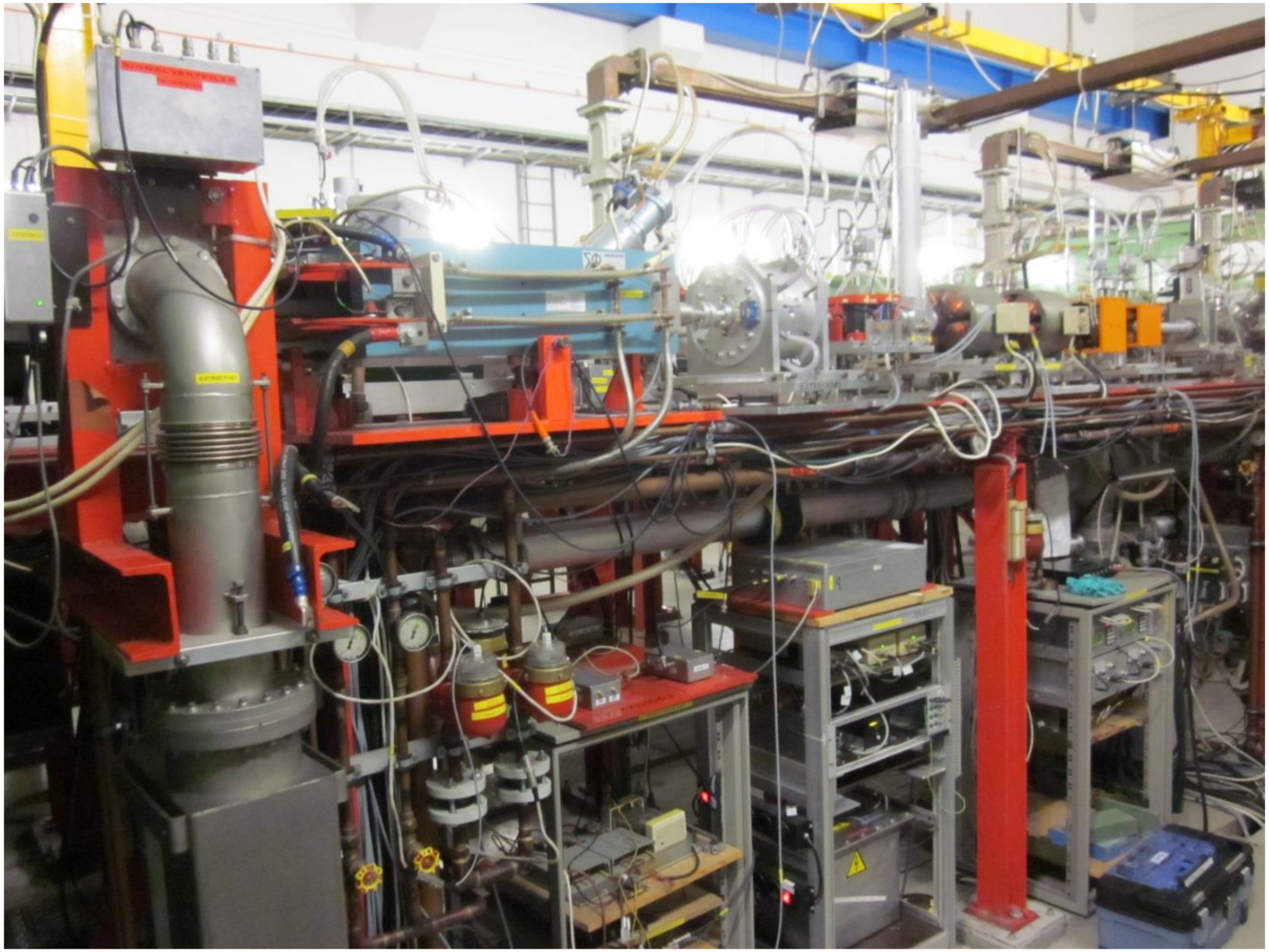
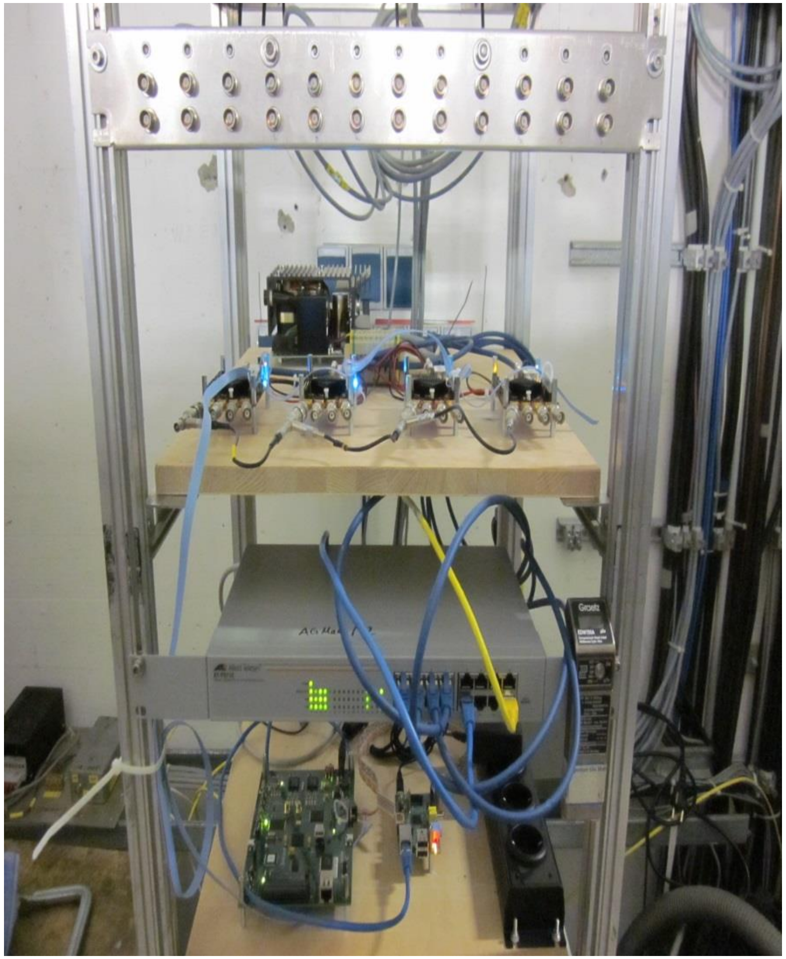


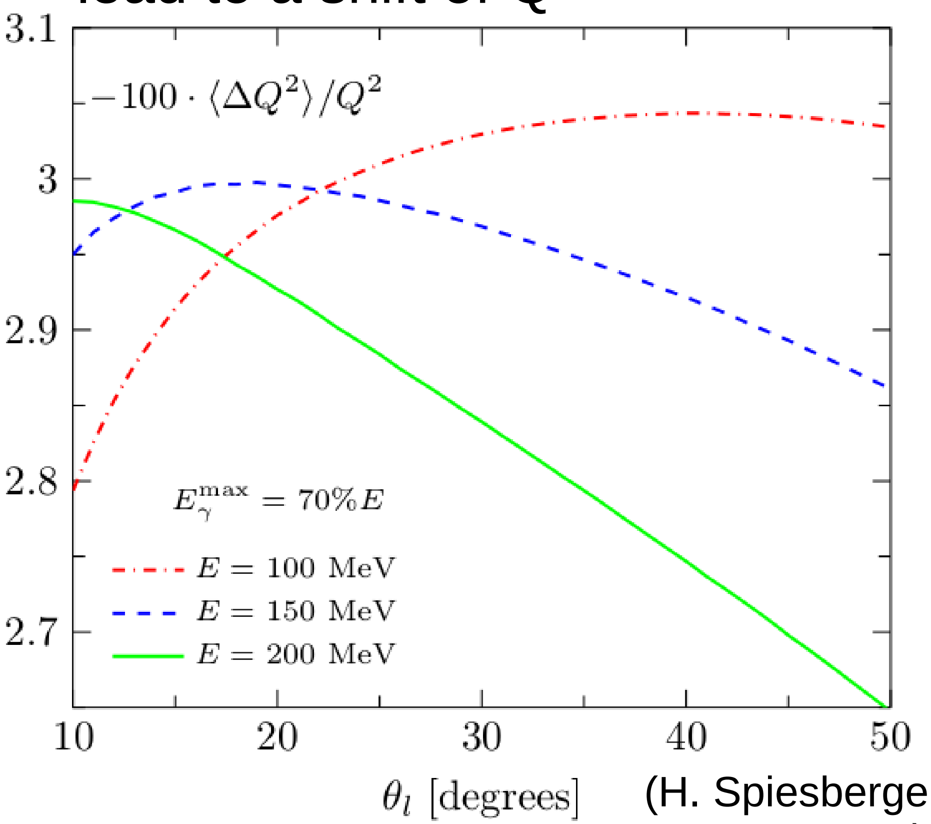


(R. Herbertz, J. Diefenbach)

Theory: Higher order corrections

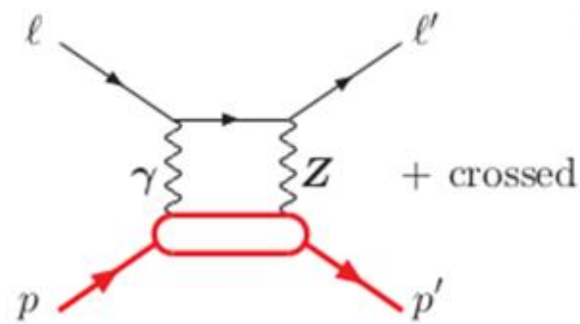
QED higher order corrections

- Straightforward to calculate, but MC simulation needed
- do not violate parity symmetry, but lead to a shift of Q^2



(H. Spiesberger, R. Bucoveanu)

Box graphs



γZ box graphs

Sensitivity to hadronic physics at low Q^2 ➜ an important source of error

3 groups with independent analyses agree in size, but disagree on errors

Hall et al.; Carlson and Rislow; Gorchtein et al.

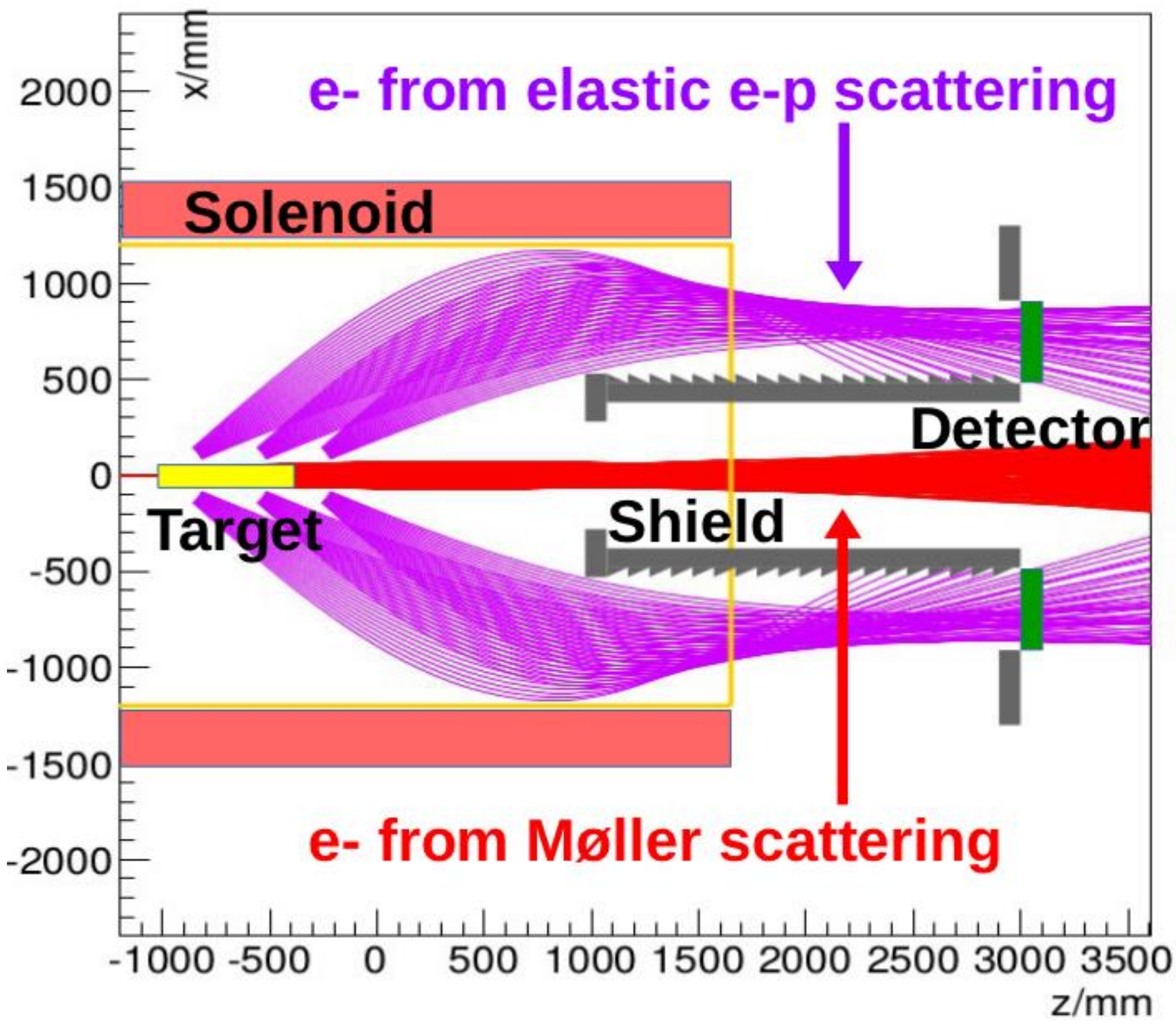
Advantage at MESA/P2: low energy

$$\Delta A_{LR}^{box} / A_{LR} = \pm 0.4\,\%$$

P2 setup: Solenoid design

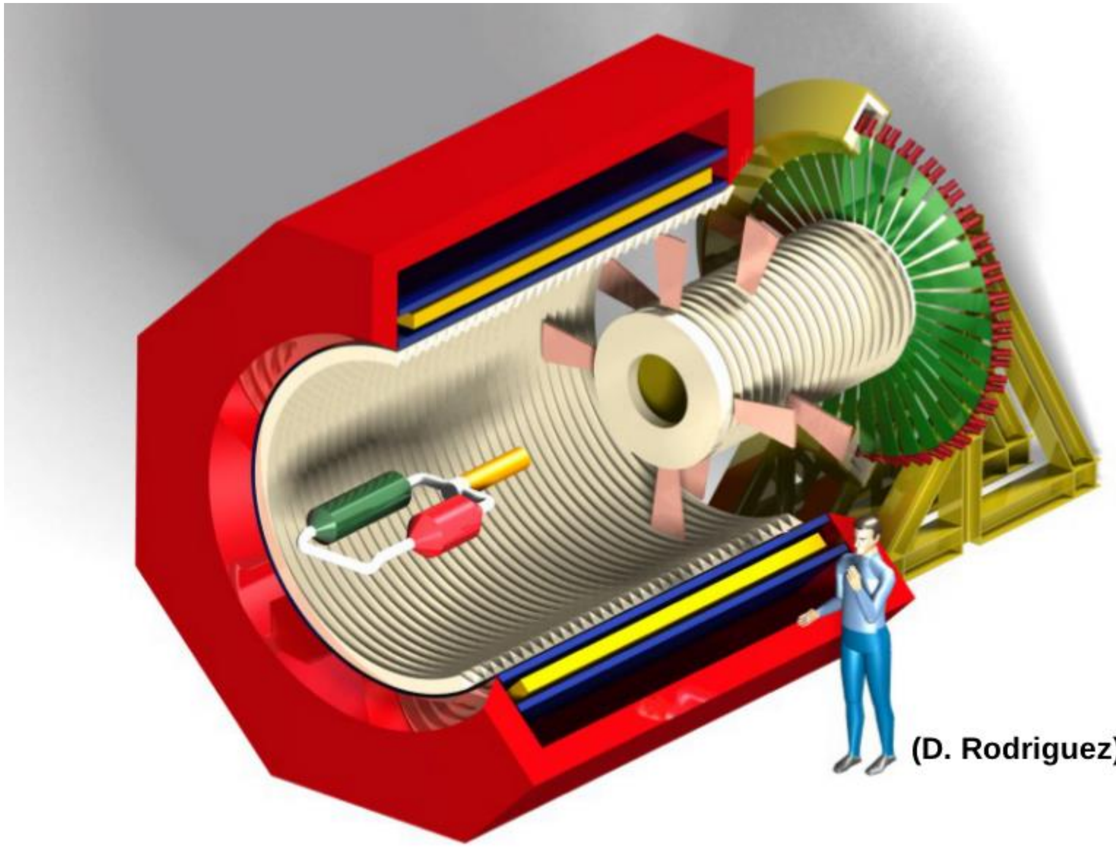
Raytracing:

- Separation of Møller events in the field of the solenoid
- Suppression of photons with shielding
- Find a suitable place for the integrating detectors



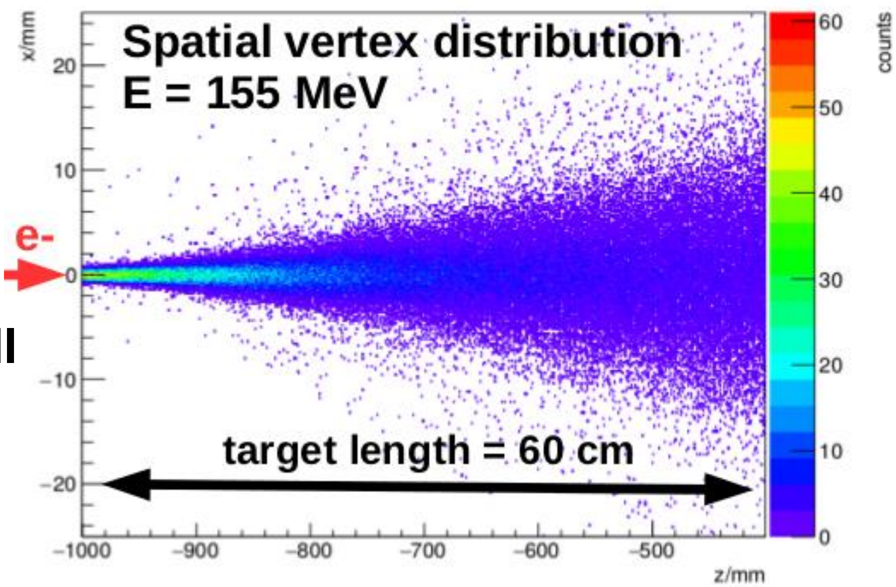
CAD Design / GEANT4 Simulations

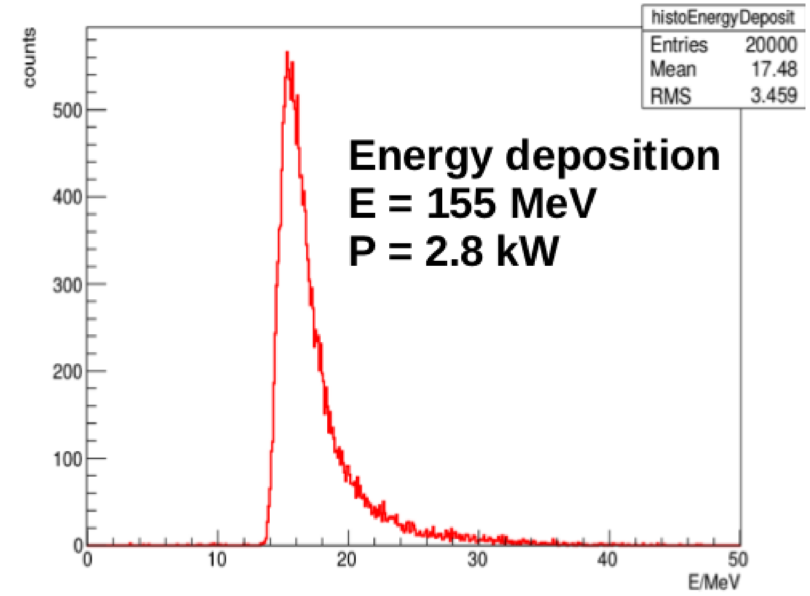
- Full GEANT4 simulations
- Interface CAD-GEANT4 was implemented
- Modifications in the design can be tested efficiently with the GEANT4 simulation

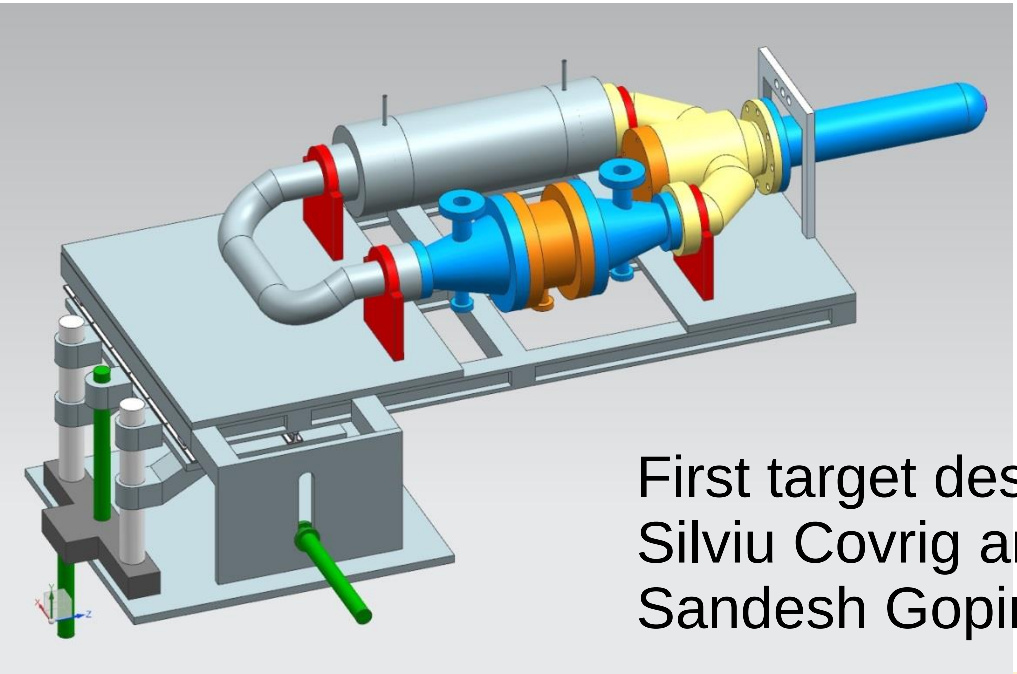


Liquid hydrogen target

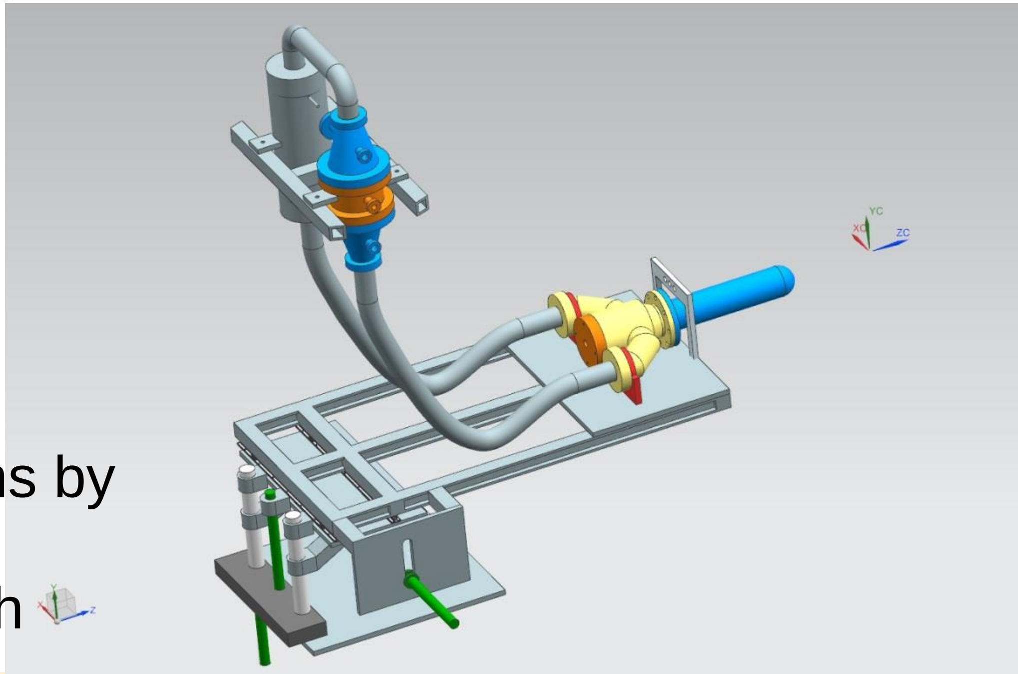
Interactions of the beam electrons in the target cell





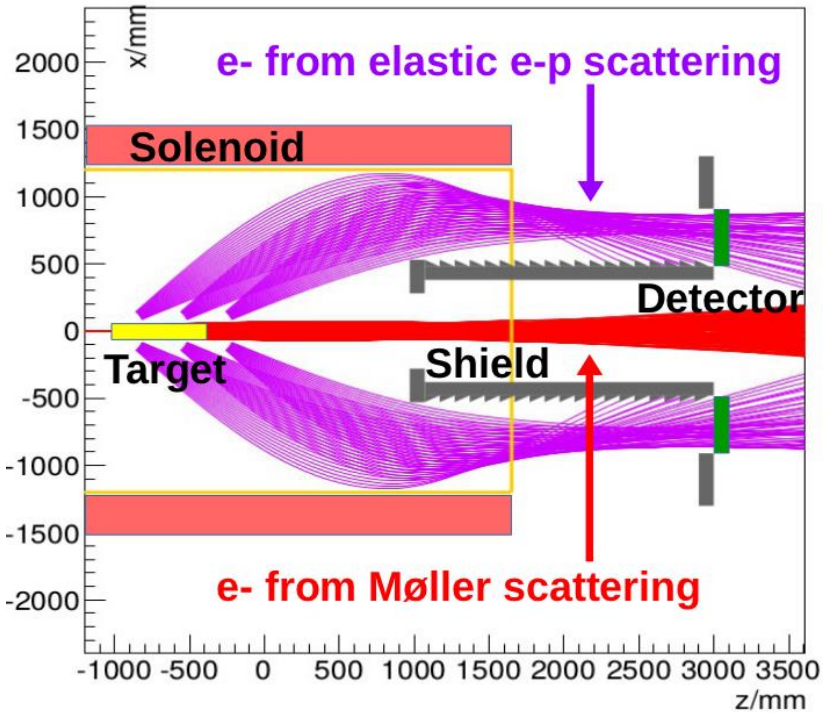


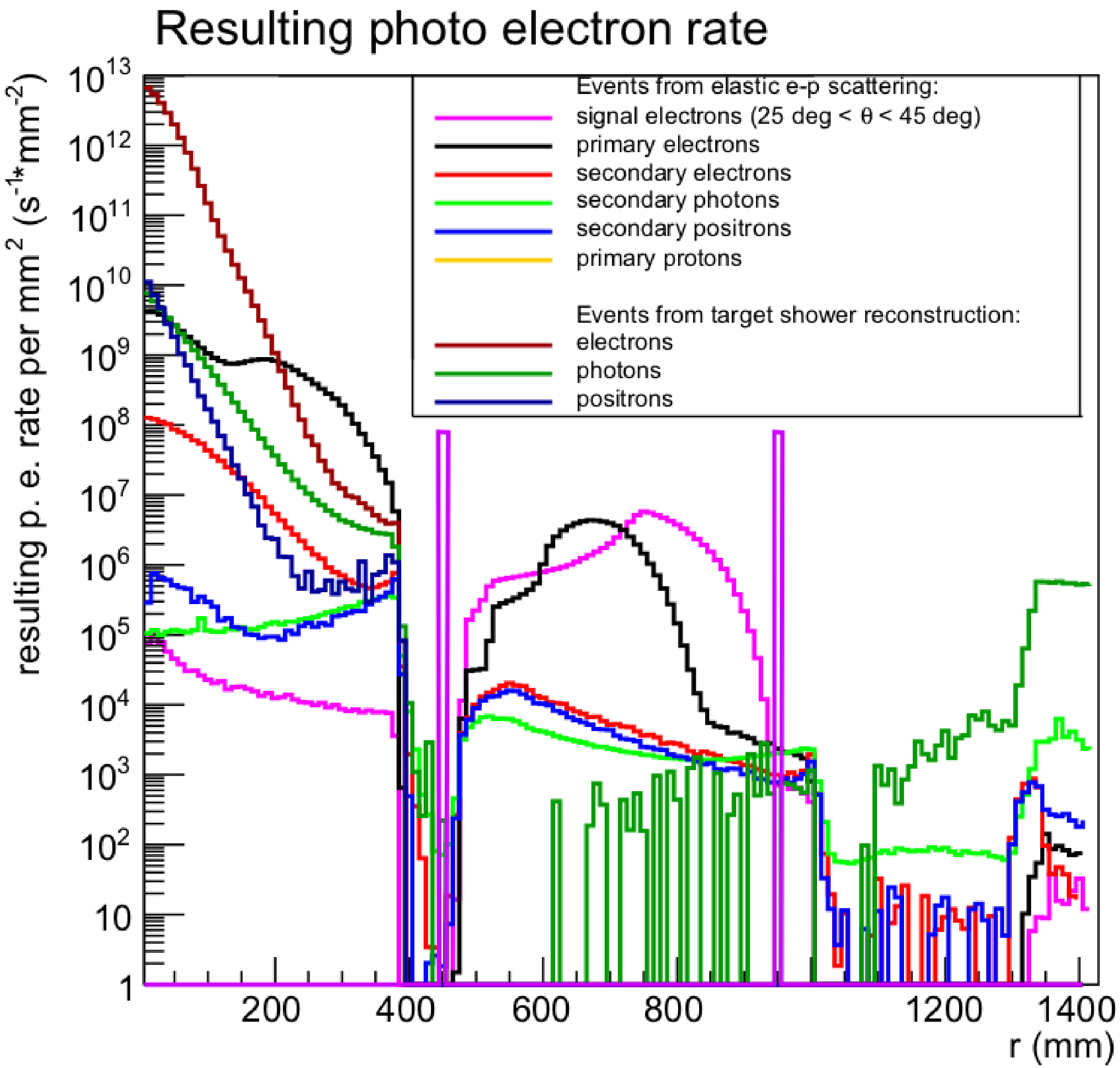
First target designs by Silviu Covrig and Sandesh Gopinath



Magnet spectrometer - Simulations

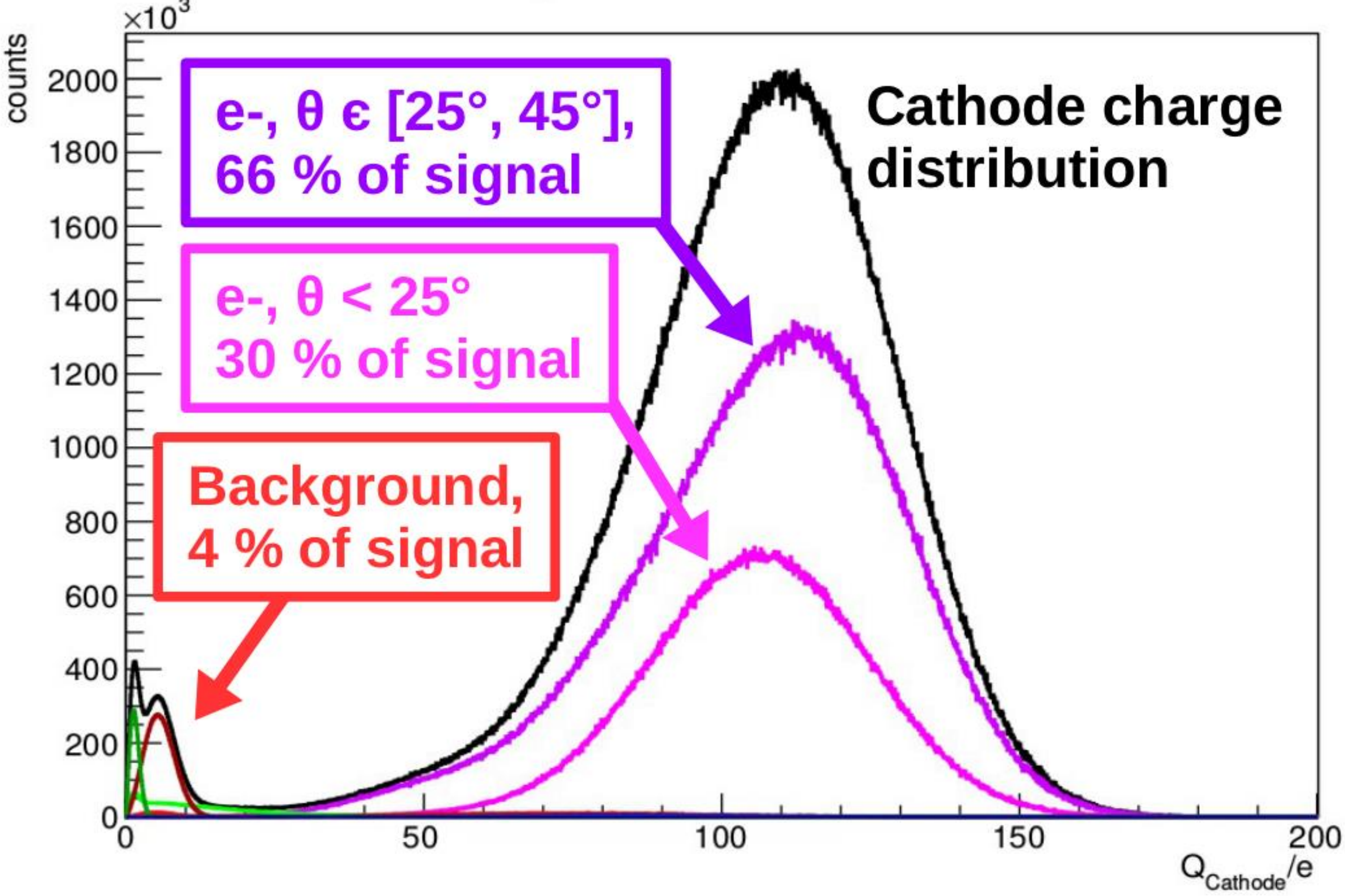
Result of the GEANT4-simulations:
Photoelectron rates for various processes



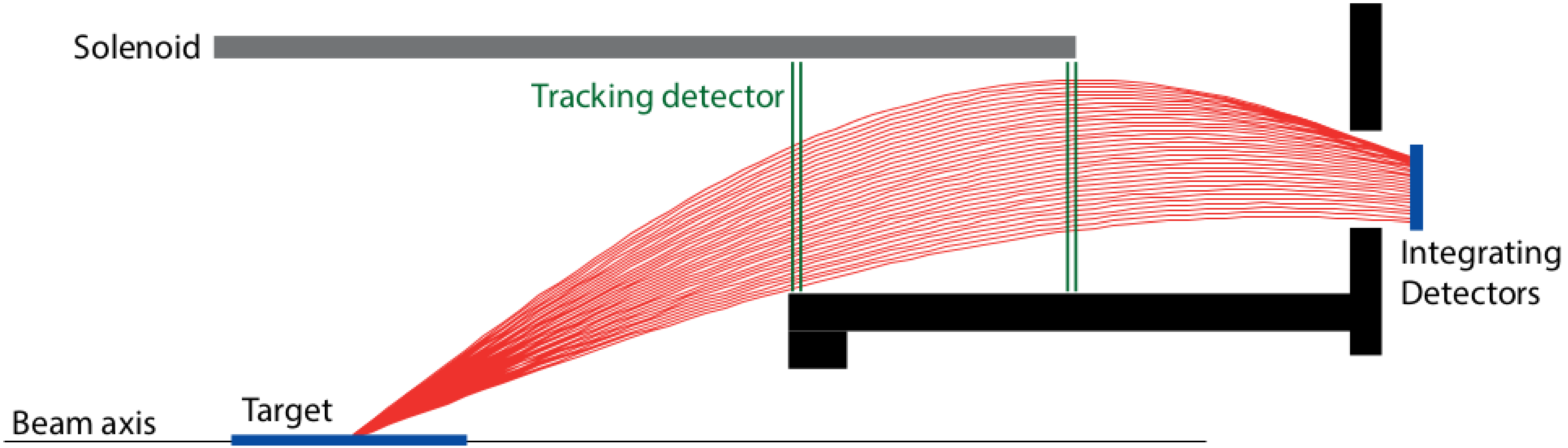


Magnet spectrometer - Simulations

Present status of the simulations:
Relative uncertainty of 0.13% für $\Delta\sin^2\Theta_W$



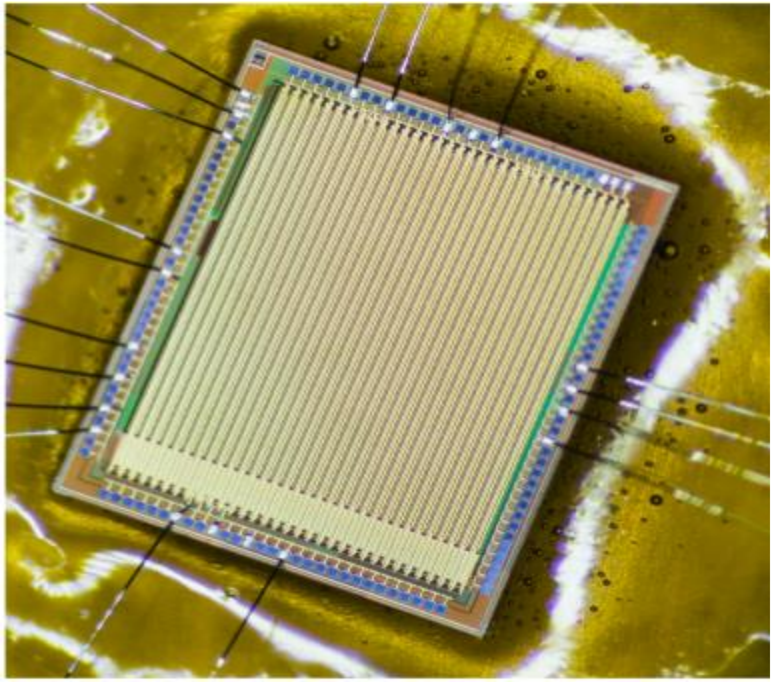
Tracking detector: Determination of Q^2



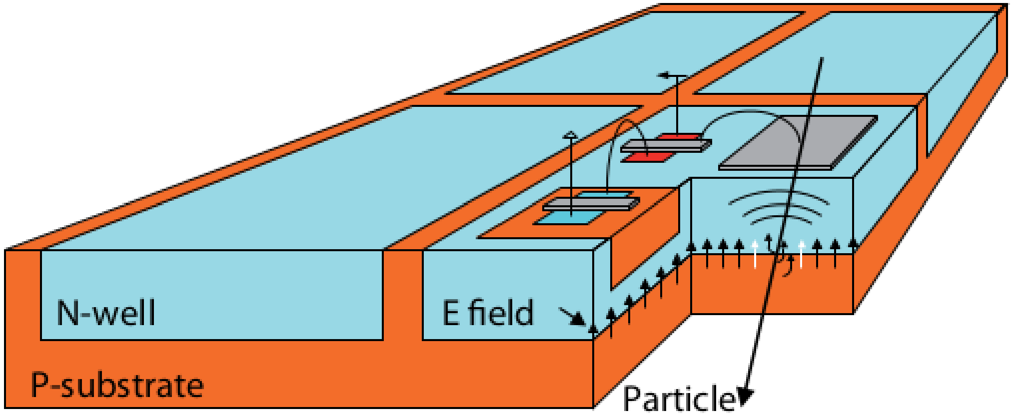
- Electrons with low momentum:
  Thin detectors

- Very high rates:
  Fast, granular detectors

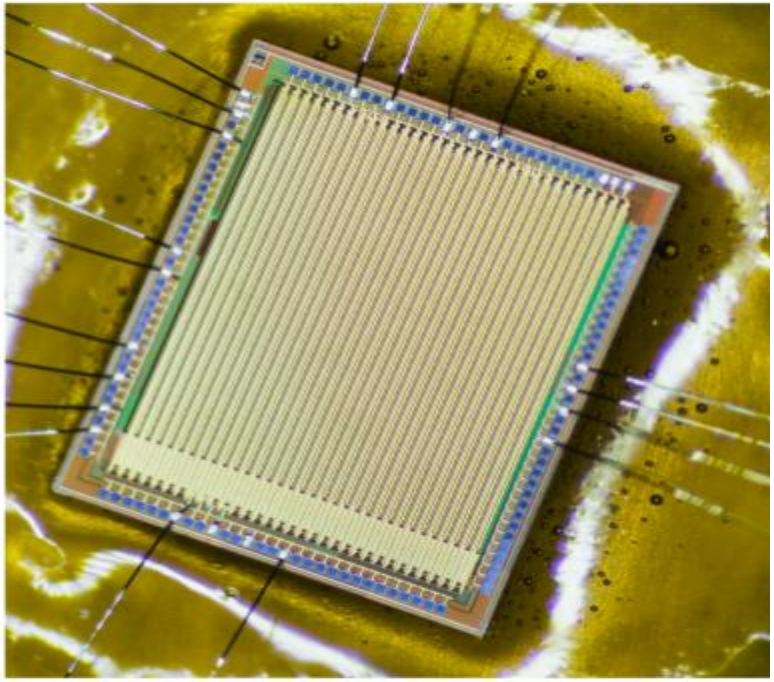
- **H**igh-**v**oltage **m**onolithic **a**ctive **p**ixel **s**ensors (**HV-MAPS**), 50 µm thick



Tracking detectors: Determination of Q^2



- Fast collection of charge
- Logics directly implemented on the chip:
  Digital Output (Adress of impact position and time stamp)



- Current generation (MUPIX7):
  40 x 32 pixels
  80 x 103 µm pixel size
  9.4 mm² active area

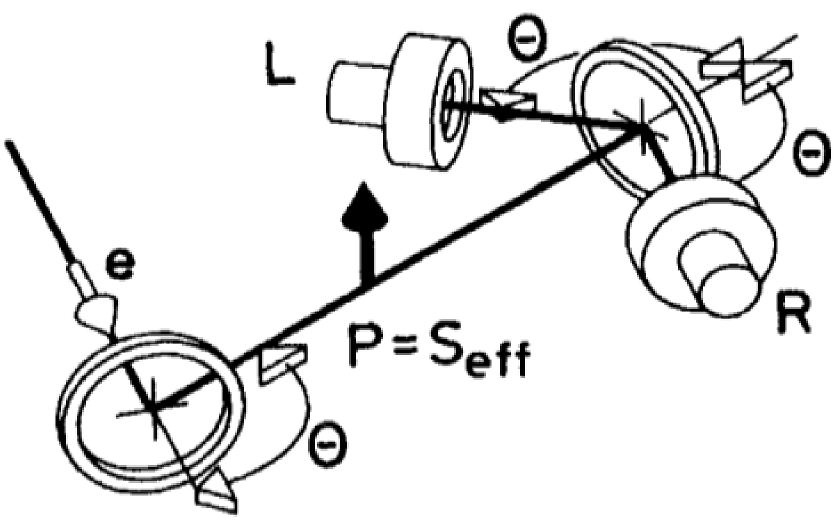
- Position resolution at the order of the pixel size
- Detection efficiency > 99%
- Time resolution <20 ns

- Beam tests at MAMI (electrons/photons)

Polarimetry

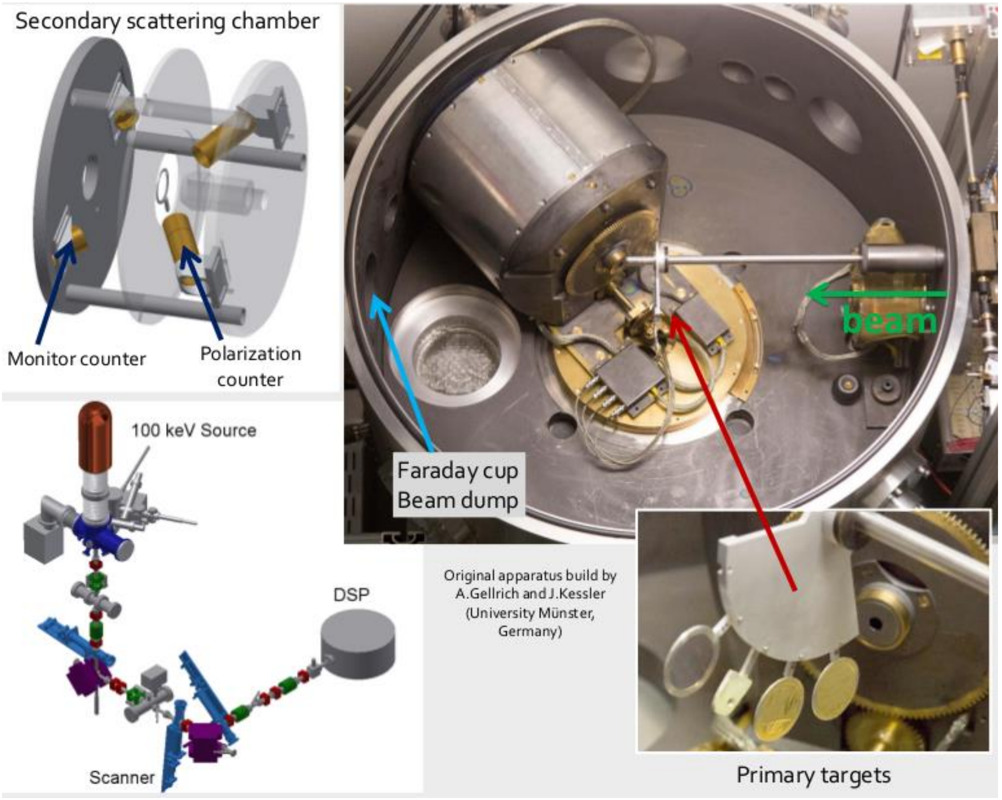
Determination of the Polarization degree of the electron beam mit $\Delta P/P=0.5\%$

- **Double Mott polarimeter**: *Measurement* of the analyzing power possible



[Gellerich and Kessler, Phys.Rev.A. 43, 204 (1991)]

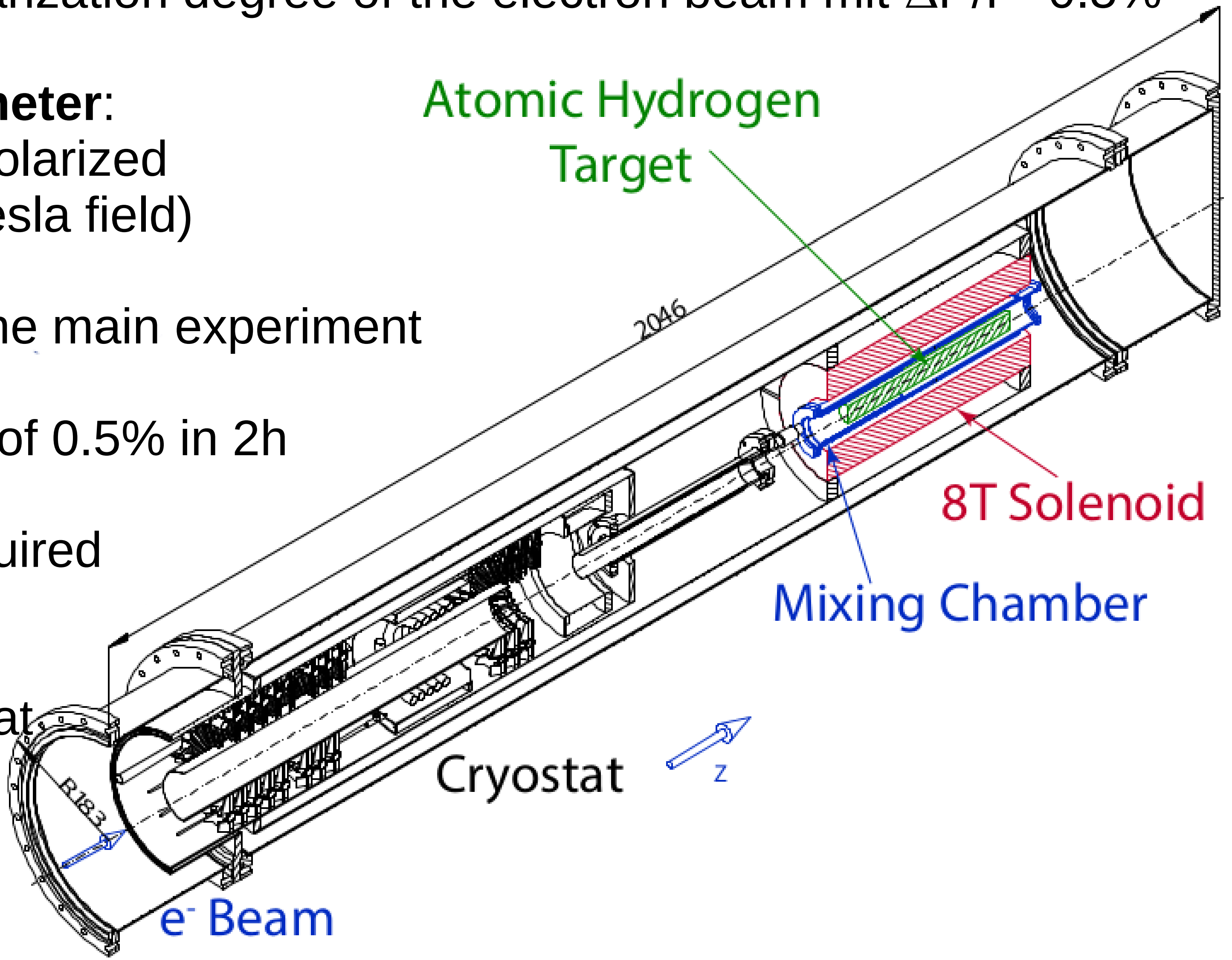
- First measurements performed at the test source at MAMI



Polarimetry

Determination of the Polarization degree of the electron beam mit $\Delta P/P=0.5\%$

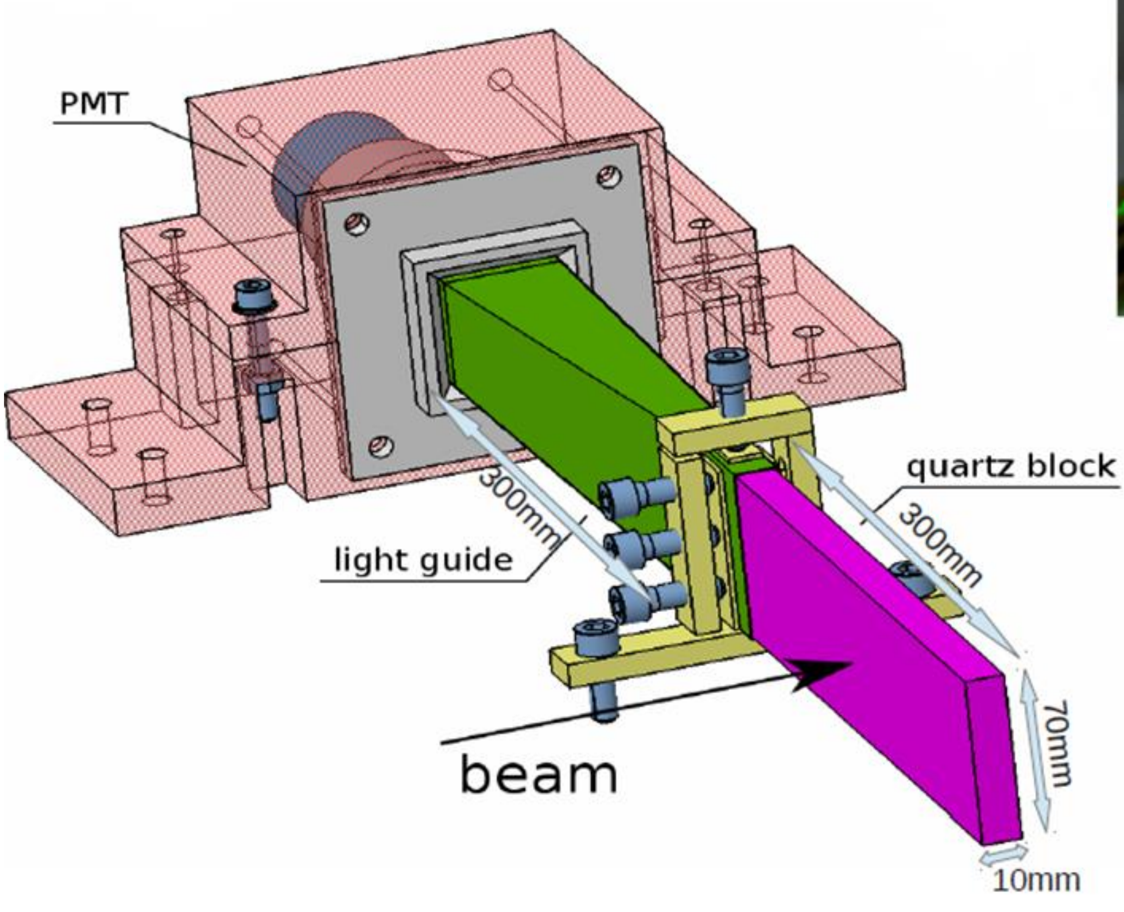
- **Hydro-Møller Polarimeter**:
  Møller scattering off polarized atomic hydrogen (8 Tesla field)
- Operation parallel to the main experiment
- Statististical precision of 0.5% in 2h
- Low temperatures required (250 mK)
- $^{3}He/^{4}He$-Mixing cryostat under development

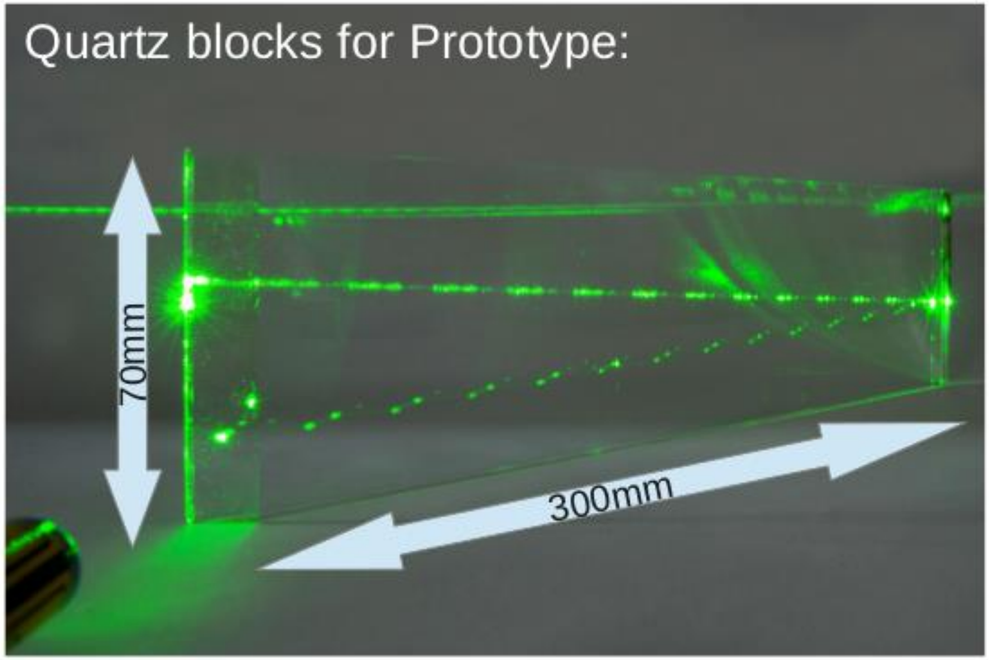


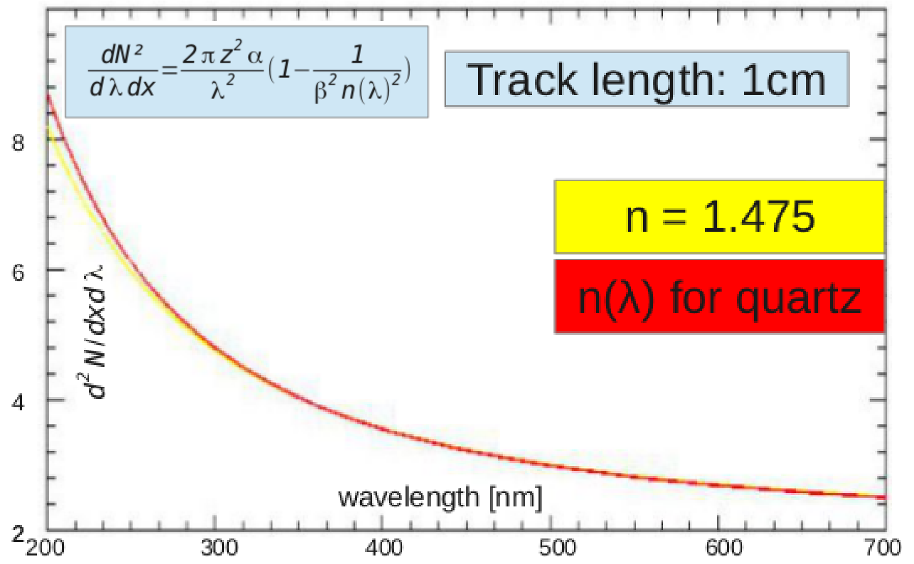
Integrating detectors

Cherenkov-Medium: Fused Silica

- Exception transmittance for UV
- Very good radiation hardness

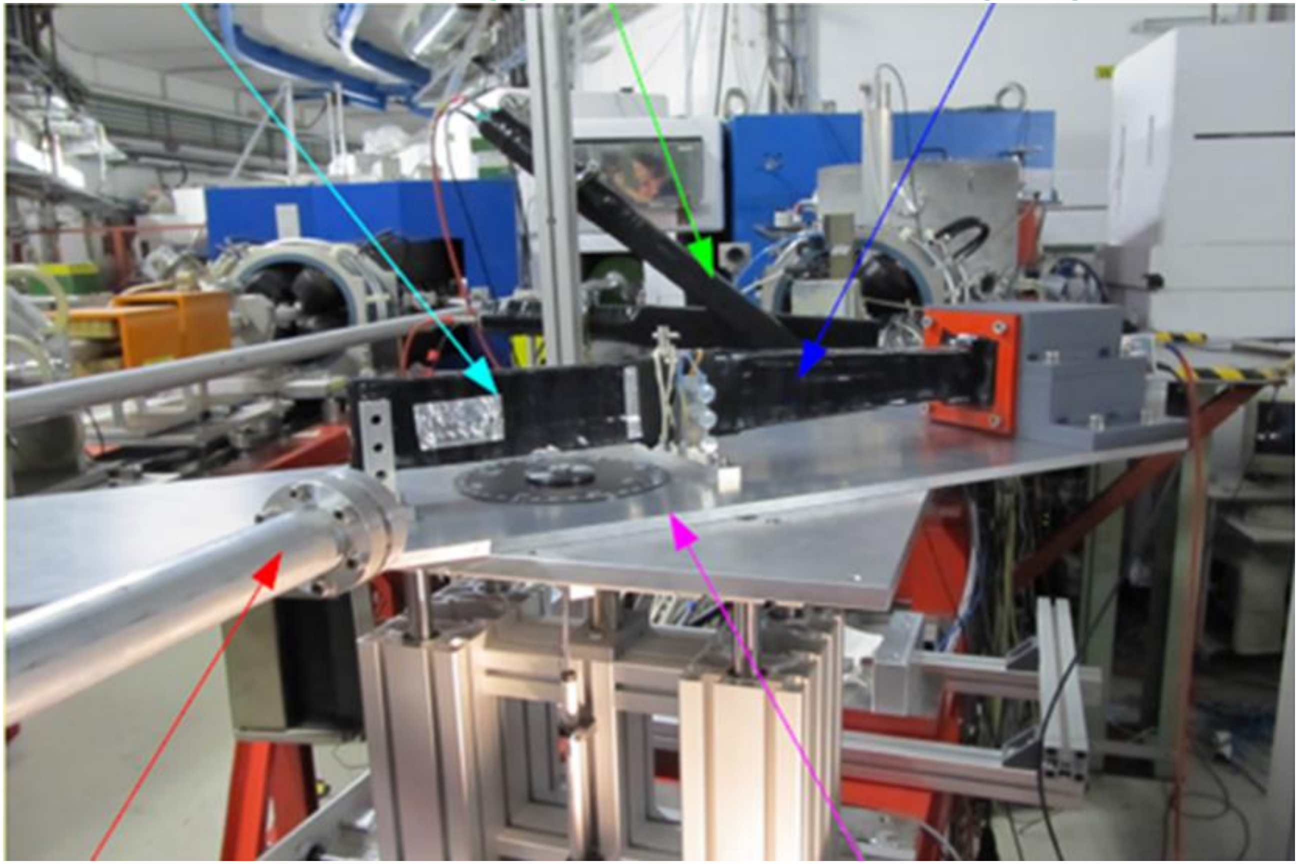






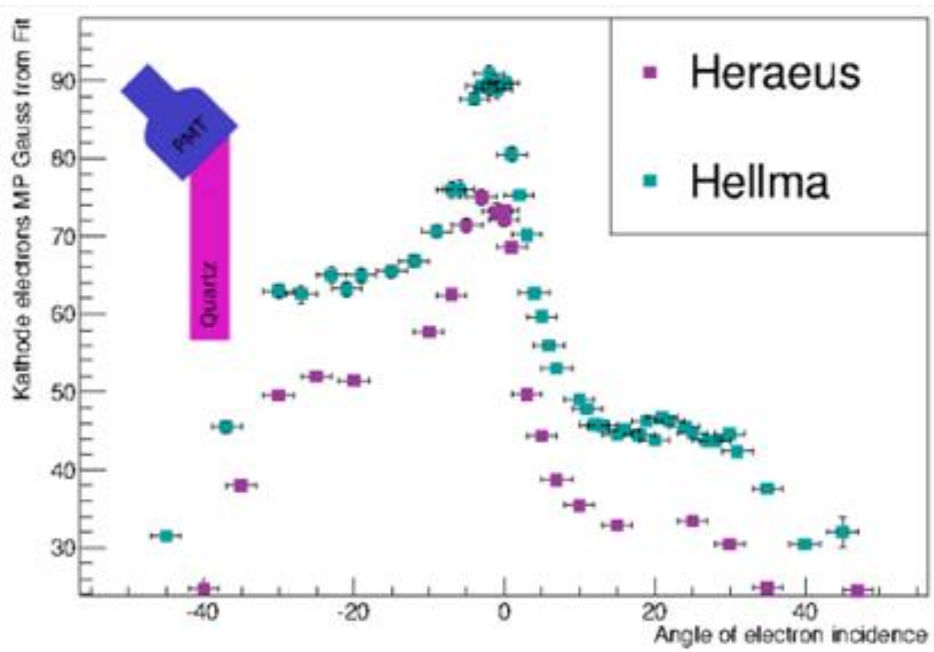
Integrating detector: Beam tests

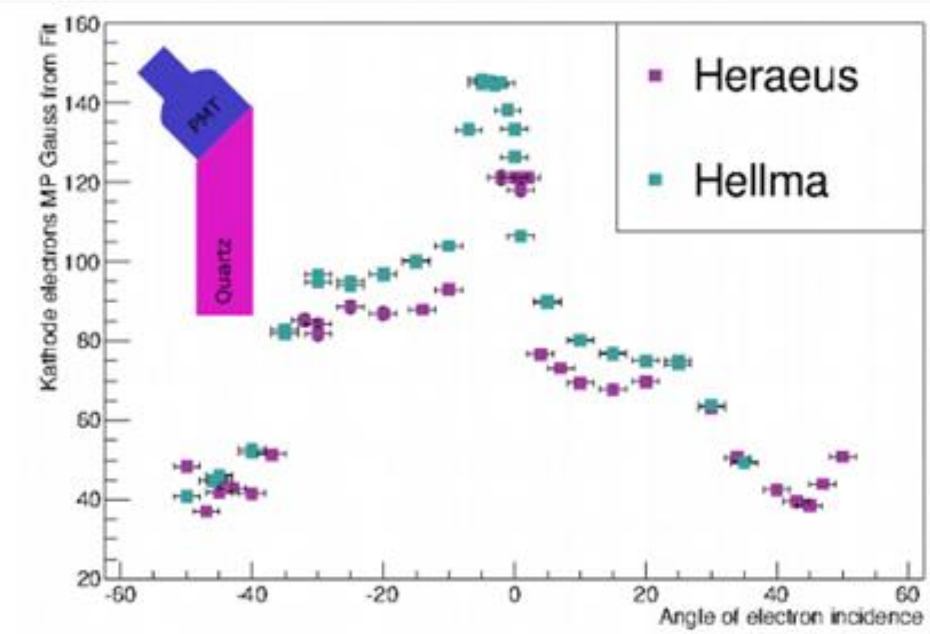
- Beam tests at MAMI

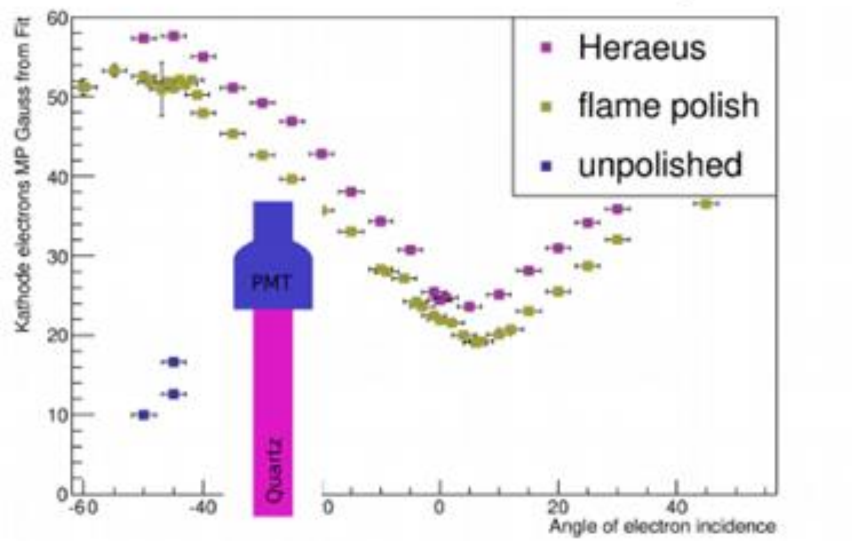


- Various Fused-Silica materials
- Various wrapping materials
- Reflecting foils for light guides
- Various Photomultiplier tubes
- Data acquisition electronics

Integrating detectors - beam tests





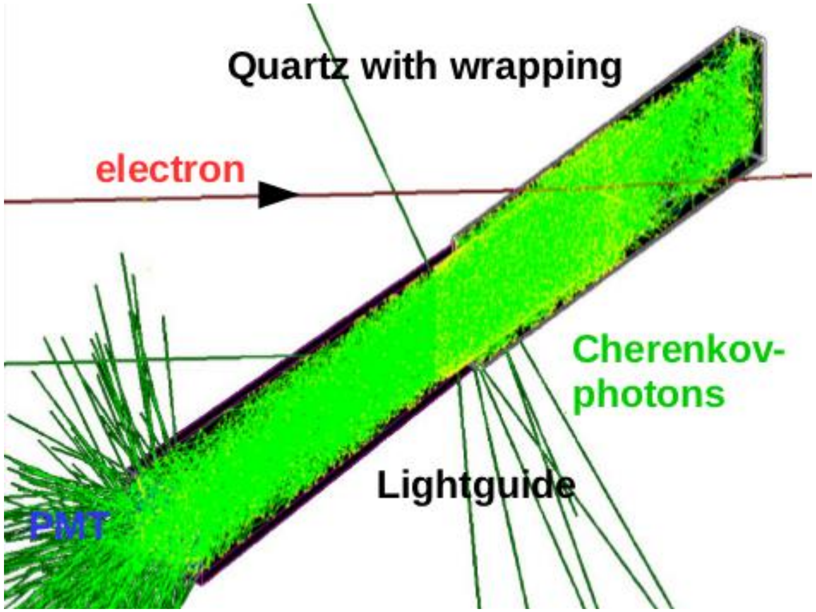


Measurements

Photo-electron yield as a function of

- impact angle
- impact position
- various polishes

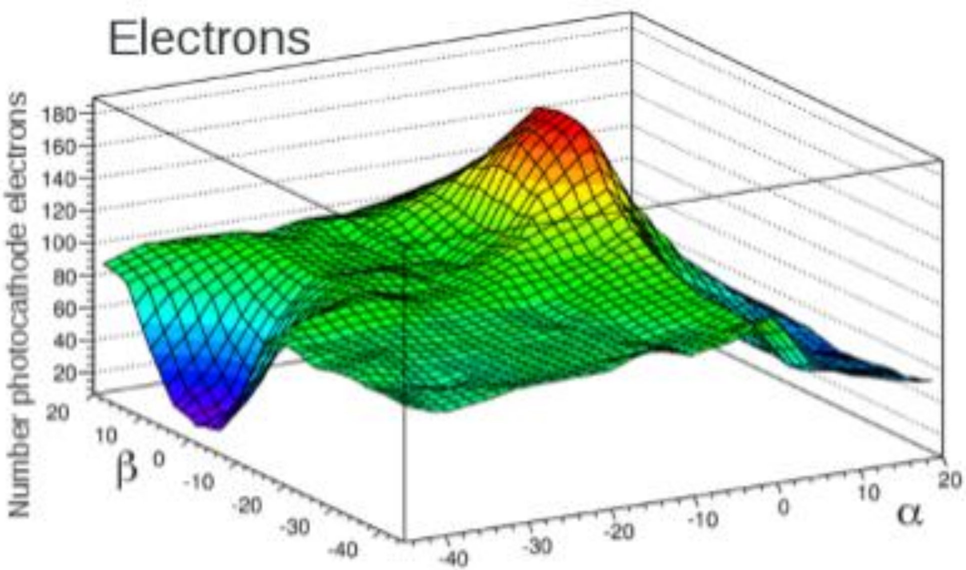
Integrating detectors: Simulations

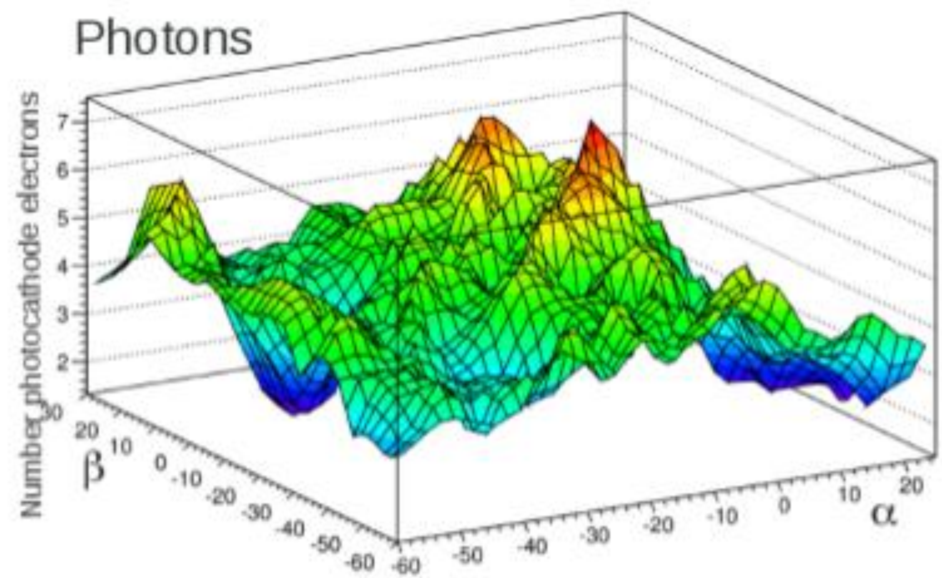


Simulations

Photo-electron yield as a function of:

- Impact position
- Impact angle
- Particle energy
- Particle species





Summary

- P2: New experiment at MESA in Mainz
- Determination of the weak mixing angle at low Q^2 with high precision: $\Delta\sin^2\Theta_W/\sin^2\Theta_W=0.13\%$
- Potential for the discovery of Physics Beyond the Standard Model
- Challenges in theory and experimental techniques
- Work in progress

Thank you for your attention!